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Nuclear Power and Radiation in Perspective

Selections from *NUCLEAR SAFETY*

J. R. Buchanan J. A. Haried

Prepared for the U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Under Interagency Agreements DOE 40-551-75 and 40-552-75

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NUCLEAR POWER AND RADIATION IN PERSPECTIVE

Selections from *Nuclear Safety*

J. R. Buchanan J. A. Haried

Engineering Technology Division

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FOREWORD

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NUCLEAR POWER AND RADIATION IN PERSPECTIVE

J. R. Buchanan   J. A. Haried

ABSTRACT

This review compiles 33 articles about nuclear power and associated radiation hazards written for *Nuclear Safety* between 1964 and 1980. A perspective on these hazards is sought by comparing them over these last 16 years with hazards inherent in other energy development technologies. Four approaches to the problem are considered: biological effects of low-level radiation, risk-benefit concepts, nuclear fuel cycle risks as compared with other risks, and the relationship between mass media and public interest.

INTRODUCTION

Throughout the 21 years of its publication, *Nuclear Safety* has monitored the debate on nuclear power. Nuclear debate issues are most clearly seen in light of the overall energy debate; always, the focus is on relative hazards to the public of the various energy development technologies (Sect. D).

Hazards unique to nuclear power are largely because of radiation from the fuel cycle and from potential accidents. Section B investigates radiation and its effects.

Hazards of fossil-fired generation of electricity are because of less spectacular problems inherent in mining and drilling, transportation, and steady-state generation of large quantities of effluents and solid wastes. Perceptual difficulties in viewing, comparing, and contrasting these hazards are discussed and analyzed in Sect. E.

The proper measure for comparing various hazards is the concept of risk-benefit analysis, introduced and enlarged in four articles in Sect. C. The guiding principle is stated by Ernest Siddall in his article, "Control of Spending on Nuclear Safety," as follows:

> The components of any safety activity should be carried out in order of diminishing cost effectiveness; the activity should be terminated when a further amount of money spent on it will not save as many lives as it would have done if spent in some other way.

The underlying assumptions of risk-benefit analysis require close scrutiny. Only economically feasible methods of generating large amounts of electricity are considered. Economic feasibility includes the concept of the greatest good for the greatest number of people. Greatest good is defined in engineering terms as the most efficient use of available resources leading to lowest total cost to the consumer. Total cost includes environmental and health effects as well as cents per kilowatt hour. The more basic issues of societal values, morality, and economic growth are assumed consistent with this definition of greatest good. "Energy Policy-Bioethical Principles and Priorities," in Sect. A, addresses these basic issues explicitly and concludes that the reasonable use of nuclear power resolves them most favorably with the greatest public good. In summary, the question is not *whether* a unit of electrical energy should be produced, but *how* it should be produced.

A. ENERGY POLICY OVERVIEW

An important concept of risk-benefit analysis often ignored in the literature is that of the risks and costs of electricity shortages and outages. The introductory paper by Dr. Margaret Maxey is a responsible view of energy supply and a bioethical approach to energy policy: "Bioethics require a scientific consideration of the entire spectrum of biohazards from all candidate energy sources, as well as from toxic chemicals and minerals in native and industrial processes, before making public policy." Various themes struck by Dr. Maxey are enlarged and elaborated throughout this report.

B. RADIATION AND RADIATION EFFECTS

The largest section of this report, Sect. B, is devoted to understanding biological risks of ionizing radiation. A comprehensive overview of radiation protection terminology and concepts was carried in *Nuclear Safety* in 1979 entitled "Recommendations of the International Commission on Radiological Protection." That report appears as article 10 in this section.

In the spring of 1964, *Nuclear Safety* published the first article in the series "Radiation in Perspective" entitled "The Potential Hazard from Radiation." This article, excerpted from a lecture by Francis L. Brannigan of the U.S. Atomic Energy Commission (AEC), discusses the observable body effects of radiation exposure.

The first of two articles by Merril Eisenbud of New York University Medical Center deals with popular misconceptions and statements taken out of context concerning radiation hazards and effects. Though it makes no positive statement for nuclear power, "Explosion of Some Radiological Myths" points out frequent pitfalls in criticizing nuclear power.

An article on the "Effect of Low-Intensity Radiation on Man" by Francis J. Jankowski, a nuclear engineering professor at Rutgers University, compares doses of radiation with doses of chemicals required for normal biological functioning. Jankowski's data suggest that a low-level radiation threshold exists below which the biological effects of ionizing radiation are beneficial.*

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*The BEIR III report, released by the National Academy of Sciences Committee on the Biological Effects of Radiation on July 29, 1980, endorses a linear quadratic model for cancer risks from low-level radiation. This model precludes any possibility of beneficial effects.

Five years after his first *Nuclear Safety* article, Merril Eisenbud wrote from his point of view as a member of the National Committee on Radiation Protection describing the background of U.S. "Radiation Standards and Public Health." Subsequent to this article, the AEC proposed changes in its regulations to keep radioactive effluents from light-water power reactors "as low as practical" (*Fed. Regist.* 36(111): 11113, June 9, 1971).

Four articles deal with population doses caused by low-level radiation in the environment and in the food chain. Population doses due to urban environments, lifestyles, and natural background radiation, in addition to doses from steady-state effluents from nuclear facilities, are analyzed in articles 5, 6, 7, and 9. The EPA report, "Radiological Quality of the Environment in the United States, 1977," summarizes estimated population doses.

Nuclear Safety has carried four critical reviews of the literature — articles 8, 12, 13, and 14 — concerning prospective and retrospective studies of large, irradiated populations and observable health effects. Extensive bibliographies are included. Article 11 in this section is a prospective study of the health impact of the radiation released during the accident at Three Mile Island.

The often acrimonious nuclear debate centers on the controversy over low-level radiation and its uncertain biological effects. These 14 articles provide the perspective of upper and lower bounds on otherwise uncertain biological effects of low-level radiation. Viewed thusly, fear and hostility generated by the nuclear debate are clearly unwarranted.

C. RISK-BENEFIT CONCEPTS

The four extensive analyses included in this section represent recent work in risk-benefit concepts. The "Comparative Risk-Cost-Benefit Study of Alternative Sources of Electrical Energy" study published by the AEC in December 1974 represented, at that time, the editors believed, the most comprehensive assessment of the risks, costs, and benefits of coal, oil, natural gas, and nuclear fuel cycles. "Risk-Benefit Evaluation for Large Technological Systems" deals with general aspects of risk-benefit methodology, societal knowledge and perception of risk, and risk-acceptance criteria. This wide-ranging project attempts to integrate with risk-benefit methodology the highly subjective questions dealt with further in Sect. E, such as "What is the dollar value of a human life?" and "How safe is safe enough?"

Edward O'Donnell and John Mauro of Ebasco Services, Inc., advocate consistent health and safety regulatory policy based on uniform risk- and cost-benefit criteria in the next article, "A Cost-Benefit Comparison of Nuclear and Nonnuclear Health and Safety Protective Measures and Regulations." The call for a unified regulatory philosophy echoes Dr. Maxey's proposal in Sect. A for a cabinet-level Department of Health and Safety as "a consolidating, streamlining, efficiency-centered governing organ to which regulatory agencies are answerable and accountable."

The cost of saving lives is a novel index used in "Control of Spending on Nuclear Safety." Because this cost varies considerably from industry to industry, Siddall suggests "that some agency should be set up to monitor and coordinate safety activities." This holistic concept of risk-benefit analysis seems to be one whose time has come.

D. NUCLEAR FUEL CYCLE RISKS VS OTHER RISKS

For purposes of perspective, potential injury caused by radiation dose is compared with other risks people confront in their everyday lives. The nine articles in this section span the development of applied-risk assessment methodology from 1964 to 1979.

In the continuing "Radiation in Perspective" series, C. Rogers McCullough of NUS Corporation examines a number of factors that influence the health and longevity of populations. He estimates, as does Andrew P. Hull, the loss in average life-span because of natural background and human-made radiation, smoking, country vs city living, and a myriad of other commonplace factors. Hull and Birny R. Fish, in separate articles, note that nuclear plants produce less air pollution, relative to applicable standards, than fossil plants. Fish describes several air pollution disasters of the past and proposes that nuclear energy has a critically important role in combatting the growing assault on our atmosphere by supplanting fossil fuel in most of the power plants to be built late in the century.

The next two articles in the "Radiation in Perspective" series are also concerned with health risks in electricity generation from fossil and nuclear plants. In a 1972 State of California long-range planning study, Chauncey Starr and M. A. Greenfield at The University of California at Los Angeles compared the public health risks of the steady-state operation of nuclear plants and oil-fired plants. L. B. Lave and L. C. Freeburg of Carnegie-Mellon University compared the occupational and public-health effects of electricity generation from coal, uranium, and oil, with particular emphasis on accident and chronic disease rates for fuel extraction and airborne emissions from power and reprocessing plants. Based on current operating practice, they conclude that the uranium fuel cycle offers a lesser health hazard than a coal fuel cycle.

Norman Rasmussen next gave a preview of "The AEC Study on the Estimation of Risks to the Public from Potential Accidents in Nuclear Power Plants" — the Reactor Safety Study. He covers organization of the study in seven major tasks and the methodology of determining accident probabilities, and he gives a one-year progress report. Following this preview we have included the section of the Report of the Reactor Safety Study entitled "Introduction and Summary."

A quartet of authors from the Oak Ridge National Laboratory (ORNL) published a report on the "Radiological Impact of Airborne Effluents of Coal-Fired and Nuclear Power Plants." The ingestion and inhalation pathways for airborne radionuclides emitted from both coal-fired and nuclear plants are considered in their population and organ dose calculations.

In April 1979, the National Academy of Sciences (NAS) Committee on Science and Public Policy released the "Summary and Synthesis Chapter" of their literature review entitled "Risks Associated with Nuclear Power." Applied risk-assessment methodology, as illustrated in nine articles in this section, provides a quantitative measure to orient our perspective on competing risks and risks in general. Decisions concerning energy policy, asserts the NAS report, "are not simply yes or no; they are decisions about alternatives, and such decisions cannot be made without assembling, *for each of the alternatives,* the best available estimates of such things as *benefits, costs, risks,* and *time scales.*"

E. THE MASS MEDIA AND THE PUBLIC INTEREST

> Nothing in life is to be feared;
> it is to be understood.
>
> Marie Curie

In the nuclear debate the fundamental issue is the public interest — the greatest good for the greatest number of people. In a democratic society, ongoing resolution of this issue places great demands and responsibilities on mass media. Responsible decisions are based on a thorough understanding both of hazards involved and of fears generated by these hazards. The courageous sentiment expressed by Marie Curie is a challenge to responsibility for both mass media and the electorate.

On the assumption that mass media both reflects public interests and molds public opinions, Dan N. Hess of ORNL reviewed, in 1970, nearly 800 articles in the daily and periodical press pertaining to public controversies within the nuclear industry. He categorizes each article as for or against nuclear power and examines their philosophical and psychological impact on the reader. In the same year H. G. later of Niagara Mohawk Power Corporation explored public and media attitudes toward nuclear power from an industry point of view. Both authors call for a more direct, open, and honest effort by the nuclear industry to communicate with the general public.

Lois Bronfman and Thomas Mattingly, working for the Social Impact Analysis Group at ORNL, attended Critical Mass '74 and '75 conventions and provide, in article 3 of this section, much helpful insight into nuclear opposition coalesced by Ralph Nader. They note that the focus of nuclear debate has shifted significantly from technical to social issues and, concurrently, that the number of issues has increased. The effect of the shift to social issues is reduced impact of technical input in decision making; the effect of the increased number of issues is increased complexity of possible solutions. The authors come away doubtful that more discussions of the technical safety issues by scientists will renew public confidence in the nuclear industry. The most important accomplishment of the antinuclear movement, in their opinion, "has been to bring to the attention of decision makers the need to consider the adverse effects that a technology may have on its people and their institutions."

The effects that nuclear technologies are having internationally on people and their institutions are assessed from the International Atomic Energy Agency's point of view by Georges Delcoigne in his article "Education and Public Acceptance of Nuclear Power Plants."

As devil's advocates, airing the hazards of nuclear power, members of mass media have done an outstanding job. Responsible decision makers, however, require a similar perspective on competing alternatives. For example, if nuclear wastes seeping from half-mile-deep waste storage facilities will endanger people 1000 years from now, what are quantitative dangers of acid rain and CO_2 buildup from reliance on coal for the next 30 years? If energy supply is not allowed to keep pace with demand, who will decide exactly how scarce and expensive energy should be? If solar power is being kept from us because oil companies do not own the sun, then why is there no solar power in those socialist countries where oil companies do not own even the oil companies? As industrialized countries continue to burn oil to produce electricity, thus depleting the world's supply of relatively cheap oil, at what point are we responsible for suppressing growth of less-developed countries whose growth and stability depend to a large degree on relatively cheap oil? The touchstone of all energy alternatives is the following question: Do they enlarge freedoms or restrict choices? A determined effort by mass media to air this balanced perspective on the nuclear debate is necessary to resolve it in the public interest.

F. THE FUTURE OF NUCLEAR ENERGY

Where do these bioethical principles, radiation effects, risk-benefit concepts, energy alternatives, and apparently opposing public interests leave us today? At the end of the first nuclear era, reported Alvin Weinberg in his address to the American Nuclear Society-European Nuclear Society Topical Meeting on Thermal Reactor Safety in Knoxville, Tennessee, April 11, 1980. Weinberg asserts, "the future of nuclear energy, whether there will be a second nuclear era, will depend upon the public's overcoming its unreasoning dread of ... exposure to low-level radiation." Today, on the threshold between the two eras, we can still responsibly choose our energy future. However, as time is lost and costs continue to rise, our choices narrow.

Epilogue

These 33 articles that have appeared over the years in *Nuclear Safety* form a very important collective source of information in comparative risks of nuclear power and radiation relative to risks that humans routinely face in their everyday lives. Equally important are comparisons of the benefits and risks of nuclear power generation. While the articles are wide-ranging in their coverage, they do not discuss every conceivable facet of the risks and benefits of nuclear power and radiation. *Nuclear Safety* will continue to inform and stimulate its readers with articles on all these topics in the future.

A. ENERGY POLICY—BIOETHICAL PRINCIPLES AND PRIORITIES

ENERGY POLICY—BIOETHICAL PRINCIPLES AND PRIORITIES

Margaret N. Maxey
Assistant Director
South Carolina Energy Research Institute

As a result of media-generated fallout from TMI, we have entered a new phase in the rancorous dispute over nuclear technology - that of obituary and epitaph writing.

Ostensibly, nuclear technology has been placed on trial and stands virtually convicted of being "a criminally conceived monster," an immoral technology from which we must be liberated by our moral guardians in the anti-nuclear movement.

I do not deny that nuclear technology is on trial. But I would like to explore a different interpretation of the events of that past ten years, that is since a generation of professional protectors discovered and espoused the anti-nuclear cause.

Permit me to suggest that what is actually, more fundamentally, on trial is not merely the future of a specific technology, but the future of democratic institutions as they have evolved in the "great American experiment."

History attests that democracies are born carrying their own seeds of destruction. A general failure of citizens in the United States to comprehend the origin and widening dimensions of the political conflict over energy policy foreshadows a period of serious reckoning.

I have no illusions that ethics is going to dictate an energy policy. It will not be an ethical choice. Energy policy will be a political choice. Since that is the case, let us not succumb to a political pitfall. It would be a tragedy - both for our political system and our national welfare - if the anti-nuclear movement is allowed to capture a plank in the platform of the Democratic party that would turn the political decision about a nuclear energy future into a Democratic vs Republican party victory. Nuclear energy is a political issue - about what is best for our country and the world - not a partisan issue - about what is likely to get votes for candidates for one party rather than another.

CURRENT CULTURAL CONTEXT

With the advent of "the energy crisis" and predictable public skepticism - plus a highly developed state of the art in measuring public risk perceptions about the disputed "safety" of various energy technologies - a new stage in the political arena has been set for a stirring psycho-drama aptly entitled, "The Moral Equivalent of War." It has yet to be made clear whether the intent behind this descriptive phrase was to justify calling a state of affairs equivalent to "war" or whether it was intended to justify war-like energy strategies as "moral." In either case, several leading actors in our current psychodrama appear to regard the political struggle over energy technologies not simply as a matter of minimizing harms and maximizing benefits to individuals and groups, but rather as a matter of survival or extinction for our only habitable planet, Spaceship Earth.

Indeed, public perception has been so shaped by prophets of environmental doom that both coal combustion and uranium fission technologies are now generally believed capable of having catastrophic consequences for our biosphere. This perception has transformed the public debate over energy policy from technical arguments about cost-effective methods for maximizing energy resource development, distribution and use, to moral and ethical assertions about the moral necessity of conserving limited resources, the social inequities of energy distribution, the immoral materialism embodied in Western uses of existing energy, and the abuses to which technology is put by concentrations of corporate power.

The difficulties of dealing constructively with public perception, and resolving conflicts about energy policy, are compounded by the widening gap between two different universes of discourse. On the one hand scientists and engineers are trained to function within a universe of discourse dictated by the physical nature and limits of things. The risks of public safety which they perceive and try to minimize are derived from considering actually achievable technical options.

On the other hand, the philosopher or humanist or social reformer is accustomed to a universe of discourse dictated by a philosophical vision of how things ought to be - quite apart from, even in spite of, the physical nature of technological possibilities and constraints. This vision leads to a negative perception of seemingly uncontrollable risks from powerful, complex energy systems which appear to take on a life of their own as they give aid and comfort to what many regard as man's myopic rape of the earth.

To characterize either level of discourse and perception of risk as "subjective" versus "objective" or "imagined" versus "real" is neither accurate nor constructive. A continued use of these terms, or any type of put-down of one party or other in the debate, only serves to divert us from getting down to the moral seriousness of the problem of bringing an acceptable energy future into existence.

We should realize that we are dealing with a new kind of technosocial problem one which requires a new quality of intellectual analysis and institutionalized processes of dealing with it. In order to deal constructively with public confusion and anxieties, as well as the politics of managing energy risks, we must become morally serious about responding to at least three ethical priorities.

FIRST ETHICAL PRIORITY

A first ethical priority is that the moral objections to certain energy sources and systems be made explicit, publicly debated, and resolved with some autoritative closure. (N. B. I use the word authoritative, not authoritarian.)

To do this, we need to be equally explicit about the goal which moral considerations are expected to achieve. Genuine moral discourse is not a vehicle for "taking sides" and staking out claims to moral superiority. Moral considerations would enable us to develop unifying, conceptually satisfying, authoritative principles.

In the case before us, energy policy, people take opposing positions on the moral preferability of one rather than another public policy on energy sources. Despite their differences, various parties to the energy controversy are tacitly in agreement on these statements of purpose:

1. A policy for conservation of energy - especially of petroleum imported from OPEC - is a moral obligation.
2. A policy causing energy shortages that would have tragic effects on human health, living standards of the poor, employment, and our national security is morally unacceptable.
3. An energy policy should be designed not only to serve the basic needs of the most vulnerable persons in our society, but also to inflict the least harm on people and their environment.
4. An energy policy must protect democratic values of individual freedom, social justice and equity, and preserve their institutional embodiments.

However much they may agree on these statements of purpose, leading parties to the energy debate are strongly opposed on the specific policy that can and will fulfill these purposes. As a consequence, there is small wonder that the citizens of this nation are confused and bewildered when they hear conflicting moral claims for or against a particular energy policy.

On the one hand, the American people are being told by the National Council of Churches, the President's Council on Environmental Quality, and Friends of the Earth, the Energy Project at the Harvard Business School, and other groups that our energy policy should be to phase out any dependence on sources that are branded as dangerous or immoral, on grounds that unacceptable risks to people and the biosphere are being involuntarily imposed on unconsulted present and future generations by radiation hazards from nuclear reactors, by air pollution from coal plants,by massive hydro-electric dams and LNG facilities. We should make up for any shortages by substituting a strategy of conservation and rapid development of solar energy, biofuels, geothermal, and other "soft" technologies. With such a policy, we cannot only be protected against physical and pyschic harm but also bring about greater advances in social justice.

On the other hand, the American people are being told by the National Academy of Sciences, the National Association for the Advancement of Colored People, Resources for the Future, and various other groups that it should be our national energy policy not only to pursue vigorous conservation, drastic reduction of imported petroleum and phasing in of solar energy in its various forms; but we should also continue developing coal conversion into electricity, into coke for steel and for synfuels, as well as all forms of nuclear fission including reprocessing and breeder reactors. The risks from coal combustion and uranium fission should be morally acceptable because they are far less than those imposed by alternative technologies, including hydro, solar, geothermal, etc., and give far more reliable protection against the tragedy which energy shortages will inflict on masses of poor people. Only this policy will prevent personal and social harm and provide for rising expectations of social justice.

There are serious discrepancies in these two sets of conflicting recommendations about energy policy. To the extent that they are genuinely antithetical and mutually exclusive, they cannot both be enacted by authoritative institutions.

Some consensus must be reached if the citizens of a democratic society are to express their moral responsibility for present and future generations. To that end, we must expect and demand that our elected leaders in Congress develop energy policy on the basis of principle, rather than on political gamesmanship based on capitulations of vacillating public opinion.

Permit me to suggest that the following bioethical principles might best serve policy makers as a method for organizing scientific evidence for sorting out competing moral claims, and to distinguish expression of idealism and hope about an energy future from actual constraints imposed by technological possibilities and institutional realities. I propose these, not in a spirit of advocacy, but in the interest of seeking discussion, refinement and consensus.

Bioethical Principles for Energy Policy

1. Public policy should develop those energy technologies that can be scientifically demonstrated to maximize the number of persons on this globe who experience minimal basic harm. By basic harm is meant - deprivation of basic goods necessary for material wellbeing for all living human beings as a fundamental condition for protecting the welfare of future generations (nourishing food, shelter, clothing, health, jobs, self-determined life style).

2. Social justice and equity require an equitable management of sources of basic harm. An "equitable management" is that which is proportional to actual, identifiable basic harm that can be reduced by human effort, time and money.

To implement this principle we would have to evaluate (a) the entire spectrum of both natural and man-induced biohazards from energy alternatives; (b) make cost-comparisons of the available methods for per capita reduction of these various hazards, giving priority consideration to those that are certain in contrast to probable and merely possible, and (c) only then make policies and set standards that will get the most public health protection for the most people out of a finite amount of money.

If we are going to be morally responsible in decision making this method of evaluation gives optimal expression to the reverence for human life which we all cherish.

3. Public policy should exercise wise stewardship in two ways: (a) by giving priority development to energy-only resources - i.e., uranium, thorium, deuterium - as to preserve for future generations the basic goods derived from precious hydrocarbons (medicines, fertilizers, and pesticides for increased food production, petrochemicals, etc.) which have no known or feasible substitutes; (b) by developing sources with net energy increments, so as to optimize their social utility, yet justifying energy conversion processes with net energy deficits when demonstrated that they yield greater accessibility and versatility for meeting basic needs that cannot otherwise be met.

It is morally irresponsible and ethically unjustifiable to single out for exclusive attention one or two energy sources - uranium or coal - as the embodiment of moral disvalue simply because they are accused of causing biological shortening of life. Bioethics require a scientific consideration of the entire spectrum of biohazards from all candidate energy sources, as well as from toxic chemicals and minerals in nature and industrial processes, before making public policy.

The first ethical priority is for the public to reach a consensus (not on nuclear energy) but on ethical and moral principles through which scientific evidence should be filtered. We have a right to demand that the representatives we elect for democratic decision-making should be governed by principles with which to transform evidence from scientific experts into public policy.

The need for ethical principles in energy policy-making leads to the question of the adequacy of our present democratic institutions which purportedly protect public health and safety.

SECOND ETHICAL PRIORITY

A second priority emerges from the unwarranted stigmatization of nuclear risks and radiation hazards. Our rancorous dispute over nuclear technology appears to have resulted from two institutional deficiencies:

1. The manner in which some scientific experts have been included and others excluded in the bureaucratic regulatory and standard-setting process;
2. The unfortunate fact that each regulatory agency both sets standards and enforces them by a process which is vulnerable to arbitrary revision and limitless litigation as career intervenors use the system for ulterior purposes.

Because the common good has become seriously jeopardized by legislative ambiguities (e.g., the Delaney amendment) and their interpretations by self-serving regulatory agencies, it has become an urgent ethical priority that the regulatory-agency system be radically restructured by a more enlightened legislative mandate.

As presently functioning, our regulatory agency system has been so chartered and mandated as to be compartmentalized, fragmented, and virtually unaccountable to any comprehensive guardian of the general welfare. Scientific risk-assessments, economic cost-benefit ratios and potential hazard management are forced to be piecemeal, ad hoc, haphazard, isolated for one-at-a-time consideration. Each regulatory agency operates in such a way that one kind of hazard is spotlighted for a time (because it is the current product of research projects), giving way to another in unending succession: DDT, lead, cyclamates, the Pill, red dye #2, PCB's and PVC's, triss, and now saccharin. Having completed a decade of concern about the "carcinogen of the week," we are entering a political climate that will doubtless force a decade of public concern over the "low-level radiation source of the week."

Each regulatory agency has its own category of so-called hazards on which to conduct research, at the same time making a case for more federal funds to do more research in further risk-reduction of units of hazards. Not only does this peicemeal, selective concentration magnify certain potential hazards at the data-gathering and risk assessment levels, but the public is misled into perceiving that, just because some risks are the more studied, they are by that very fact the more dangerous to public health and safety. Not only is this not the case, but by capitulating to the policy of appeasement only exacerbates public fears. For example, some nuclear proponents insist upon throwing more money and time and study into getting minor reductions in the mere probability of nuclear accidents as if that reduction were actually achieving a net increment in public safety. This insistence only signals the public that indeed there must be a huge hazard. A policy of appeasement siphons attention away from much more harmful hazards, and with that distraction, makes it less likely that much more effective reductions in threats to public safety will be given priority in budgetary allocations.

The public needs to be confronted with a whole new perspective on possible threats to health and safety. The average citizen needs to know, with the most comprehensive overview,

1. How much tax-payer's money is being spent to reduce ordinary diseases and ordinary accidents which cause premature deaths to large numbers of the population;

2. The cost per capita that Congress is spending to reduce them;

3. Then how much ought to be spent to reduce them effectively; and

4. Precisely at what point huge amounts of money are pouring into budgets that can deliver only miniscule gains in the status of public health - if any at all.

We have a surfeit of statistics on public health, but that data is not arranged by any responsible public institution so as to look at basic harms to the entire population relatively, to make comparisons, to maximize cost-effectiveness so as to get the most public health protection for the many out of the expenditure of a finite amount of money.

Instead of appeasing American citizens as if we were children - and then multiplying regulators and regulations in the advanced stages of Social Parkinsonianism, our regulatory-agency system must be profoundly altered. Its deficiencies must be treated with moral seriousness so as to assure that regulative standards for protecting health and safety actually consider the common good of the many, and to assure that finite amounts of public money are allocated in a just and equitable manner.

The time is long overdue for the institution of a separate cabinet level Department of Health and Safety. It should fall to this department's jurisdiction to make a comprehensive review of cost-effective health and safety standards. It should be required to make social impact studies as a justification for budgetary allocations. From an ethical perspective, the Congress should have chartered and mandated this department to consolidate and govern the following regulatory agencies: Environmental Protection Agency, Nuclear Regulatory Commission, Federal Drug Administration, Occupational Health and Safety Administration, Federal Aviation Administration, Public Health Service, Department of Transportation, and any other agency currently engaged in setting standards and regulating conditions affecting public health and safety. The Department of Health and Safety should not be conceived as still another bureaucratic level or agency, but rather the contrary - a consolidating, streamlining, efficiency-centered governing organ to which regulatory agencies are answerable and accountable.

If properly mandated, this department could eliminate major jurisdictional disputes, duplicative standards, piecemeal regulations which obstruct justice and equity in protecting the quality of our common life. Moreover, if properly chartered, this department would be set up to institutionalize a more enlightened process of developing regulatory standards. Optimally, it should fall to professionals in the sciences and engineering to set evolving standards for health and safety according to strict procedures of peer review. This could remedy an unhealthy situation in which a regulating agency both sets its standards and then enforces them with a self-serving goal.

An alternative, proven model has been successfully operating over fifty years - ASTM's Voluntary Consensus System of professionally established standards. If this model were adopted, the enforcing agencies would not be the arbiters of conflicts among competing experts in any given profession. The professions themselves by their own peer review would be responsible to adjudicate conflicting judgments about scientific or engineering matters. Policy-making and standard-setting could thus be derived from the best scientific judgment available at any given time. Haphazard or arbitrary revisions could be avoided.

THIRD ETHICAL PRIORITY

The Department of Health and Safety might also be the proper governmental arm for institutionalizing a method of dealing with a third ethical priority, namely, the resolution of newly emerging technosocial issues by some authoritative closure for policy-making (beyond standard-setting) with respect to public health and safety. Current public disputes over fetal research, recombinant DNA research, and nuclear technology should be evidence enough that there is an urgent imperative to devise a new kind of social institution for establishing public policy and guidelines to govern increasingly controverted technological innovations.

Technosocial issues are of such a nature that they are seeking a policy-making end-product, and traditional democratic institutions are no longer adequate to that task. Heretofore, policy has been set by the courts, reacting to individual cases, and decided by judicial fiat. Public policy has also been set by legislatures whose members are responsive to a constituency with vested interest, and policy is decided by political tradeoffs.

A new phenomenon in the sphere of public-policy-making emerged in the aftermath of an outcry about fetal research at the National Institute of Health. In 1974, a National Commission for the Protection of Human Subjects was convened for the purpose of fact-finding and policy formation. Constituted as a public commission, its members represented diverse backgrounds, competencies, and convictions in various disciplines - law, medicine, various sciences, ethics. It conducted public discussion, deliberated openly and candidly, heard from each representative of public responsibility. This commission may well offer a precedent that could be emulated, amended with a broader objective in mind, and institutionalized for the purposes of policy-making in the Department of Health and Safety.

The application of a Science Court concept has many positive uses, yet its role in policy-making seems to have serious drawbacks. According to its originator, Arthur Kantrowitz, the intent is to adjudicate and judge the preponderance of scientific fact on any given issue so as to settle a factual dispute. But the term suggests that a legal adversarial model would dominate the procedure. In practice, this model substitutes courtroom rhetoric, innuendo, dramatic overstatement, and pre-structured questioning which seeks "an optimum resolution of conflict" profitable to a victor, rather than an established procedure which seeks the preponderance of scientific truth as a foundation for wise policy. Granted that courtroom adversary models are an appropriate method for adjudicating disputes over rights between individuals and groups, they fail miserably to provide a method for making enlightened policy about technological innovations.

If we are to deal constructively with public misperceptions and rising expectations about safety - and if we are to avoid becoming a nation of hypochondriacs - we would do well to ponder Max Singer's observations:

> Safety is one of the reasons it is better to be wealthy than poor. But as we get wealthier and safer, we become more concerned about safety -- like most social problems, the death tool from hazards requires a complex, balanced and limited response. We cannot give ourselves up to eliminating or even reducing hazards. As individuals and a society we must not become cowardly, fearful or hypochondriacal. The weakening of our character can do us more harm than all the auto accidents and all the fires.

In conclusion, I would invite you to consider a thought-provoking analogy proposed by Dr. Krafft Ehricke. It offers us an entirely new horizon for a re-interpretation of growing concerns about our environmental quality.

He asks us to consider an embryo in the womb as it grows larger and larger and enters the seventh month. Assuming an incipient intelligence, the embryo becomes increasingly sensitive to its environment - its source of nourishment, blood supply, oxygen, quantity of wastes to be disposed of. When it extrapolates into the eighth month, into the ninth month, and then into the tenth month, it is seized with panic at the prospect of destroying its only habitable environment.

What the embryo fails to realize, however, is that the natural pressure of events will - at the end of the ninth month - bring about a profound change in its "frame of reference." Whereas in the womb, the embryo lives parasitically off its environment, with birth it rapidly develops its own metabolism - as well as an entirely new mode of sustenance and supply of natural resources.

What Dr. Ehricke has in view, of course, is the prospect of human exploration and development of the vast resources of Space.

Clearly, the analogy has inherent dissimilarities, with the present state of humankind as we become sensitive to our environment at the end of the Twentieth Century. Yet, it is just as clear that we may indeed now be standing at the threshold of a New Frontier through which our present limits will be transformed into passages for a new universe inviting expansion and greater maturity.

B. RADIATION AND RADIATION EFFECTS

The Potential Hazard from Radiation*

Francis L. Brannigan

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We, as transient occupants of this terrestrial sphere, are the inevitable recipients of substantial quantities of radiation whether we like it or not. This radiation originates both from cosmic sources and from sources in the earth itself. As a consequence of these sources of radiation, we are not only subjected to radiation from our surroundings but, as a consequence of our environment, are ourselves radioactive sources. Considered in this light, the real question is not how dangerous radiation is but how much radiation is dangerous. This is particularly true when we realize not only that man has never existed in a radiation-free environment but also that it is possible that he owes his own development to changes induced in part by radiation.

"The background level of radiation to which we are subjected varies widely all over the world and scientists have not yet been able to come up with any correlation between these variations in the background level and any injury. We have on the one hand this background level of radiation, and on the other hand the fact that high doses of radiation can cause death. The [real] question is: 'How much more radiation over background can we take without injury?' "

This question may be compared to slapping one's hand on the desk. "It is possible to argue that I have damaged my hand, though the damage is invisible. At a harder slap, I would get a reddening. At even a harder slap, black and blue marks. Harder than that, broken bones. The ultimate degree of damage, of course, is to break the hand off at the wrist. So the question 'Is it dangerous to slap your hand on the desk?' is answered by 'It depends upon the energy involved.' "

On the basis of our knowledge of radiation exposure delivered in a short time, we conclude that the effects corresponding to various levels of exposure (i.e., amounts of energy) are as tabulated below:

Total body exposure, r	Effect
Below 25	No observable effect
At about 25	Threshold level for detectable effect
At about 50	Slight temporary blood changes
At about 100	Nausea, fatigue, vomiting
From 200 to 250	Fatality possible, though recovery more likely
At about 500	Half of the victims might die
Around 1000	All victims would die

Although the above effects and exposures describe conditions that might be expected in the event of nuclear hostilities or in the confined environs of a nuclear facility following an incident, it does not describe the significant situation of public concern, viz., what is the effect of repeated small doses of radiation, each one of which is so low that there is no identifiable effect. This problem, in turn, divides into two parts — consideration of the somatic effect and of the genetic effect. Thus, if we attempt to extend the exposure vs. effect relation (as in the above table) to smaller and smaller doses, we run out of information. The most conservative extrapolation of this relation is the so-called "dose equivalent" concept in which we extend the dose-effect relation to zero, assuming implicitly that for every dose there is an "insult" — regardless of how small and regardless of the fact that we cannot find it. This is the approach adopted by the federal government in establishing recommended radiation limits. In particular, radioactive operations are regulated by the government so that no member of the general public receives a whole-body dose in any calendar year in excess of 0.5 rem.[18] Thus in 50 years an individual member of the public could receive a maximum

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*Except where noted the information herein was adapted from a 16-mm film entitled "Radiation in Perspective," which presents a lecture by Francis L. Brannigan of the AEC, Division of Health and Safety. The film is available on loan from the motion picture libraries of the AEC.

of only 25 rem (an amount that produces no observable effect when received in a short time) without taking any credit for the body's natural repair processes, which would have been quite effective for low-level insults in a prolonged period.

The other part of the problem is the genetic effect. However, although it is true that radiation can produce genetic effects, it has also been estimated[19] that the background radiation (which in this country averages 0.13 r/year and is greater than 1 r/year in some areas) accounts for only a small fraction of spontaneous mutations. Further, some hundreds of chemical agents are known to be mutagenic, although none has been studied in such detail as radiation. Some active mutagens are listed in Table 1-1 (from Ref. 19). These are substances that affect the genetic material at concentrations lower than those which would cause cellular

Table 1-1 SOME EFFECTIVE MUTAGENS STUDIED IN DIFFERENT ORGANISMS*

Mutagen	Drosophila	Neurospora reversions	Higher plants	Bacteria	Source of exposure
Mustard derivatives	†	†	†	†	Therapy
Nitrogen mustards					
Epoxides‡	†	†	†	†	Industry
Epoxide					Domestic use
Diepoxybutane					
Imines	†	†	†	†	Therapy
Triethylenemelamine (TEM)					
Alkane-sulfonic esters	†	†	†	†	Therapy
Dimethylsulfonoxybutane (Myleran)					
Other alkylating agents	†	†	†	†	
Dimethyl sulfate					
Diethyl sulfate					
Peroxides‡					Smog
Tert. butyl hydroperoxide	†	†	§	§	
Dihydroxymethyl peroxide	†	†	§	§	
Aldehydes‡	†	†	¶	†	
Formaldehyde					Industry
Propionaldehyde					Smog
Acrolein					Disinfectant
Basic dyes‡	†	§	§	†	Industry
Proflavine					
Pyronine					
Acridine orange					
Purines‡					
Caffeine	¶	§	§	†	Beverages
8-ethoxy caffeine	**	§	Chroms††	§	Widespread use
Antimetabolites‡	**	§	§	†	Therapy
5-bromouracil					
2-aminopurine					
Pyrrolizidine alkaloids	†	§	§	§	Herbs
Miscellaneous					
Nitrous acid	§	§	§	†	
Phenol	†	**	Chroms††	§	Industry
Manganous chloride	**	§	§	†	
Urethane	†	**	Chroms††	§	
Diazomethane	†	†	§	§	
Beta-propiolactone	§	†	†	†	
Maleic hydrazide‡	**	**	Chroms††	**	Food and agriculture
Ethyl alcohol‡	**	**	Chroms††	**	Widespread
Nicotine‡	**	**	Chroms††	**	Widespread

*One or more typical examples listed in each class of mutagen.

†Mutagenic.

‡Of common occurrence, at least in certain human environments.

§No reference to mutagenic activity available.

¶Weakly mutagenic.

**Not mutagenic.

††Produces chromosome breaks in plants.

(somatic) damage. Although none of the results tabulated are for the human species, it is reasonable to presume that these chemicals can also produce mutations in man and may be responsible for the majority of the mutations known to occur.

We can get some feel for the conservative nature of the radiation regulations if we compare the ratio of the allowable to dangerous levels for radiation with the ratio of allowable to dangerous levels for another substance, such as carbon monoxide gas (see the accompanying tabulation).

This does not necessarily mean that the prescribed maximum radiation levels are 80,000/15 or > 5000 times safer than allowable exposure levels for carbon monoxide, since "the two cases are not directly comparable. However... [it is true] that there is a tremendously greater spread between the acceptable level and the immediately dangerous level in the case of radiation than there is for other noxious substances" and this undoubtedly reflects both the extremely conservative approach employed in establishing permissible radiation levels and the empirical approach used in establishing permissible levels for other substances.

Carbon monoxide	Radiation
We are permitted 100 ppm in the air of carbon monoxide gas for breathing over an extended period of time	If we were to divide the lifetime exposure figure by the number of working hours in a lifetime, we would come out with an hourly average of 2.5 mr/hr
A level of 1500 ppm of carbon monoxide gas in the air is extremely dangerous such that, if we were to breathe that level of carbon monoxide gas for 1 hr, we would be in serious danger of death	The dangerous level of radiation exposure comparable to the 1500 ppm of carbon monoxide is 200,000 mr/hr, inasmuch as a 200-r dose is the level at which an employee would be in danger of death
The ratio between the acceptable level and the dangerous level is 1:15	The ratio between the acceptable level and the dangerous level in the case of radiation is 1:80,000

References

18. AEC Rules and Regulations, Title 10 of *Code of Federal Regulations*, Part 20, Standards for Protection Against Radiation, June 1, 1962.
19. Third Report of the Expert Committee on Radiation, Radiation Hazards in Perspective, *World Health Organ. Tech. Rept. Ser. No.* 248, 1962.

Explosion of Some Radiological Myths

Merril Eisenbud

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Complex concepts can sometimes seemingly be simplified by repeated use of phrases that soon become familiar to the ears, that come right to the point, that are completely unequivocal, and that in time become insidiously convincing. Often the phrases express truths, but more often only misleading half-truths, and sometimes total untruths.

In the United States and other countries where the acceptability of nuclear energy as a source of nuclear power is being debated, adages that have come into being in the last few years are misleading the public into unnecessary apprehension about the hazards of nuclear energy. This article identifies some of these adages and discusses the reasons why they are misleading. Only a few have been selected, and these are limited to references to the normally operating reactor, as follows:

1. "We haven't had enough experience."
2. "The air and water will become radioactive."
3. "All unnecessary radiation exposure should be avoided."
4. "Very little is known about the effects of small doses of ionizing radiation."
5. "There is no such thing as a safe dose."

That "we haven't had enough experience" is a reminder of the fact that artificial release of nuclear energy has been accomplished within the present generation and that we have had only a little more than 20 years of experience with reactors. In the present state of technological development, this is a long time, particularly in view of the remarkable developments in the field of industrial safety since World War II. A spectacular case in point is the current record of the space program. Never has there been an undertaking more hazardous to an individual than the program of manned missions being conducted by the United States and the Union of Soviet Socialist Republics. It is a remarkable accomplishment that all the manned flights into outer space conducted up to the present time have been completed without loss of life. To be sure the risks will become greater with each bolder step forward, and there are undoubtedly tragedies somewhere ahead at some stage of development in the program of space exploration. However, the fact remains that man has demonstrated his ability to project an astronaut, from the top of a giant rocket containing an enormously explosive concoction of chemicals, into outer space at a velocity of 25,000 mph, to place him into an orbit, and to return him safely to a predetermined location on earth. The fact that there may be failures in the future does not detract from the wonder that man can accomplish this at all. What a contrast with the repeated failures and tragedies among the polar explorers before Peary reached the North Pole two generations ago, or among the aviators who attempted to cross the Atlantic before Lindbergh successfully flew from New York to Paris in 1927.

Modern safety derives basically from our knowledge of the characteristics of materials under various kinds of stress, from methods of quality control in manufacturing, from modern methods of educating and training people, and from the desire at every level of government and industry to keep accidents to an absolute minimum. Contemporary industrial safety records are astonishing in comparison with the experience of a generation ago. I can recall, in the mid-1930's, the feeling of real accomplishment among safety engineers when the first industrial company accumulated a million man-hours without a lost-time accident. Today this is a commonplace occurrence, and many large companies accumulate more than 20 million man-hours of experience between lost-time accidents. Modern industry knows how to do a job safely, as one can see from the spectacularly successful safety record of AEC and its contractors.[23]

The fact that reactor safety can be achieved by well-understood techniques of design and operation is illustrated by the earliest experience of the program. The Oak Ridge air-cooled natural-uranium and graphite reactor was completed in 1943 and performed well and safely throughout the years until it was finally retired, late in 1963, after 20 years of practically continuous operation. Similarly, three reactors designed to produce plutonium began operation at Hanford in 1944 at their designed initial power levels of 250 Mw. These powerful reactors, with modifications in their designs, have continued to operate to the present time. Thus it was possible to build four reactors during World War II with essentially no prior experience. The designs were based on new physical principles, and new construction materials and new techniques of fabrication were used. Moreover, these reactors were built under wartime conditions on a timetable that was accelerated to an extent that is not likely to be repeated. It is a compliment to the thoroughness of the designers that reactors of such size were built during World War II and that they have operated so successfully up to the present time. The record also suggests that perhaps to the nuclear physicists and engineers there are fewer mysteries in reactor design and operation than most people believe!

The public frequently becomes alarmed that if a proposed plant is constructed "the air and water will become radioactive." This is a hard statement to deal with because many people are unable to think quantitatively about radioactivity. They know what can happen if their neighborhood should be subjected to massive fallout from a thermonuclear bomb, and, after all, are not the radioactive substances discharged from a reactor very similar to bomb fallout? It will take another generation of education before people will differentiate between picocuries and megacuries, and in the meantime we must be patient in explaining that the presence of radioactivity of itself means nothing unless we know how much is present and what kind. The public must become better acquainted with the fact that radioactivity is one of the ubiquitous phenomena in nature and that every living cell contains radioactive substances of natural origin.

An interesting recent finding is that relatively large amounts of naturally occurring radionuclides are routinely discharged into the atmosphere by plants burning coal and oil.[24] A 1000-Mw coal-burning plant having good fly-ash control will annually discharge about 30 mc of mixed radium (^{226}Ra + ^{228}Ra) isotopes into the atmosphere. From the ratios of the maximum permissible concentrations, 1 mc of radium consisting of equal parts of ^{226}Ra and ^{228}Ra can be shown to be comparable to about 400,000 mc of ^{85}Kr and about 400 mc of ^{131}I. These two radionuclides have been selected for comparison because ^{131}I is one of the major short-lived constituents of fission products and ^{85}Kr is the principal long-lived volatile constituent. Thus the atmospheric effluents from a well-operated coal-burning power plant of 1000-Mw(e) capacity contain the "equivalent" of 10^4 curies of ^{85}Kr and 10 curies of ^{131}I. Plants that do not provide mechanical or electrical dust separation will discharge much more than this — about 1 curie of mixed radium isotopes per year, which is "equivalent" to more than 4×10^5 curies of ^{85}Kr or 400 curies of ^{131}I. An oil-burning plant of this size would discharge considerably less radium, "equivalent" to about 200 curies of ^{85}Kr and about 200 mc of ^{131}I.

Certainly no one would suggest that this amount of radium being discharged into the atmosphere of our large cities is a health hazard. In fact, only a small fraction (~0.2%) of the daily radium intake of the average person originates from this source. Most of the radium we absorb (~4 pc/day) is ingested from food in which radium is present as a trace element that has been assimilated from the soils.

From these data we conclude that electric generating stations that derive their thermal energy from fossil fuels discharge relatively greater quantities of radioactive substances in the atmosphere than power plants that derive their heat from nuclear energy. During 1961 the Yankee Nuclear Power Station at Rowe, Mass., discharged only 1.9 mc of gaseous wastes into the atmosphere; that is much less than the radioactivity that would be discharged if this 141-Mw(e) pressurized-water nuclear plant was operated with coal! Similar comparisons could be made for nuclear power plants employing direct-cycle boiling-water reactors. The number of curies of activity discharged into the atmosphere by such plants is higher than in the case of pressurized-water reactors, but the radioactivity is of far shorter half-life, and correspondingly greater maximum permissible concentrations. The liquid-waste activities are similarly minuscule, and, when the waste is mixed with large volumes of water, the activity results in insignificant environmental contamination in the vicinity of commercial reactors.

We frequently hear that "all unnecessary radiation exposure should be avoided." This is a statement with which we would not disagree, but certainly the benefit of reducing exposure should be weighed against the cost or inconvenience of reducing exposure. This is certainly the everyday attitude toward the radioactivity from nature, which contributes the largest component of the total dose received by people in most parts of the world. We receive, on the average, about 100 mr/year from this source, but the deviations from average are quite pronounced, and in normal situations the dose from natural radioactivity probably varies from 50 mr/year to about 200, depending on altitude above sea level, geological factors, the amount of radium in drinking water, and the materials from which our homes are constructed. If we accepted literally the admonition that unnecessary radiation exposure should be avoided, people would avoid living in cities like Denver, Salt Lake City, or Albuquerque, where the external radiation levels are about twice those at sea level. Hundreds of thousands of people in Illinois and Indiana would be discouraged from drinking their local water supply because the radium content is above normal. In metropolitan areas, such as New York, people would compete to live in areas that have low levels of natural radioactivity, there being a difference of almost 20 mr/year between most areas of Brooklyn and Queens and upper Manhattan Island, where the radiation level is normally higher due to the igneous rocks on which almost all of Manhattan Island is built.

It would be absurd to allow the level of natural radioactivity to influence where we live, and, so far as I know, no one has suggested that we do so. Convenience and economics dictate our choice of living place, with logical disregard of the levels of natural radiation. In respect to the 50 mr/year or more that could sometimes be avoided by altering our place or manner of habitation, the admonition "all unnecessary radiation should be avoided" is a meaningless platitude.

We are often cautioned that "very little is known about the effects of small doses of ionizing radiation." This of itself is a correct statement that can be found in proper context in most authoritative studies on the delayed effects of radiation. It will be found in the reports of the United Nations Scientific Committee on the Effects of Atomic Radiation, the National Academy of Sciences Committee on the Biological Effects of Atomic Radiation, and in many statements made by expert witnesses testifying before the various hearings of the Joint Congressional Committee on Atomic Energy.

As a qualitative statement it is certainly true that we know very little about the biological effects of radiation at doses of a few milliroentgens to a few hundred milligroentgens per year, but this is because the effects of small doses cannot be measured. The effects, if they occur at all, are so infrequent that it is not feasible to study them, even with the best tools available to science and with the extensive resources available for investigations of this kind.

In fact, the effects of small doses of ionizing radiation have been studied more thoroughly than the effects of any other of the noxious agents that man has introduced into his environment. The policies established after World War II by AEC, supported actively by the Joint Congressional Committee on Atomic Energy, have resulted in appropriation of public funds on a scale that has yet to be matched in other fields of environmental health. It is only in the last year or two that there has been a general awareness of the need to accelerate the investigations of the effects of possible environmental hazards such as air and water pollutions, insecticides, food additives, and tobacco smoke. As yet, however, there is little comparison in size between the AEC budget for investigating radiation effects and the budget authorized for the study of the effects of chemical pollutants.

If people are told we know nothing about the effects of small doses, they will understandingly oppose *any* exposure to man-made radiation. They are told that radiation can produce cancer, genetic changes, and a general reduction in life-span, and, since so little is known about the effects of small doses, their children might be injured if a nuclear reactor were built near their home. However, the implications of the statement that we know little about the effects of small doses of radiation are considerably less ominous when it is added that this is because the effects occur so infrequently that they cannot be observed in either humans or populations of experimental animals.

Most people would say that the dose is safe if the effect is so small it cannot be observed. Yet, we are told that for radiation "there is no such thing as a safe dose." This is another way of saying that "all radiation exposure is bad," which is a concept that is used all too frequently to counter statements that a proposed installation will be operated safely and that people in the environs will be exposed to only a fraction of the permissible dose. The idea that there is no such thing as a safe dose of ionizing radiation derives from the hypothesis that there is no threshold for some radiation effects. This assumption is commonly accepted for genetic effects, and, on the basis of data obtained with experimental animals, it is sometimes applied to the carcinogenic and life-shortening effects of ionizing radiation, although these data are far more equivocal. Actually a strong case can be made for a threshold hypothesis in the case of the carcinogenic effects that have been studied in experimental animals.

For the purpose of this discussion, we can accept the "no threshold" hypothesis and consider the effect of this assumption on the proposition that there is no such thing as a safe dose of ionizing radiation. To a considerable extent, this involves quibbling about the absolute meaning of the word "safe." Most parents believe that their children are safe in the home, although the statistics of the National Safety Council would disagree with this in the absolute sense. As is well known, many children die in accidents in the home. In almost all uses of the word "safe," we mean "reasonably safe" rather than safe in the absolute sense. We normally say that something is safe when the risk of injury is so small that the person has a feeling of security and is heedless of the very small but finite danger. It was perhaps first in connection with the potential dangers of ionizing-radiation exposure that the word "safe" was required by some to have an absolute meaning. More recently the same restriction has been placed on the purported safety of insecticides and food additives.

There are a number of reasons for the recent concern with absolute safety. The very nature of the times demands that we be more prudent in our evaluation of environmental risk than has been true in past generations. There is a new public consciousness concerning environmental risks of all kinds, a development that is desirable and which everyone should encourage, although we may wish sometimes for less extremism and fewer appeals to emotions.

It is only comparatively recently that man's activities have resulted in contamination of the environment on a national or even global scale. It is no longer only the people living in less cultured areas of industrial communities that are exposed to the environmental contaminants. Air pollution is now a metropolitan problem; food additives and pesticides expose people on a national scale; and the radioactive debris from weapons tests can be detected all over the world in all forms of life from single-celled organisms to man.

A small probability of injury may be an acceptable risk to an individual and may be of minor concern to a population of small size. However, the same probability of injury may be totally unacceptable when it is applied to the total population of the world. As a matter of fact, it was this difference that was at the basis of the fallout controversies of the late 1950's in which scientists seemed to disagree about the risks inherent in the atmospheric testing of nuclear weapons. The difference was primarily the basis for estimating the risk. Some scientists considered the risk on an individual basis and, after concluding that the probability that a given individual would develop leukemia was of the order of 10^{-6}, decided that the risk was "negligible." However, others took note that the population of the world was 3×10^{9} and that, if such a population were exposed to a risk of 10^{-6}, there would be 3000 cases of leukemia! Thus we see that what may be safe for an individual may nevertheless be a risk of sufficient magnitude, when the entire population is considered, to justify a further reduction in exposure or, if possible, elimination of exposure entirely.

Industrial atomic-energy installations expose a very few people in the immediate environs of the plant to a very small fraction of the permissible doses established by AEC regulations. If there is a threshold dose that must be exceeded before deleterious effects are produced, there may be no effects at all. If there is no threshold, the effects produced by the levels of permissible exposure would occur at such a low frequency that the effect could not be measured. If we make certain conservative assumptions that (1) there is no threshold, (2) the effect is independent of dose rate, and (3) the effect is linearly proportional to dose, we can calculate the probability of injury. These calculated values will be maximal figures, with the true value being somewhere between zero and the calculated values. By these methods it has been concluded that the risk of developing leukemia from ionizing-radiation exposure is about one case per million per rad for each year at risk. A person exposed to the Federal Radiation Council maximum permissible dose of 0.5 rad/year would have 1 chance in 2 million of developing leukemia. However, the exposure of people in the vicinity of nuclear reactors is far less than 0.5 rad/year and, even in the case of reactors built in the center of populated areas, need be no more than 10% of this value or 0.05 r/year. In this case the maximum risk of developing leukemia could be as high as 1 in 20 million, but the actual risk might be as low as zero. Certainly we can tell an individual living in the community that the plant is safe so far as he and his family are concerned and that in all probability he is much better off living near a nuclear plant, since, at a cost of a few milliroentgens per year, he avoids a whole spectrum of noxious agents that are of necessity introduced into the atmosphere from fossil-fuel plants.

This article has been concerned with some of the fallacies underlying five frequently quoted reasons why nuclear reactors should not be built near population centers. These are not all the reasons why people object to construction of these plants, but the analysis does serve to illustrate the way in which these statements contribute to the morass of misunderstanding when they are taken out of context and repeated over and over again in public discussions.

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Effect of Low-Intensity Radiation on Man

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The ratio of radiation-dose-rate threshold for somatic damage to the normal background dose rate is of the order of a few hundred (100 to 500). This is in the range of the ratio of harmful concentration of several chemicals to the amount needed or believed to be needed for health. This observation raises the question as to whether all radiation is harmful, a question which has been raised before and which is under investigation. It also suggests further experiments at low or very low (below background) dose rates.

An analogy applied to phenomena not well understood can be useful in suggesting new approaches to a problem and in providing new insight into the nature of a problem. An analogy is drawn here between the biological effects of inorganic chemicals and the effects of radiation. As a result of this analogy, suggestions are made for future work.

Little is known at the present time about the effects of small radiation doses. There is no firm basis for interpolating or extrapolating radiation effects to small exposures, and many data[8–10] seem to show effects opposite to those predicted; i.e., they show a lengthening of lifespan rather than a shortening, or they show an ability of the body to tolerate the radiation where deleterious effects might be expected. A need for information on the effects of low radiation doses is recognized, and projects currently under way or proposed can help to fill this need.[11,12] A further insight into radiation effects will be sought through the analogy drawn below.

Large doses of most chemicals are injurious to the body, but, from studies and observations of nutrition, we find that many chemical elements are essential in small quantities to maintain health. This suggests comparison with radiation effects.

Such a comparison cannot be made to a high degree of accuracy. Quantitative data needed on nutrition, toxicology, and radiation effects are not generally available and, when available, are frequently expressed as ranges of values rather than as single fixed values. Thus only "ballpark" values can be expected in making the comparison.

The comparisons are made between the somatic effects of radiation and the effects of chemicals, both on adults. Genetic effects are not considered, nor are the effects on children, who appear to be much more sensitive both to chemicals and to radiation.

Three sources of information on nutritional amounts of chemical elements are available. The first, and most accurate, is the compilation of the U. S. Food and Drug Administration laws contained in the *Code of Federal Regulations.*[13] The amounts given are based on recommendations of the National Research Council. In addition, there are other elements that have been found or suspected to be needed by the body but for which agreement as to amount or certainty as to need are lacking. Here it is assumed that pharmaceutical companies have made a search of this field and that their conclusions are reflected by the mineral content of their vitamin-mineral tablets. This is taken as a second source of nutrition requirements. A third source is provided by reports on daily intakes by the body of certain elements. These intakes often vary over a large range; further, there is the possibility that the average intake exceeds the average need. However, intake values provide some information where information is generally scarce.

The amount of a chemical that constitutes a hazard is just as difficult to specify quantitatively as is the nutritional amount. Data on poisoning by ingestion are very scarce. Poisoning by inhalation is a much more probable occurrence in industry and has been studied more. An excellent review and summary of known information on inhalation hazards has been assembled in an industrial hygiene handbook edited by Patty.[14] The threshold values used below were all obtained from this volume. In most cases these are limits set by the American Conference of Governmental Hygienists, but, where such limits are absent, the thresholds are ones proposed by investigators in the field. The thresholds set for inhalation hazards are given in milligrams per cubic meter. These were changed to daily intake by multiplying by an assumed breathing rate of 20 $m^3/24$ hr.

A daily need has not been established for radiation; it is generally believed, but not proven, that the need is zero. However, the daily intake is known quite well. It varies over the earth's surface and depends on altitude and local concentrations of radioactive materials. A general average is 0.6 mrad/24-hr day.

The acute radiation dose that produces somatic damage is generally taken to be approximately 100 rads. However, to make a comparison with chemical poisoning, the threshold for chronic-exposure damage is required. This is less well understood. Taylor[15] reports that radiation effects have not been demonstrated in cases where exposures of 50 to 500 times background have existed for years. Thus 500 times background might be taken as a limit on the threshold for chronic-exposure hazard. Another measure of a threshold value is the daily permissible dose of 500 mr/week suggested by the International Commission on Radiological Protection (ICRP) during the early days (1936) of handling radioactive materials before concern over genetic damage developed strongly. Adjusting this tolerance to a continuous level gives a value of 120 times background as a measure of the lower limit for the threshold for damage from chronic exposure.

The data discussed above are summarized in Table I-1. In the last column of the table, a ratio of threshold to need (or threshold to intake) is given for each element and for radiation. The relations are shown more clearly by a plot of the data in Fig. I-1. Where a range is given, the extremes of the range are linked by a dashed line. The points may be identified by reference to Table I-1.

Table I-1 SUMMARY OF NUTRITION, TOXICOLOGY, AND RADIATION-EFFECTS DATA GIVING A COMPARISON OF CHEMICAL AND RADIATION EFFECTS ON MAN

Element	Source of information	Need or intake, mg/day	Threshold for chronic-exposure damage, mg/day	Ratio of threshold to intake values
Iron	CFR*	10	300	30
Iodine	CFR	0.1	20	200
Aluminum	Intake	10 to 100	300	3 to 30
Copper	V-M†	1	2 to 60	2 to 60
Copper	Intake	2	2 to 60	1 to 30
Mercury	Intake	0.005 to 0.020	2	150 to 400
Mercury	V-M	1	300	300
Manganese	V-M	1.5	120	80
Manganese	Intake	3 to 6	120	20 to 40
Zinc	V-M	1.4	300	210
Zinc	Intake	10 to 15	300	20 to 30
Radiation		0.6 mr/day		500‡
Radiation		0.6 mr/day	70 mr/day	120

*Code of Federal Regulations (see Ref. 13).
†Vitamin-mineral tablets.
‡From Ref. 15.

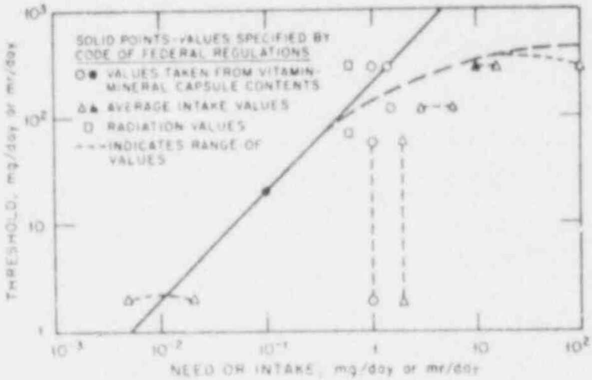

Fig. I-1 Threshold for chronic-exposure damage vs need or intake of chemical elements and of radiation.

It is not improbable that an intake of 1 g/day, or a substantial fraction of a gram, continued over an extended period would be injurious, even if the element was not chemically poisonous. Therefore we might expect a bulk, or volume, effect in addition to any chemical poisoning effect. This would tend to place an upper bound on the threshold curve.

In Fig. I-1 the heavy dashed line (showing the volume effect) joining the lower solid line (a constant ratio) was placed through the points representing iron and iodine (CFR data[13]) to produce a reasonable fit. These results appear to indicate some validity to a common value for the poison-to-nutrition ratio for a chemical element.

Points representing the radiation believed to represent the lower limit of the threshold for somatic damage relative to that absorbed from background (the intake) are also plotted in Fig. I-1. These points may be seen to correlate quite well with the chemical data. This observation raises the question of whether all radiation is indeed harmful to biological systems or might radiation perform some useful function in the operations of these systems, as do the chemicals.

The nature of the analogy made is such that conclusions are not justified, but questions and experiments are suggested. The principal suggestion is to attack the radiation-effects problem by using the principles of chemical-effects experiments. Here the experiment important to chemical nutrition but untried in radiation effects is to withhold the affecting agent from the biological system.

To withhold radiation would require a reduction of the various sources of normal radiation dose, which include cosmic rays, terrestrial sources, and radiation in food, primarily ^{40}K. These sources each contribute approximately one-third of the total dose.

The cosmic-ray contribution could be reduced to a negligibly small amount by performing the experiments in a cave or mine. At a depth of 1000 m, the cosmic-ray intensity would be reduced by a factor of approximately 10,000 from the sea-level value.[16] The reduction of terrestrial radiation would require some attention and effort. The intensity of the surrounding sources would largely determine the effort required, and selection of the location might be the single largest factor in reducing this component. Shielded rooms with low-activity wall materials would likely be used. Low-activity steel plates and water have been used.[17] Also, control of the airborne activity, primarily radon, might be necessary and would depend on the surroundings. The radioactivity entering the body via food might also have to be controlled, as it would be the largest single contributor once radiation from cosmic-ray and terrestrial sources had been reduced.

In this low-radiation environment, several generations of animals, plants, and insects would be raised. The use of control groups might or might not be required and would depend on the environmental control possible. The subjects would be examined for growth, health, intelligence (in animals), and any other factors that might be significant. An initial experimental group comparable in size to that which would be used for nutrition studies is suggested.

Continuing the analogy to chemical nutrition studies brings further suggestions which may be fruitful (or which may be under way at some laboratories). With radiation the initial studies were on whole-body radiation, and these were followed by radiation-effects studies on individual organs. It may prove profitable to investigate the microscopic effects of radiation on cell biology. Such studies would take note of all effects of radiation known or suspected, determine their probable magnitude, and ascertain their effect on specific life processes.

Many other ideas follow from the reasoning presented here. One of the more intriguing ones comes from theories proposed by biologists. It has been suggested that the ratios, and perhaps even the concentrations, of inorganic components of the blood are the same as those existing in seawater at the start of the Cambrian period, when life on earth was just beginning. Perhaps the radiation ratios reported in Table I-1 and Fig. I-1 should be based on the radiation background existing at the beginning of the Cambrian period. If radiation is found to be beneficial, this may be the optimum value (perhaps the value leading to the maximum life-span, if the experiments indicating lengthening of life-span should be confirmed).

In conclusion, the need for further data on effects of small doses of radiation is generally acknowledged. Performing experiments in which radiation is withheld could contribute significantly to this need.

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Radiation Standards and Public Health

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Abstract: *The radiation-safety record of the AEC has been good, but changes in the present regulatory system are needed to reconcile differences between public attitudes and the AEC. AEC regulations are based on the recommendations of the ICRP and the NCRP, and the standards contain extensive built-in conservatism. However, the emphasis on the maximum permissible concentrations of radionuclides in air and drinking water should be changed to specify the maximum permissible daily intake from all sources to take into consideration multiple sources and ecological factors. Further, the dual responsibility of the AEC for the development of nuclear power and the protection of the public has contributed to lack of public confidence in the AEC. Accordingly it is recommended that responsibilities for setting radiation limits be shifted to another agency of the federal government. The same agency, in cooperation with the states, should assume responsibility for environmental monitoring in the vicinity of AEC-licensed facilities.*

The AEC has relied from the beginning of its existence on the National Council on Radiation Protection and Measurements (NCRP) and the International Commission on Radiation Protection (ICRP) to recommend the basic numerical values of permissible radiation exposure. The AEC has assumed for its part the role of translating the recommendations of the non-AEC independent expert groups into administrative language that lends itself to use by regulatory authorities.

The NCRP was founded about 40 years ago and until recently had its headquarters in the Bureau of Standards. In 1964 NCRP was granted a congressional charter and now operates as an independent organization financed by voluntary contributions from government, scientific societies, and manufacturing associations. The 65 members of this council and about 175 members of the 18 NCRP scientific committees have the responsibility for developing the technical reports of the organization.

In 1928, 1 year before NCRP was formed, the International Society of Radiology sponsored formation of the International Commission on Radiation Protection. This group has operated in close cooperation with NCRP and receives support from the World Health Organization. It is essential to this discussion of standards of permissible radiation exposure to understand that AEC standards originate in the work of these national and international bodies among whom there is total harmony and whose recommendations are based on objective evaluation of existing information that is motivated by a common interest in the public health.

ROLE OF U. S. ATOMIC ENERGY COMMISSION

When the U. S. Congress passed the 1946 Atomic Energy Act that established the AEC, it gave the AEC responsibility for assuring the safety of atomic energy workers and the public at large. The unusual step of vesting this responsibility in a federal agency rather than the states was taken for a variety of reasons, among which were that (1) much of the required technical knowledge was then highly classified, (2) the specialists who had this knowledge were, for the most part, located in a few large laboratories owned by the federal government, and (3) the potential risks of this new industry were not necessarily limited to state jurisdictions.

The record of the AEC to date with respect to radiation safety can be easily summarized. There have been no known radiation injuries to any member of the public resulting from any of the civilian activities of the AEC. Among the approximately 200,000 employees of the AEC and its contractors, there have been six fatal injuries due to nuclear accidents, all of which occurred in the course of experimental research. There was one additional death in a privately operated industrial company licensed by the AEC. Further, among this large population of industrial workers, there are no known injuries from the cumulative effects of exposure. During the same period, 1946 to the present, there have been 276 on-the-job accidental deaths from all causes, such as vehicle accidents, falls, etc. This indicates that the safety record of the AEC is very good, with the occupational fatality rate being about 25% of the average for all industry.[1] The excellent occupational safety record is cited to illustrate that the AEC has demonstrated a high degree of concern for protection of its personnel. It has exercised similar concern for public safety.

Because of a technicality in the Atomic Energy Act, responsibility for the health of uranium miners was not preempted by the AEC but, rather, has continued to reside with the states. The radiation-safety record in the mines has been far less satisfactory, and more than 100 deaths from lung cancer have resulted from the cumulative exposure to the radioactivity of the mine atmospheres.[2] It is regrettable that federal preemption of health and safety matters in the atomic energy program did not include the mining industry, because this tragic record would have been avoided had the AEC standards of permissible occupational exposure been enforced.

Another governmental agency concerned with radiation protection is the Federal Radiation Council, which consists of representatives of several federal departments and agencies. It was established by the President about 10 years ago to assure a consistent governmental approach to radiation protection matters. The Council has promulgated a number of radiation protection guides to assist in evaluation of hazards from nuclear weapons testing and, more recently, for control of radiation exposure in uranium mines.

RADIATION STANDARDS

The recommendations of ICRP and NCRP were originally intended for protection of workers exposed to ionizing radiation. Prior to World War II, there was so little use of these radiations that the need for standards to protect the public had not yet arisen.

The pre-World War II students of radiation protection did not have the benefits of governmental grants that were later available, nor did they have the sophisticated laboratory equipment now used in research. However, the tragic misuses of ionizing radiations during that period provided an all too ample research resource from which to devise protection measures. Although before World War II there were relatively few X-ray machines and the radioactive material to which people were exposed was some part of the approximately 2 lb of radium that had by that time been extracted from the earth's crust, hundreds of deaths and many injuries resulted from inadequate understanding of the principles of radiation hygiene. Fortunately the effects of the misuses of these sources of ionizing radiation were studied with such extraordinary diligence and perception by our colleagues of a generation ago that much of the basic information needed for protecting the employees of the atomic energy program was already on hand when it was needed during World War II. Two very basic recommendations were already available that pertained to the upper limit of permissible exposure to external X-rays and gamma radiation and to the maximum permissible body burden of radium. The recommendation that the permissible body burden of ^{226}Ra be limited to 0.1 μCi has not been changed since it was first established early in World War II. This yardstick has had a strong influence in setting the permissible body burdens of other bone-seeking radionuclides.

The maximum permissible dose of external radiation exposure permitted before and during World War II was 0.1 R/day, based on the scanty information available up to that time, and was equivalent to 20 R/year. If we allow for the difference between roentgens and rads and for the fact that the radiations now encountered in the atomic energy program are more penetrating than the 75- to 125-kV X-rays that were the principal source of radiation before World War II, we find that the permissible dose for occupational exposure recommended by NCRP as long as 30 years ago is within a factor or 2 of the tissue dose permitted today for occupational exposure.

The problem of setting standards for protection of the general public is much more complex for several reasons. Because radiation workers comprise a relatively small fraction of the total population and because the genetic effects are related to the per capita gonadal dose of the population, genetic effects are less important than somatic effects, insofar as occupational exposure is concerned. The probability of somatic injury at a given level of exposure in the general population is increased by the fact that children and fetuses are involved. Additionally, it is necessary to become more conservative as the size of the exposed population increases, and in this country the general population is about one thousand times the population industrially exposed.

Leukemia and genetic mutations are believed to be the effects of ionizing radiation exposure that should be of greatest concern relative to the general population, and the following discussion of AEC standards focuses on these. An increased incidence of leukemia[3] has been reported among several groups of humans exposed to relatively high doses of ionizing radiation. These may include such groups as Japanese survivors of the atom bombings of Hiroshima and Nagasaki, patients irradiated for ankylosing spondylitis, radiologists exposed to ionizing radiation in the course of their work, and children irradiated *in utero* in the course of pelvic X-ray examinations. This epidemiological experience involves mainly single or multiple exposures at high dose rates compared with those permitted by existing standards. To estimate the expected effect of doses of a fraction of a rad delivered in small bits, we must extrapolate from these epidemiological data. In the interest of maximum safety, this is done by assuming that there is no threshold and that the biological response is proportional to the dose and independent of the dose rate. Both the United Nations Scientific Committee on the Effects of Radiation[3] and the ICRP[4] have emphasized that the estimates made in this way represent an upper limit of risk and that the actual risk may in fact be very much less. Subject to these conservative assumptions, the epidemiological evidence suggests that a dose of 1 rad delivered to 1 million people may produce a maximum of about 20 extra cases of leukemia during the lifetime of the population. The incidence of leukemia in the normal population is about 70 cases per million per year.

Insofar as genetic effects are concerned, there are no epidemiological data on which to draw. However, extensive research has been done with lower animals which suggests that there is no threshold for genetic effects and that the frequency of mutation is directly proportional to dose but the relation is not independent of dose rate.[5] According to these data a per capita dose of about 10 rads per generation, delivered to successive generations, will eventually cause the spontaneous mutation rate to double. It has recently been shown,[6] however, that, when the dose is fractionated, the genetic effect is less by a factor of about 6. Thus for continuous exposure a dose of 60 rads per generation, delivered to many successive generations, might be expected to cause the spontaneous mutation rate to double. For a reproductive span of 30 years, the doubling dose would thus be about 2 rads/year.

The basic criterion for the upper limit of permissible occupational exposure is that an employee should not accumulate more than $5(N - 18)$ rads, where N is the employee's age in years.[4,7] Stated another way, the employee should not work with ionizing radiation until he is 18 years old and then should not be exposed to more than an average of 5 rads/year.

When internal radiation exposure is involved, the ICRP methodology introduces the concept of the "critical organ," which is the organ in which a given radionuclide tends to accumulate and give the highest radiation dose and/or most significant effect.[8] For example, the critical organ for radioiodine is the thyroid, and for ^{90}Sr, it is the skeleton. With a few exceptions, exposure to internal emitters is controlled by limiting the quantity of radionuclides that may be absorbed by ingestion or inhalation to that amount which will result in exposure of the critical organ to less than 5 rads/year. The ideal, of course, in every case is to hold the absorption to as little as possible consistent with the activity.

The maximum permissible mean dose to the gonads or blood-forming organs, according to AEC regulations, is one-thirtieth of the permissible occupational dose. The regulations are based on this average not being exceeded if the individual with the highest exposure in a given population is not exposed to more than one-tenth of the permissible occupational dose. In short, the mean exposure of a given population should not exceed 0.17 rad, and the maximum individual exposure should not exceed 0.5 rad.

NATURALLY OCCURRING SOURCES OF IONIZING RADIATION

It is helpful to review what is known about the radioactivity of the natural environment[9] so that we may have a yardstick with which to compare the AEC standards. An appreciation of the kinds and amounts of ionizing radiation exposure due to natural sources is relevant to this discussion of the significance of reactor-produced radiation.

Radioactive substances are naturally present in the air we breathe, the water we drink, and the food we eat. These substances become incorporated into our tissues in such amounts that on the average our body tissues are literally disintegrating at a rate of about 500,000 atoms/min due to radioactive decay.

The total-body irradiation received by man in most parts of the world is about 0.1 rad/year. This figure varies somewhat from place to place, with an addition of about 0.028 rad/year for each 1500 m of altitude above sea level. Further deviations from the norm occur in places where the thorium or uranium content of the rocks and soils is above normal. In one village in Brazil, some people can be exposed to as much as 12 rads/year.

The lung and skeleton are selectively exposed over and above the dose received by the body as a whole. A large component of the dose to lungs is due to the presence of atmospheric radon, the concentration of which varies from about 10^{-11} μCi/ml to about 2×10^{-10} μCi/ml in different parts of the world. A concentration of 10^{-10} μCi/ml will deliver a dose of about 1.3 Rems/year to the basal cells of the bronchial epithelium, which is the tissue of the lung known to be particularly radiosensitive.[3] Doses as high as 10 times this value are possible indoors, particularly when the building is made of materials having a high radium content.

Radon-222, which has a half-life of 3.8 days, decays progressively through several shorter lived progeny to ^{210}Pb, which has a half-life of 22 years, and this radioactive substance ultimately deposits on the earth's surface. Only in the last few years have we begun to appreciate that mankind has always been subject to this form of natural fallout and that broad-leafed plants in particular have relatively high concentrations of this isotope because of foliar deposition of ^{210}Pb. According to one investigator this phenomenon contributes an additional 41 mRems/year to the lungs of individuals smoking one pack of cigarettes per day.[10]

Two naturally occurring nuclides, ^{226}Ra and ^{228}Ra, which are chemically similar to calcium, enter our bodies through the foods we eat, and they deposit with calcium in our skeletons. The daily radium ingestion of individuals in this country is about 5 pCi/day, approximately equally divided between the two nuclides. Studies of food and water in various parts of the world have shown that there are wide variations from these mean values. In certain parts of the Middle West, the radium intake is elevated owing to the presence of abnormally high amounts of radium in the drinking water, and the dose to the skeleton is thereby increased by about 0.06 Rem/year. Considerably higher doses have been reported from Brazil and India, where there are radioactive anomalies of the type mentioned earlier.[11]

Thus we can conclude that the whole-body dose from natural radioactivity in most parts of the world is about 0.1 Rem/year. The lung receives a greater dose due to the superimposed radiation from atmospheric radon, as does the skeleton in certain geographical areas where the radium content of food and water is elevated above normal.

EXTERNAL RADIATION

The actual external radiation exposure to the general population from nuclear power plants does not approach the so-called permissible dose rates because of certain inherent factors. For example, the heavy shielding required to protect men working around the reactor in the normal course of their activities gives assurance that the external radiation dose to the public will not be detectable. I know of no case in which radiation from the plant proper has caused a perceptible change in the levels of radiation exposure beyond the property boundary.

In the case of a boiling-water reactor, the principal way in which the general population would be exposed to external radiation would be by direct irradiation from the passage of radioactive gases discharged from the stack of the plant, but, if the maximum exposed individual received no more than 0.5 rad, the per capita exposure would be very much less than 0.17 rad. For example, consider a hypothetical situation in which a boiling-water reactor stack is located 100 m from a 360° fence at which the dose is assumed to be 500 mrads/year. In this situation, people living right on the fence would receive no more than the AEC maximum permissible dose to individuals. From known rates of diffusion of gaseous effluents from point sources, it can be calculated that the dose rate beyond the fence would, on the average, diminish inversely with the 1.8 power of distance from the sta[illegible] The per capita doses have been calculated for populations of 10^5, 10^6, and 10^7 people uniformly distributed around the fence at a density of 1000 people/km^2. The annual per capita doses for the three populations turn out to be 1.9 mrads, 0.28 mrad, and 0.04 mrad, respectively. We must recognize that this, in fact, overestimates the per capita dose because a dose of 500 mrads would occur only in the downwind sector, which would be perhaps one-eighth of the plant fence circumference. For seven-eighths of the plant circumference, the dose would be very much less than 500 mrads/year. We now begin to s[illegible] the kind of built-in conservatism that exists in [illegible] AEC regulations and that, even under the worst co[illegible] conditions, 10 million people distributed [illegible] boiling-water reactor would receive no more [illegible] total of 400 man-rads instead of the 1.7 million man-rads permitted under a literal interpretation of current regulations.

As mentioned earlier, 10^6 man-rads may produce 20 cases of leukemia in the lifetime of the exposed population. Four hundred man-rads may on this basis cause 0.008 case per million exposed people. Assuming the mean sensitive life-span to be 60 years, 400 man-rads/year could produce 0.5 case per million people per generation of 60 years. As explained earlier, this is an upper limit of risk, and the true risk is somewhere between zero and this upper estimate. Since the incidence of leukemia in the general population is about 64 cases per million per year, the 0.5 case in 60 years would occur against a normal background of 4200 cases.

With respect to genetic effects, if the doubling dose for spontaneous mutations is a per capita exposure of 2 rads/year, 0.17 rad/year delivered over many generations would result in about an 8% increase in the spontaneous mutation rate. However, since the man at the fence can receive no more than 0.5 rad, the external radiation dose from the plume would, at the limit of permissible exposure, result in a per capita annual dose of 0.04 mrad in a population of 10 million people, as previously shown. On the improbable assumption that these 10 million people constitute a closed breeding population for as many generations as it takes to reach equilibrium, the spontaneous mutation rate would eventually be raised by about 0.05%. This rise is equivalent to the change in radiation exposure that might be expected from living at a difference of about 10 ft in altitude.

To place all this in further perspective, note not only the well-established fact that increased temperature, like ionizing radiation, can cause genetic mutations but also the suggestion that as many as 50% of the mutations that occur normally in contemporary man might be due to the increase in testicular temperature caused by the male practice of wearing trousers. Although this observation on the effect of trousers appeared in the literature in 1957, I am unaware of any subsequent popular movement to prescribe kilts in place of the more mutagenic habit of dress of the American male.[12]

STANDARDS PERTAINING TO ENVIRONMENTAL CONTAMINATION

The ICRP and NCRP standards for permissible human exposure to radioactive substances are based on the assumption that the permissible amount of radioactive substances accumulated within the body or in the critical organ should not cause the permissible annual dose to be exceeded. These figures are then translated into maximum permissible concentrations of each radionuclide in air or water by using a set of physiological parameters that describe the movement of each element to the critical organ and the daily rate at which the contaminants are inhaled or ingested. In the case of ingestion, the AEC regulations give only the maximum permissible concentrations in drinking water. This is a defect since ingestion may be by way of food or water. The Federal Radiation Council approach is different and more logical since their recommendations, which they call radiation protection guides, focus on the permissible daily intake of a given nuclide, regardless of the source.

Where several nuclides are present, the AEC regulations provide a method for weighing the effects of each in relation to the others in such a way that the maximum permissible radioactivity of the mixture of nuclides takes into consideration the contribution of the individual nuclides. In this case the method errs on the side of safety. For example, if ^{131}I and ^{90}Sr are present in drinking water, the maximum permissible concentration of the mixture might allow 50% of the ^{131}I permissible concentration and 50% of the ^{90}Sr permissible concentration despite the fact that one nuclide irradiates the thyroid, the other irradiates the skeleton, and the effects are not thought to be additive.

Another safety factor exists insofar as the long-lived radionuclides are concerned because the maximum permissible concentration is taken as that concentration which will result in accumulation of the lifetime permissible body burden in 50 years. It can be shown from the mathematics of ^{90}Sr accretion in the skeleton that this provides a significant additional safety factor.

Since the AEC regulations are stated in terms of the maximum permissible concentrations of radionuclides in air and water, the regulations implied for many years that, if the maximum permissible concentration is not exceeded at the point of discharge to the environment, the dose to humans will not be exceeded anywhere beyond the site boundaries. In most cases this is an enormously conservative assumption since dilution up to several orders of magnitude can and does take place beyond the point of release. However, it is also possible for physical or biological concentration to take place, and when this occurs the risk can be correspondingly increased.

Within the past few years, the AEC standards have been modified to allow for biological concentration. In the case of ^{131}I, the maximum permissible concentration in air has been reduced by a factor of 700 to allow for the fact that exposure to man is increased by the tendency of iodine to deposit on forage and eventually pass to cow's milk. In addition, the regulations have been modified to require the licensee to demonstrate that accumulations in the food chain are not taking place. The discharges to the environment are considered to be excessive if the radionuclides ingested by a sample of the population by any route of exposure exceed one-third the annual intake permitted for water and air.

It should be noted that the Commission has always had the right to place upon the prospective licensee the responsibility of demonstrating that such concentration will not take place, and, although the AEC regulations were formerly silent on this point, no one who has followed the course of reactor licensing procedures over the years has ever doubted that the AEC has meticulously probed into questions of biological concentration beyond the point of discharge. Under the AEC regulations a licensee can discharge radioactive waste to the environment in concentrations greater than those permissible for immediate inhalation or ingestion if he can demonstrate the extent to which dilution takes place.

The AEC requires the licensee to conduct monitoring programs in the vicinity of the reactor. This provides information about the concentration of radioactive substances in air and water and also in whatever food products may be grown in the vicinity. Thus the question of human safety is not left to conjecture but is based on actual measurement of samples collected from the environment. Some of the AEC facilities, such as Oak Ridge and Hanford, have been collecting data for more than a quarter of a century, and experience at these places has produced valuable information that in many cases is directly applicable to civilian power reactors.

For several years many of us in the field of public health and environmental protection have argued that, on the balance, electrical generating stations powered by nuclear fuels make better neighbors than those using coal or oil. It is true that nuclear plants of the current generation discharge more heat to the environment than do the newest fossil plants. This places more stringent limitations on the use of water for condenser cooling, but regulations dealing with this problem are being promulgated in the various states for application to both nuclear- and fossil-fueled stations.

Much has been said about the ecological effects of radioactivity discharged to the environment, but there is no evidence that this occurs at or above the levels of radioactivity permitted by AEC. Putting it more strongly, there is a considerable body of scientific data that demonstrates that such effects do not take place. In contrast, we do know that certain vegetation is adversely affected by traces of sulfur dioxide and possibly other components of the combustion products of coal and oil.[13] There have been millions of dollars spent investigating the ecological effects of low levels of ionizing-radiation exposure, but there have been comparatively few studies of the ecological effects of the chemicals in fossil-fuel effluents, despite the fact that we know these effects take place and can be observed.

In most parts of the country, fossil fuels are the only practical alternative to nuclear fuels. We know, beyond any doubt, that sulfur dioxide discharged to the environment by plants burning fossil fuels has been responsible for many deaths in the general population, particularly during periods of meteorological stagnation. Even the innocent gas, carbon dioxide, produced by combustion of fossil fuels, is accumulating in the earth's atmosphere and is regarded as a long-range threat to the world's heat balance, with the possibility of eventual climatic changes on a disastrous scale.[14] Finally, it is a curious fact that, because radium and other radioactive substances are normally present in fossil fuels, the radioactive atmospheric emissions from fossil-fueled plants are not insignificant compared with those from many nuclear plants.[15,16] These are among the reasons that some of us are convinced that nuclear reactors make good neighbors.

Additional reasons are to be found in the actual operating experience of the civilian power-producing reactors. The atmospheric and liquid effluents are in most cases less than 1% of the amounts permitted by AEC standards, and the public-health risks, though finite, are so small as to be more than offset by even the most modest of the benefits of increasing man's available electrical resources.

CONCLUSIONS

From the foregoing it is possible to draw certain conclusions which constitute the thesis of this presentation and which indicate that, although the record of the AEC has been a good one from the point of view of the public-health official, changes in the present regulatory system are being demanded to continue to lessen differences between public attitudes and the AEC that are still not completely resolved after 15 years of almost continuous debate.

The AEC regulations are substantially compatible with the recommendations of ICRP and NCRP. Moreover, they are both scientifically and philosophically compatible with evaluations of the state of our knowledge of radiation effects that have been undertaken from time to time by other national and international bodies, including the United Nations Scientific Committee on the Effects of Atomic Radiation, our National Academy of Sciences,[5] and the British Medical Research Council.[17]

The AEC regulations have resulted in a safety record that is unsurpassed for any major industry. In the 27 years that have passed since the first reactor went critical in December 1942, there has been ample time to evaluate the basic adequacy of the systems of control that have been derived.

Although there are ambiguities, inconsistencies, and perhaps even deficiencies in the AEC regulations for permissible discharges to the environment, they are adequate to protect the public health. The standards contain enormous built-in conservatism.

The present system of AEC regulation, which puts major emphasis on the maximum permissible concentrations of radionuclides in air and drinking water, should be changed in favor of specifying the maximum permissible daily intake from all sources. This is the method used by the Federal Radiation Council and is preferable because it automatically takes into consideration such factors as multiple sources of exposure and ecological factors.

Although neither NCRP nor AEC is sacrosanct, considerable weight must be given to the fact that the ponderous procedures of these organizations have produced a set of regulations that are workable and that have successfully protected the public health for more than a quarter of a century.

An examination of 27 years of experience would seem to indicate that the AEC has been fully prudent in discharging the responsibilities Congress bestowed on it in the health and safety field. However, it is clear that this judgment is not shared by many people. For reasons probably related to factors other than the excellent safety record it has achieved in the nuclear power field, the AEC does not have the high degree of public confidence that is necessary for smooth development of the electrical generating industry. There remains a credibility gap that has not been closed after more than 15 years of debate.

A significant factor in the credibility gap is the unusual dual responsibility of the AEC for both development of civilian nuclear power and protection of the public health. Although I personally believe that the AEC has an excellent record of accomplishment in both areas and has retained a high degree of objectivity in facing its responsibilities for health and safety, the public is not fully convinced that this is so. For this reason I believe it would be in the public interest to begin active consideration of the means by which the regulatory responsibilities of the AEC can be transferred to some other agency of government or shared with them. Only in this way can we hope to assure the public that the present apparent conflict of missions is not operating to its detriment. However, a transfer of regulatory responsibility cannot be accomplished easily. The AEC has well-developed regulatory machinery of a type that does not exist in any other branch of government. Although in theory it would be possible to transfer this organization *in toto* to another agency, this would not be wise because interagency transfers are always disruptive of morale and working efficiency.

As a compromise the newly created Environmental Protection Administration (EPA) should be given a more prominent role in the regulatory program. The EPA rather than the AEC should promulgate the numerical standards of permissible exposure. The AEC, with its highly developed capability to evaluate reactor designs, should continue to consider applications for new reactors and should continue to monitor construction and operation to assure compliance with the terms of the license. However, the EPA, in collaboration with the states, should undertake the responsibility of effluent monitoring and ecological surveillance. By sharing its present statutory regulatory authority with the EPA in this way, the credibility gap that now exists between AEC and many segments of the public can hopefully be closed.

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Natural Radiation in the Urban Environment

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Abstract: *Natural radiation is the largest source of population dose and is important as a base line with which radiation-protection standards may be compared. In this article previous work on natural background radiation levels is summarized, and some new data from Boston, Mass., are reported. Gamma dose rates, corrected for cosmic radiation, were measured with large ionization chambers: dose rates inside wooden single-family dwellings were 25 to 50% lower than those outside; in masonry multiple-family dwellings, they were about 10% lower. Concentrations of radon daughters in the air were measured by predecay and postdecay alpha spectrometry: concentrations in dwellings were comparable with outdoor concentrations, but concentrations in basements were higher by a factor of about 5. Concentrations in office buildings were quite low, the radon daughters being removed by the ventilation system. Effects of building type, construction materials, and ventilation on human dose are discussed, as are possible ways of reducing population dose.*

Radiation of natural origin is widely recognized as the largest source of human exposure to ionizing radiation. Natural radiation is generally considered to contribute a dose equivalent of 80 to 200 mrems/year to people in the United States.[1] This may be compared with the genetically significant dose-equivalent average of 55 mrems/year[2] from medical radiation and of less than 5 mrems/year from all other man-made radiation sources.

[*Note Added in Proof:* A genetically significant dose from medical radiation of 36 mrems/year was reported from a 1970 survey at the 49th annual meeting of the American Congress of Radiology, Miami Beach, Fla., Apr. 6, 1972, by R. Brown, R. R. Fuchsberg, and J. N. Gitlin in "Preliminary Dose Estimates from the U. S. Public Health Service 1970 X-Ray Exposure Study."]

The natural radiation to which man is exposed in the United States has not yet been delineated in detail; however, it seems that such a description is necessary as a basis for the evaluation of the significance of man-made increments to radiation exposure. Presented in this article is a preliminary report of a study to determine the feasibility of establishing the dose of natural origin and of exploring possible methods for its reduction. Sources of natural origin include cosmic radiation, radiation from naturally occurring radionuclides in the earth or in materials in man's immediate environment, and radiation from radionuclides within the body. However, for purposes of this study, naturally occurring sources were considered only if they had not been intentionally concentrated. Thus masonry materials were included, whereas such sources as uranium mill tailings, radium dials, and medical radium sources were omitted. Also included is a review of previous measurements of natural-radiation doses supplemented by measurements of cosmic-radiation doses, terrestrial gamma doses inside and outside various buildings, and concentrations of radon-daughter products in the air.

BACKGROUND DATA

Measurements of natural background radiation have been made at numerous places throughout the world. In the United States these measurements tend to fall into three categories. First, single measurements were made at widely varying locations selected on the basis of their convenience to a given laboratory or their unusual geological characteristics. Many of these measurements were made in studies of nuclear weapons fallout.[3,4] Second, aerial surveys were conducted in the vicinity of nuclear installations, and, third, special studies were conducted to estimate background radiation dose rates to a particular group of people.[5-7] American studies of natural background radiation have not generally been concerned with the variability of the radiation background over small areas or short spaces of time. This aspect has been studied, however, by some European investigators.[8-10]

The experimental data in this article are expressed in terms of absorbed dose rate in soft tissue (muscle), usually in microrads per hour (1 μrad/hr = 8.77 mrads/year). Data from the literature, many of which were originally given in terms of exposure rates, have been expressed as absorbed dose rates, using a conversion factor of 1 R as equivalent to 0.95 rad. Where a conversion from absorbed dose to dose equivalent was desired, a quality factor of 1 has been assumed for low linear energy-transfer radiation (beta, gamma, and cosmic), so that the absorbed dose rate is the same as the dose-equivalent rate. For the neutronic component of cosmic rays and the alpha radiation from radon and its daughters, the specific quality factor used is given with the data.

Cosmic Radiation

Cosmic rays, at the altitudes where man can live, consist of an ionizing component, mainly muons (μ-mesons) and electrons, and a neutron component.[11] Estimation of the dose equivalent received from cosmic radiation has been difficult because of uncertainties as to the neutron spectrum and its associated quality factor. The dose rate from the ionizing component at sea level in middle latitudes is considered to be about 28 mrads/year (Ref. 11). The best value for the neutron dose rate, again at sea level in middle latitudes, is probably about 0.7 mrad/year (Ref. 11), as compared with a previous estimate of 2 mrads/year (Ref. 1).

The variation of exposure rate from cosmic radiation with altitude and latitude is well documented.[1,11,12] At 50° geomagnetic latitude, the cosmic-ray intensity at 5000 ft is 60% greater than at sea level; at 10,000 ft, it is more than three times the sea-level value. Variation with latitude is much less. At sea level the cosmic-ray intensity at the poles is perhaps 12% greater than at the equator. There is a somewhat greater latitude effect at higher altitudes, but even at 10,000 ft it is only about 50% greater at the poles than at the equator. Within the United States the latitude effect may be neglected for all practical purposes.

The cosmic-ray dose to people in aircraft is of some interest. O'Brien and McLaughlin[13] estimated the dose rate from cosmic radiation at 55° geomagnetic latitude to be 0.24 to 0.29 mrad/hr (0.28 to 0.38 mrem/hr) at 11 km (36,000 ft) and 0.81 to 0.93 mrad/hr (1.05 to 1.35 mrems/hr) at 20 km (65,500 ft). An International Commission on Radiological Protection task group[14] estimated the dose rates in polar latitudes to be 0.70 mrad/hr at 60,000 ft, 0.81 at 70,000 ft, and 1.34 at 80,000 ft. The corresponding dose-equivalent rates are 1.23, 1.80, and 3.10 mrems/hr. The average dose equivalent to the U. S. population from air travel can be estimated at less than 1 mrem/year from data given by Schaefer.[15]

Terrestrial Radiation

Terrestrial radiation includes beta and gamma rays from radionuclides in rock and in soil. The major contributors to terrestrial gamma-radiation dose are ^{40}K and the ^{238}U and ^{232}Th decay series, in the approximate ratio 2 : 1 : 2. A number of literature surveys of terrestrial gamma dose are available.[1,11,12,16-18]

Terrestrial gamma-radiation exposure is strongly influenced by geology.[1,12] Over large freshwater lakes, for example, there is virtually no terrestrial gamma radiation. Highest values are observed over acidic igneous rocks, such as granites, where dose rates up to 350 mrads/year have been found. In a few places, primarily monazite areas, dose rates as high as 1300 mrads/year have been observed. Radiation from terrestrial gamma sources is also affected by meteorological conditions. Probably the most important effect is shielding by snow cover and by moisture in the soil after heavy rains.[8,19]

Published data on the beta contribution to the terrestrial dose differ somewhat. At 1 m above the ground, beta radiation has been estimated to contribute from 4% (Ref. 20) to 25% (Ref. 21) of the total. More recent estimates[4,22] of the beta dose rate at 1 m above the ground are 3 to 4 μrads/hr (26 to 35 mrads/year), or about 30% of the total. The beta contribution to genetic dose is less than this because of shielding by the body.

Radon and Daughters

The naturally occurring radioactive gas radon (^{222}Rn) is a daughter of ^{226}Ra. It reaches the atmosphere by effusion from the earth. The isotope thoron (^{220}Rn), a member of the thorium decay series, reaches the atmosphere in a similar manner but to a much smaller extent since its half-life is much shorter. Both radon and thoron have a number of short-lived radioactive daughter nuclides that become attached to air particulates. Radon concentrations in the atmosphere vary from about 0.01 to 1.0 pCi/liter. Thoron concentrations outdoors vary from about 0.0001 to 0.01 pCi/liter. Concentrations of these gases and of their daughters are markedly affected by geology, by ease of diffusion from the ground, and by meteorological conditions. The daughter products become attached to dust particles and may be removed by natural aerosol clearing processes.

Radiation Within Buildings

The radiation dose within a building is affected by the nature of the building materials, which act as both a source and a shield. Since an average person (in western urbanized cultures) spends upward of 80% of his lifetime indoors, population dose estimates that disregard this fact can be very unrealistic. Exposure levels within brick, concrete, and stone buildings tend to be substantially higher than those in wooden houses or outdoors, as shown in Table 1, which gives data on measurements within buildings in various countries. It should be noted that measurements were made by

Table 1 Gamma Dose Rates Inside Buildings

Country	Exposure rate, mrads/year	Technique*
Germany (East)[10]	106; up to 1200	a
Germany (West)[23] and Switzerland	120% of outdoor	a
Japan[24]	29 to 41 (wood, Tokyo)	
	80 to 100 (wood, Kyoto)	e
	48 to 68 (concrete)	
Japan[25]	20 to 40	c
Poland[9]	84 to 106 (97 apartments, Warsaw, Lodz, Silesia)	c
Sweden[8]	48 to 57 (wood)	
	99 to 112 (brick)	a
	158 to 202 (concrete)	
United Kingdom[26]	73 to 94 (wood)	d
	87 to 122 (granite, Leeds, Aberdeen)	
United Kingdom[27]	26 to 70 (brick, concrete, London, Sutton)	d
United Kingdom[28]	145 (granite, Cornwall)	d
United States[29]	60 (wood)	b
	130 (concrete)	
United States[30]	55 to 110 (wood)	a
	60 to 120 (brick, stone)	
United States[6]	70% of outdoor, wood	a
Australia[31]	11 to 35 (wood and asbestos, coastal plain)	
	41 to 127 (brick, coastal plain)	b
	32 to 193 (brick, Darling range)	

*a = Ionization chamber, gamma + cosmic; b = ionization chamber, cosmic contribution subtracted; c = sodium iodide scintillator; d = Geiger–Mueller counter, cosmic contribution subtracted; and e = plastic scintillator.

several techniques, so that the results are not comparable. In particular, several investigators subtracted the cosmic-ray contribution, so that their data refer to terrestrial gamma contribution only, whereas others did not. Scintillation techniques, especially with sodium iodide scintillators, probably underestimate the cosmic-ray component, so that values obtained by these techniques represent dose levels between gamma only and gamma plus cosmic. Most of the results are for one- and two-story buildings. Pensko[9] and Ohlsen[10] have recently provided data for multistory buildings in Poland and East Germany, but no comparably extensive data appear to be available for the United States. The weighted average of Ohlsen's values is 101 mrads/year, but values up to 200 mrads/year were not uncommon. The two highest values were 450 and 1200 mrads/year.

A few authors[32-34] have examined building materials for their radioactive-material content. As would be expected, the dose rates were found to vary considerably depending on the origin of the building materials.

The concentrations of radon and thoron and of their daughters within buildings are of importance since, in general, the levels indoors are higher than those outdoors and are dependent on the construction materials and on the ventilation rate. Radioactive gases may be evolved readily from some building materials.[35,36] This effect may be particularly great when the materials are warmed, as occurs especially with radiant heating systems. Sievert[17] has summarized the concentrations of radon and its daughters in various types of buildings. The average level of radon in buildings has been estimated[11] as 0.5 pCi/liter, with a corresponding thoron average of 0.02 pCi/liter.

METHODS AND RESULTS

Cosmic Radiation

In the new measurements reported here, two kinds of 16-liter ionization chambers were used for gamma-plus-cosmic-ray exposures. One chamber[37] (MEC) had 6-mm muscle-equivalent walls and contained muscle-equivalent gas. The other chamber[38,39] (FFC) was filled with dry Freon-12 (dichlorodifluoromethane) containing less than 1.5% impurities. The walls of this chamber were polymethylmethacrylate (PMMA), 400 mg/cm^2.

Each chamber was connected to a Cary vibrating-reed electrometer, which in turn was coupled to a chart recorder and to a voltage-to-frequency converter and scaler. The converter–scaler combination made it possible to integrate the very small ion currents over a period of 5 min, giving results reproducible to within 2%.

The two chambers were calibrated with a 1.72-mCi ^{226}Ra standard source. The source–chamber distance was 4 m. Corrections were made for the absorption in air and in the source container and for wall scattering.

A daily calibration check of the FFC showed that the response declined with time. It was also observed that the pressure dropped from 41.7 torrs above atmosphere to 81.0 torrs below atmosphere over a period of 4 months. Both the change in response and the loss of pressure were attributed to loss of Freon-12, apparently by dissolution in the PMMA walls followed by evaporation from the outer surface of the chamber.

Cosmic radiation was measured with these instruments in a boat on Quabbin Reservoir, a large freshwater lake. Under such conditions, virtually the total ionization is due to cosmic radiation since the instruments are shielded from terrestrial radiation by the water and the long air path to shore.

Cosmic-ray physicists normally report their data in terms of I, the number of ion pairs produced per second per cubic centimeter of air. This measurement is essentially the same as the measurement of exposure rate in roentgens, one ion pair per second per cubic centimeter being equivalent to 1.7 μR/hr. Since neither the MEC nor the FFC is air filled, the I values were calculated from the ionization current by correction for the nature of the gas.

With the FFC, the ionization density I was found to be 2.18 ion pairs per cubic centimeter per second, or 2.06 when corrected to sea level.[38] This measurement compares well with reported values of 2.1 (Ref. 40) and 2.18 (Ref. 38) ion pairs per cubic centimeter per second. The measurement of I with the MEC was 2.57, corrected to sea level, or 25% higher. This discrepancy may be due to an incorrect ionization-efficiency factor for the gas (as compared with air), to response to the neutron component, or to some unknown effect. It was not due to instrument malfunction, since the exposure-rate measurements on the instruments, which are relative to radium calibrations, agreed. They were 4.27 μR/hr (37 mR/year) for the FFC and 4.43 μR/hr (39 mR/year) for the MEC, both corrected to sea level. In terms of absorbed dose, these measurements become 4.06 μrads/hr (35 mrads/year) and 4.21 μrads/hr (37 mrads/year) for the two instruments.

When these measurements were made, the air concentrations of radon daughters were not determined. Failure to correct for their contribution introduced an error into the measurements. However, this error can be estimated as about 3% from the work of Pensko,[41] in Poland, who found the contribution to gamma radiation from radon daughters to be 0.13 μrad/hr in 1964 and 0.14 μrad/hr in 1965. In spite of diurnal variations in radon content, the error is not expected to be greater than this because the readings were made during the afternoon on a clear, sunny day. Under these circumstances, radon-daughter concentrations are generally not at a maximum.

Gamma Radiation

Gamma-radiation dose was measured at 1 m above the ground or floor with the MEC and FFC chambers described previously. Use of two chambers simultaneously provided a check against spurious readings that sometimes occur in measuring extremely small currents through very high resistors. These chambers had been calibrated in roentgens, using gamma radiation from radium. The readings have been converted to absorbed dose, however, as previously described. To the extent that beta radiation can penetrate the chamber walls and produce ions, the beta dose is also included. In the actual situation, of course, the ionization in the chambers is produced by gamma radiation from the surroundings (plus beta, if any) and also by cosmic radiation. The dose from terrestrial sources is therefore obtained by subtracting the cosmic-ray dose values from the total. The values obtained at Quabbin Reservoir, corrected for the difference in altitude between Quabbin and Boston, were used for the subtraction. No correction was made for absorption of cosmic rays by building materials, since the cosmic radiation at sea level is very hard.

In these measurements the chief concern was the radiation levels within buildings. In many cases, outdoor levels were also measured for comparison.

Single-Family Dwellings. Table 2 shows the absorbed dose rates due to natural gamma radiation in seven single-family dwellings. These were wood-frame houses with poured-concrete basements. Since no significant differences were found between measurements with the MEC and the FFC, the dose readings were averaged.

Table 2 Gamma Dose Rates (μrads/hr) in Single-Family Dwellings*

Place	Outdoors	Basement	First floor	Second floor
ASG	6.2	5.3	5.0	
MWF			7.3	
FSH	9.0		6.8	
WAB	4.9	4.9	4.2	2.5
SP	8.1	6.2	4.3	4.1
FJV	5.8	6.0	4.4	
DWM	6.5	6.8	6.2	3.2

*A cosmic-ray contribution of 4.1 μrads/hr has been subtracted from all values.

It can be seen that the dose from natural gamma radiation is reduced by 25% inside on the first floor and 50% on the second floor (assuming cosmic rays are not attenuated in a wooden building). The dose rates will of course not be reduced by this large a percentage, since a constant cosmic-ray contribution of 4.1 μrads/hr must be added to all values to obtain the total dose rate.

Multiple-Family Dwellings. Measurements were made in three multifamily dwellings. These were what are normally called "brick" buildings, but details of their construction were not available. For example, it is not known whether these buildings were solid brick, brick facing on concrete block, or some other type of construction. Measurements were made in one residence in each apartment building. Each residence happened to be on the second floor. Only in one case was a corresponding outdoor measurement made. The measurements are given in Table 3.

Table 3 Gamma Dose Rates (μrads/hr) in Multiple-Family Dwellings*

Place	Outdoors	Second floor
MLC		6.2
JS		7.5
OG	7.2	5.5

*A cosmic-ray contribution of 4.1 μrads/hr has been subtracted from all values.

The average for the three apartments, 6.4 μrads/hr, is substantially greater than the average value for the three second-floor readings in single-family dwellings (Table 2). This indicates additional dose, which may be attributed to radioactive nuclides in the construction materials. In the one case where a comparison with the outdoor exposure is available, the gamma radiation is lower by 24%, showing that the terrestrial radiation is attenuated by the building materials. In this case the attenuation more than compensates for the radiation contributed by radionuclides in the construction material.

Multistory Office Buildings. Measurements were made in four office or office-plus-laboratory buildings. The most extensive series of measurements was made in the Harvard School of Public Health (HSPH) Research Building 1. This is a modern 14-story office-plus-laboratory building of reinforced-concrete construction with interior wall facings of cinder block. Measurements were made in the corridors of several floors to investigate the variation of exposure rate with height in the building (Table 4).

These measurements were made in part to test whether the attenuation of terrestrial gamma radiation on the upper floors would be greater or less than the possible attenuation of cosmic radiation on the lower floors. The data of Table 4 show a fairly constant radiation level for the first eight floors in the HSPH building and then a slight decrease. These data were supported by nonspectrometric gamma measurements with a 3- by 3-in. NaI(Tl) crystal (Fig. 1). A possible

Table 4 Gamma Dose Rates in Office Buildings

Building	Year completed	Construction	Interior walls	Height, stories	Floor	Gamma dose rate,* μrads/hr
JFK	1966	Reinforced concrete	Sheetrock partitions	23	Basement	6.7
					5	4.8
					20	4.9
					23	6.5
HC	1962	Reinforced concrete	Sheetrock partitions	10	2	9.0
SO	1917	Steel and concrete	Sheetrock partitions	12	Basement	5.5
					5	7.2
					12	7.3
HSPH†	1969	Reinforced concrete	Cinder block	14	Basement	7.3
					1	7.5
					3	7.4
					7	8.9
					9	7.8
					11	4.6
					12	6.7
					13	5.8
					14	6.8

*A cosmic-ray contribution of 4.1 μrads/hr has been subtracted from all values.
†First four floors, 1962; next 10 floors, 1969.

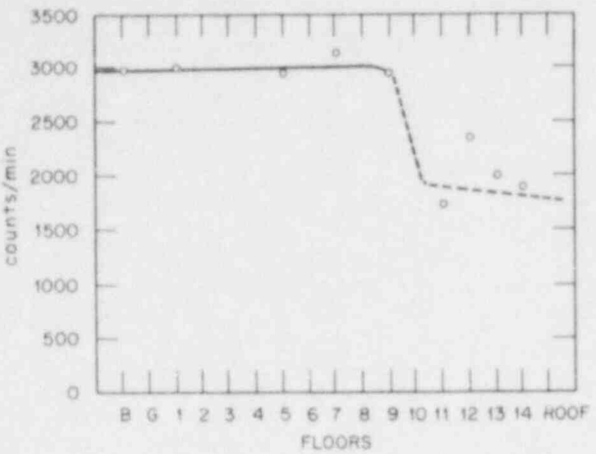

Fig. 1 Total gamma count rates on various floors.

explanation is shielding by heavy machinery on the 10th floor.

Measurements were also made on four floors of the John F. Kennedy Federal Building (JFK) in Government Center, Boston. This is a 23-story steel-and-concrete building that was completed in 1966. Interior walls are Sheetrock partitions. All measurements in this building were taken in office spaces. In addition, measurements were made on three levels of an older office building (SO) housing part of the Massachusetts Department of Public Health and on the second-floor level in the main building at the Holyoke Center (HC) of Harvard University. The HC building had a slightly higher dose rate than the other buildings tested. This may be attributed to differences in the radionuclide content of the concrete. The data for these three buildings are also presented in Table 4. The average gamma dose rate in these buildings was 7.3 μrads/hr, the cosmic-ray contribution having been subtracted.

The data of Table 4 fail to show any significant change with height in the buildings. It can be inferred that the gamma dose measured originates primarily in the building itself and that the cosmic-ray dose is not significantly attenuated. This is in agreement with Ohlsen,[10] who reported no change in radiation-exposure rates on various floors of multistory buildings.

Radon-Daughter Concentrations

The daughter products of ^{222}Rn are not generally present in the air in equilibrium concentrations. It was therefore necessary to measure the absolute concentration of each daughter, using a modification of Duggan's[42] method. Radon-daughter products, attached to air particulates, were collected on a membrane-filter apparatus, shown in exploded view in Fig. 2. An alpha spectrum of these particulates was taken during the 30-min sampling period and again after a 30-min decay period. Figures 3 and 4 show typical examples of these two spectra. The first is characterized by peaks at alpha energies of 6.00 and 7.68 MeV, corresponding to ^{218}Po and ^{214}Po; the second shows only the single 7.68-MeV peak. The counting rates in each peak were corrected for geometric efficiency[43] and peak overlap. Self-absorption loss was taken to be zero. At a flow rate of 15 to 20 liters/min, sensitivity was about 0.01 pCi/liter for each of the three significant short-lived daughters ^{218}Po, ^{214}Pb, and ^{214}Bi. At this level precision is poor, but the method is quite satisfactory over the range 0.1 to 100 pCi/liter. The determination does not give the concentration of ^{222}Rn itself, but this can be approximated[44] by using the ratio ^{222}Rn/^{218}Po = 1.12.

Ventilation rates, which affect the state of equilibrium of the radon daughters, were measured by injecting about 0.5 lb of CO_2 into the room from a CO_2 fire extinguisher. The CO_2 concentration was measured with Kitagawa low-range tubes after a mixing period of several minutes and again at a suitable later time. The ventilation rate (air changes per hour) was then calculated.[45]

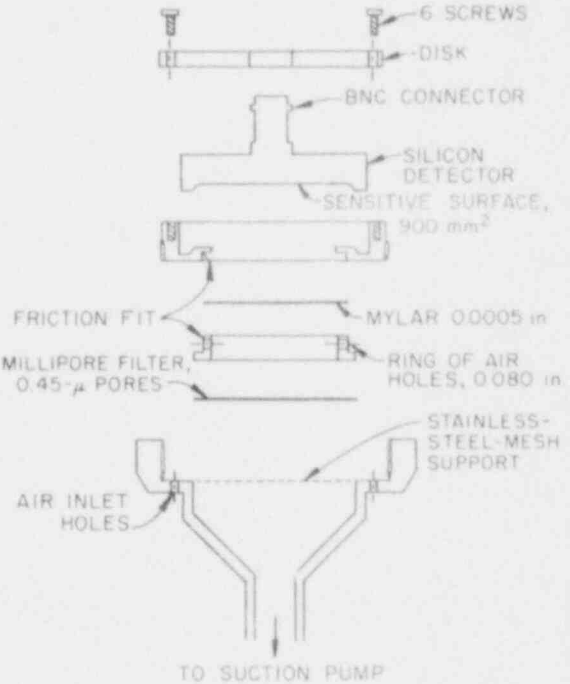

Fig. 2 Air filter and alpha-spectrum detector (exploded view)

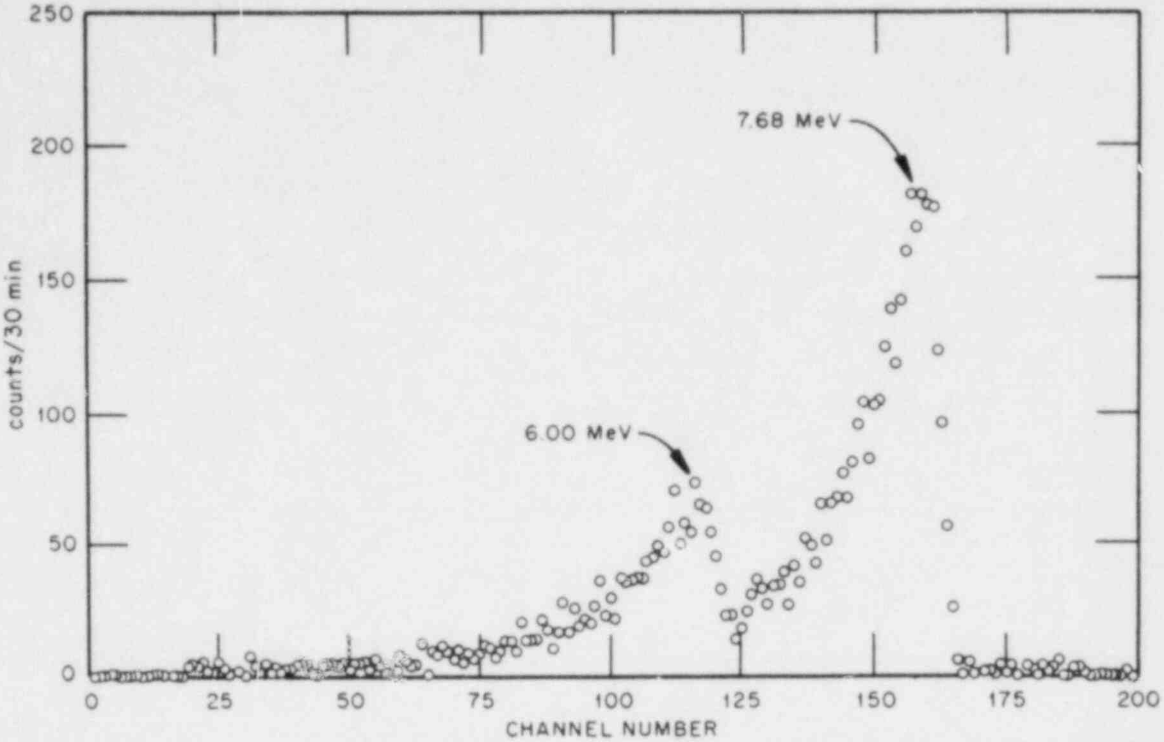

Fig. 3 Radon-daughter alpha spectrum during collection period.

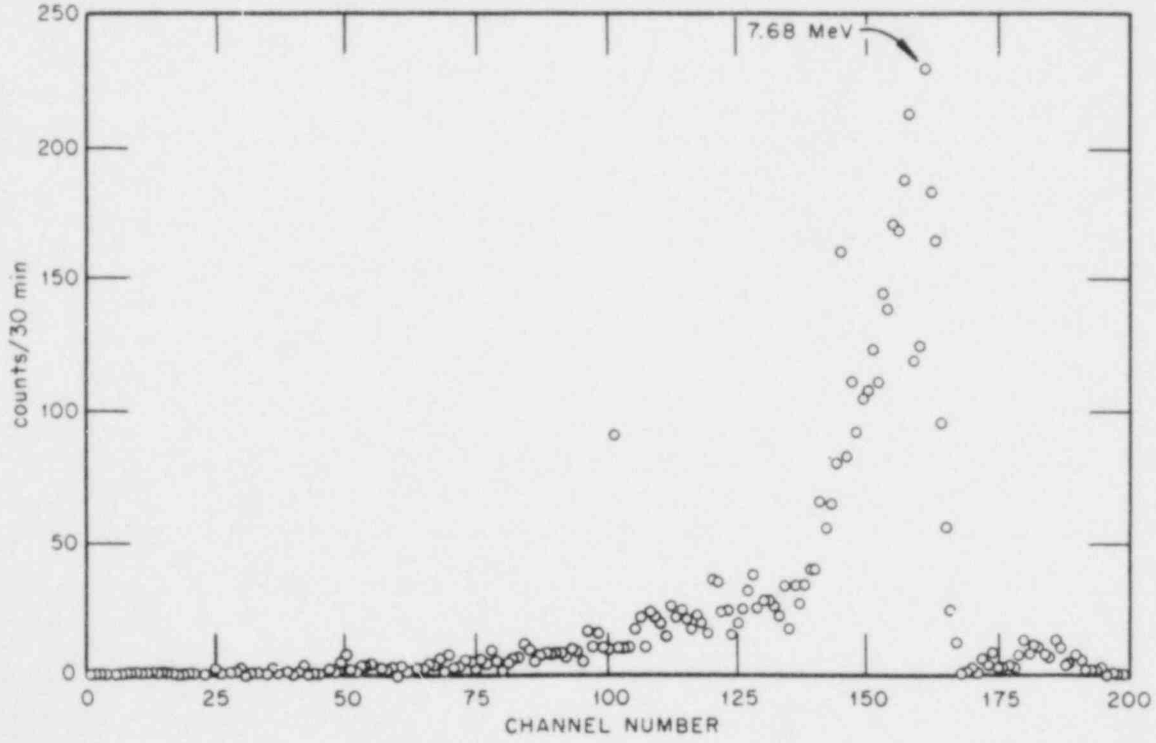

Fig. 4 Radon-daughter alpha spectrum after 30-min delay.

Because of the exchange of air between the room being measured and the remainder of the building, the ventilation rate obtained by this method may have been greater than that for the whole apartment or building in which the room was located. In some cases, however, it was not feasible to fill the whole apartment or building with an equal concentration of CO_2, so more accurate determinations were not possible.

All measurements of radon-daughter concentrations in this study were made in the summer months and therefore are limited by any seasonal effects that may exist. The concentrations of the various nuclides and the ratios of these concentrations for single- and multiple-family dwellings are summarized in Table 5. It can be seen that the concentrations in basements were 4 to 23 times those found on the first floors, with the exception of the basement of WAB, which was ventilated just before this measurement. The concentrations outside and inside wood houses are not significantly different. The low levels of concentration in apartment buildings are thought to be due to better ventilation.

Concentrations of radon daughters in the four office buildings were also quite low. All the buildings had central air conditioning except the SO building, which had a number of individual units. Most of the radon daughters in office buildings were thus removed by the filtering system and the rapid circulation of air. Table 6 shows the concentrations measured.

The data of Tables 5 and 6 show a general decline of radon-daughter concentrations with increased ventilation. The concentration of the third radioactive daughter, ^{214}Po, relative to the others, seems to be a little lower in dwellings with three or more air changes per hour, but this trend is not apparent in the office buildings (Table 6). It may be that the filtration provided by the air-conditioning systems in the office buildings removes all the daughters to an extent sufficient to hide the depletion of ^{214}Po.

Calculation of the absorbed dose and of the dose equivalent from radon daughters is not straightforward, primarily because of uneven distribution of the daughters in the respiratory tract and in the body. Much work has been done on this problem, particularly in connection with uranium miners. Parker[46] has aptly described the situation as "The Dilemma of Lung Dosimetry." He has suggested that exposure to radon daughters amounting to one "working-level-month" (WLM) corresponds to a dose of 7 rads to a portion of the bronchial epithelium. An approximate calibration for the levels observed in air in buildings may be obtained from this. The "working level" was defined[47] as that amount of radon daughters that would liberate 1.3×10^5 MeV of alpha energy per liter. This corresponds to a concentration of 100 pCi/liter of each of the three nuclides ^{218}Po, ^{214}Pb, and ^{214}Bi. The WLM is equivalent to exposure at this level for 173 hr. If these values are translated to the building situation and if exposure for 24 hr/day, 365 days/year is assumed, then a concentration of 1 pCi/liter would correspond to

$$\frac{(7000)(365)(24)}{(173)(100)} = 3500 \text{ mrads/year}$$

Quality factors of 10 to 20 have been recommended for alpha radiation, so that a concentration of 1 pCi/liter corresponds to 35 or 70 rems/year.

DISCUSSION

The data presented in this paper indicate that there can be substantial differences in the doses received from sources of natural origin, depending on the mode of life of the individual. For example, cosmic dose would be highest for those population groups living at high altitudes or latitudes, for those whose recreation involves skiing or mountain climbing, and for those whose work or pleasure includes considerable air travel. The greatest dose from terrestrial sources would be received by those population groups living on land containing high concentrations of naturally occurring radionuclides and those living in certain brick, stone, or concrete buildings. Those living in poorly ventilated homes, especially in basement apartments, or working in poorly ventilated buildings would receive the greatest dose to the lungs.

The increased doses received by some people under the above-mentioned conditions are not trivial. Based on data collected in the greater Boston area, the differences in dose rates for persons living on the second floor are as much as 35 mrads/year. These dose (rad) values are the same as dose-equivalent (rem) values since the quality factor of this beta–gamma and cosmic radiation is 1. A difference of 35 mrems/year is more than half as much as the estimated genetically significant population dose from medical uses of radiation[2] and far higher than any projections of population dose from nuclear power applications in the near future. Of course, the population or genetic significance of dose differences from various kinds of buildings depends on the fraction of the population living in each type. Relatively few people live in

Table 5 Radon-Daughter Concentrations in Dwellings

Code	Location	Concentrations, pCi/liter			Ratio	Number of air changes per hour
		^{218}Po	^{214}Pb	^{214}Po		
Single-Family Dwellings*						
ASG	Outside	0.04	0.04	0.03	1 : 1 : 0.8	
	1st floor	<0.005				
	Basement	~0.1				
MWF	1st floor	0.04	0.04	0.02	1 : 1 : 0.5	6
FSH	Outside	0.01	0.01	0.007	1 : 1 : 0.7	
	Inside	0.06	0.06	.06	1 : 1 : 1	2
WAB	Outside					
	1st floor	0.23	0.17	0.17	1 : 0.7 : 0.7	2
	2nd floor					
	Basement	0.14	0.16	0.05	1 : 1.2 : 0.4	3
SP	Outside	0.03	0.02	0.04	1 : 0.7 : 1.3	
	1st floor	0.03	0.03	0.02	1 : 1 : 0.7	
	2nd floor	0.03	0.02	0.01	1 : 0.7 : 0.3	
	Basement	0.30	0.26	0.16	1 : 0.9 : 0.3	3
FJV	Outside	<0.01				
	1st floor	0.04	0.04	0.04	1 : 1 : 1	3
	Basement	0.94	0.97	0.84	1 : 1 : 0.9	1
DWM	Outside					
	1st floor	0.12	0.15	0.13	1 : 1.2 : 1.1	2
	2nd floor					
	Basement	0.52	0.46	0.34	1 : 0.9 : 0.6	1
Multiple-Family Dwellings†						
MC	2nd floor	0.01	0.01	0.01	1 : 1 : 1	
JS	2nd floor	0.07	0.07	0.03	1 : 1 : 0.4	9
OG	Outside	0.15	0.09	0.07	1 : 0.6 : 0.5	
	2nd floor	0.19	0.18	0.13		5

*All single-family dwellings were wood frame with poured-concrete basements.

†All multiple-family dwellings were brick.

Table 6 Radon-Daughter Concentrations in Office Buildings

Code	Type of building	Interior walls	Location	Concentration, pCi/liter			Number of air changes per hour
				RaA	RaB	RaC	
HSPH	Offices and laboratories	Cinder block	Basement				
			1st floor	~0.02	0.02	0.02	6
State offices	Offices	Sheetrock	5th floor	0.08	0.08	0.08	6
			12th floor	0.10	0.11	0.13	7
			Basement	0.05	0.04	0.05	
Holyoke Center	Offices	Sheetrock	2nd floor	0.05	0.04	0.04	7
JFK	Offices	Sheetrock	5th floor	0.03	0.02	0.02	12
			20th floor	0.05	0.04	0.01	5
			23rd floor	0.04	0.03	0.03	14
			Basement	0.07	0.07	0.03	

basement apartments; a much greater percentage live in brick or masonry homes.

More dramatic differences exist in the dose equivalents to lung, specifically to basal cells in small bronchi. Radon daughters are the major contributors to the dose equivalent. The concentrations of these daughters in basements with one air change per hour were from 4 to 15 times higher than those on the first floors of the same houses, with two to three air changes per hour. The average level of ^{218}Po in five basements was about 0.4 pCi/liter. Using the previously calculated relation between dose and radon-daughter concentration, this average level would correspond to a dose rate of 1400 mrads/year. Reduction of radon-daughter concentrations by a factor of 10, which is approximately the average ratio between basements and first floors, would amount to a dose reduction of 1250 mrads/year. Application of the recommended quality factor of 10 to 20 for alpha radiation would convert this to 12.5 or 25 rems/year to some basal cells in the bronchial epithelium.

Implications

Health physicists generally have paid little attention to the control of radiation exposure received by the population from natural sources. It appears probable, however, that significant reduction of radiation dose may be achieved in the design of living and working environments. The relative constancy of dose levels on various floors of masonry office buildings, noted here and by Ohlsen, suggests that most of the gamma radiation originates in construction materials rather than in the ground. Provision of better ventilation and air-filtration systems, reduction of the number of basement dwelling units, and screening of construction materials to eliminate those which emit excessive radiation would seem to be promising areas of investigation. Such reduction of population dose equivalent received from buildings may well be comparable with the projected increase from development of nuclear power.

Although definitive data are lacking, it may well be that some people, because of the nature of their environments, are experiencing unnecessarily increased exposure to radiation from sources of natural origin and that this increased exposure is greater than that expected from many man-made sources. Considering this possibility, it would seem wise that greater attention be given to obtaining data on the population dose equivalent from natural sources and the influence of man's living habits on this dose.

Prospectus

Older construction, even in central cities, was largely wood. The data for Boston[48] may be cited as an example. As of January 1968, 68.5% (96,689) of all buildings in Boston were of wood construction. The remaining 31.5% (44,546) were made up of a variety of types, the older ones being predominantly brick and the newer ones concrete or cinder block.

In the newer construction, there is a shift from predominantly single- to multiple-family-dwelling construction. The Boston building-permit records for the period 1959 to 1968 indicate that the number of single-family dwellings decreased from 95% of the total number constructed to 33% and that multifamily (three or more) dwellings increased from 1% of the number constructed to 58%. There was an increase in two-family dwelling construction from 2% in 1959 to a high of 26% in 1965, followed by a decline to 8% in 1968.

The large increase in the number of multifamily dwellings implies a large increase in the fraction of the Boston population living in masonry buildings since virtually all the new multifamily dwellings are of masonry construction. Although quantitative data are not available, observations indicate that more masonry apartment buildings are being built in the suburbs as well. It therefore appears that the urbanization and suburbanization of the population are accompanied by an increase in the fraction living in masonry construction.

To the extent that masonry construction is increasing, higher external exposure of occupants may be expected. To the extent that newer buildings include modern ventilation systems, lung exposure to radon daughters may be decreased.

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Population Doses from the Nuclear Industry to 2000 AD

Nuclear Safety Editorial Staff
Adapted from WASH-1250

Nucl. Safety, 15(**1**): 56–66 (January–February 1974)

[Editor's Note: This article was adapted by the editors of *Nuclear Safety* from a portion of Chap. 4 of USAEC Report WASH-1250, The Safety of Nuclear Power Reactors and Related Facilities. The material presented there was, in turn, partially derived from USAEC Report WASH-1209, The Potential Radiological Implications of Nuclear Facilities in a Large Region in the U.S.A. in the Year 2000. The subject is of such current interest that it is presented here with changes as required only to make the adapted material self-sufficient. However, the reader is reminded that the reactor effluent information is derived from 1971 data, and the article does not necessarily reflect the latest developments on effluent control as are evolving from the "as-low-as-practicable hearing."]

Abstract: *During the next few decades, it is anticipated that the nuclear power industry in the United States will undergo a remarkable growth. To project the effect of this growth on the radiation doses of the general public, the U. S. Atomic Energy Commission made a review of current reactor operating experiences. From this review a detailed analysis of the radiation dose to a major section of the country due to effluents from nuclear facilities for conditions projected for the year 2000 was undertaken. The study indicates that the average dose to the U. S. population from nuclear power will increase from an estimated 0.003 mrem per person in 1970 to as much as 0.2 mrem in the year 2000. This contribution remains a small fraction of the radiation dose from either natural or man-made sources of ionizing radiation.*

The nuclear power industry is expected to undergo a remarkable growth during the next few decades. The question of how this growth will affect the radiation doses to the general public has been receiving considerable attention, both from the government and the nuclear power industry. Although radiation doses arising from the nuclear industry have thus far been very small,[1] the industry itself has also been very small. In 1970, 1 commercial fuel-reprocessing plant and 18 nuclear power plants, with an aggregate capacity of about 6900 MW(e), were in operation. By the year 2000, it is projected[2] that the aggregate capacity will be about 1.2×10^6, which will require the operation of about 20 fuel-reprocessing plants and on the order of 1000 nuclear power plants. Growth in the nuclear industry will undoubtedly continue beyond that time.

The U. S. Atomic Energy Commission (AEC) has made a detailed analytical study of the radiological implications accompanying this projected growth, taking into consideration existing and developing technology for the control of radioactive releases from nuclear facilities as well as contemplated changes in the regulated limits of such releases.[3] On the basis of this study, it appears certain that radiation doses due to the nuclear industry can and will be maintained indefinitely at a small fraction of natural-background radiation doses.

NUMERICAL GUIDES FOR MAINTAINING RADIOACTIVE RELEASES AS LOW AS PRACTICABLE

In June 1971 the AEC proposed revising 10 CFR 50 to include Appendix I, which would provide numerical guides for light-water-reactor (LWR) design and operation with respect to keeping radioactivity in effluents as low as practicable.[4] The "as-low-as-practicable" concept was expressly established in an amendment to Title 10, Parts 20 and 50, of the *Code of Federal Regulations*, published Dec. 3, 1970, and means "as low as is practicably achievable, taking into account the state of technology and the economics of improvement in relation to benefits to the public health and safety and in relation to the utilization of atomic energy in the public interest."[5] The proposed guides consist of (1) numerical values for levels of radioactivity in effluents to be used as design objectives for LWR stations and (2) limiting conditions of operation for LWR stations.

The basic objective of the design guides is to limit the dose to the whole body or to any organ of an individual off site to a maximum of 5 mrems/year from radioactive material in liquid effluents and 5 mrems/year to the whole body or to any organ of individuals off site from radioactive material in gaseous effluents.

Design Objectives: Liquid Effluents

The proposed design-objective guides for liquid effluents would limit radioactive material (except tritium) in liquid effluents from each LWR at a site to a total annual quantity of radioactive materials not exceeding 5 Ci and an average annual concentration of 20 pCi/liter or less prior to dilution in a natural body of water. The proposed design objective for tritium is an average annual concentration of 5000 pCi/liter or less prior to dilution in a natural body of water.

Operating Experience

The quantities and concentrations of radioactive materials in liquid effluents from the operating major light-water-cooled nuclear power reactors in the United States during 1971 are given in Table 1. The maximum quantity released was 81 Ci, and the minimum was ~0.01 Ci; 7 of the 15 stations listed had releases that exceeded the proposed design objective of 5 Ci. The average of all releases to date is greater than the design objectives; however, existing nuclear facilities would have to upgrade their effluent-control systems at such time as more restrictive licensing guidelines are adopted, as proposed in 10 CFR 50, Appendix I:[6]

> . . . In any event, all holders of licenses authorizing operation of a light-water-cooled nuclear power reactor should, *after* 36 months from *effective* date of this *guide*, develop technical specifications in conformity with the guides of this section.

The related concentrations ranged from a high of 220 pCi/liter to a low of 0.041 pCi/liter, and 5 of the 15 stations had release concentrations in excess of the design objective of 20 pCi/liter. The average concentration is about 1.4 times the design objective.

Tritium concentrations were in the range <20 to 7800 pCi/liter, and three of the stations (all PWRs) had concentrations greater than the design objective of 5000 pCi/liter. The release data and comparisons with the design objectives for 1969 to 1971 are given in Tables 1 and 2.

Estimated Maximum Doses to People

If it is assumed that all of an individual's drinking water is obtained from a reactor effluent canal that contains the design-objective concentration of 20 pCi/liter of mixed fission and activation products, his annual whole-body dose would be 0.68 mrem. If the water also contains the design-objective concentration for tritium of 5000 pCi/liter, he would receive an additional whole-body dose of 0.83 mrem. If this individual also eats an average of 50 g/day of fish grown in this effluent, he would receive an additional annual whole-body dose of 3.8 mrems, making the total annual whole-body dose about 5.3 mrems. For a

Table 1 Releases in Liquid Effluents During 1971 Compared with Proposed Design Objectives*

	Mixed fission and corrosion products				Tritium		
Facility	Curies released	Ratio of release to design objective	Concentration, Ci/liter	Ratio of release to design objective	Curies released	Concentration, Ci/liter	Ratio of release to design objective
Pressurized-Water Reactors							
Indian Point	81	16	220	11	725	1890	0.378
Yankee Rowe	0.115	0.0058	0.041	0.002	1685	5940	1.19
San Onofre	1.54	0.31	2.4	0.12	4570	7200	1.4
Connecticut Yankee	5.88	1.17	1.3	0.065	5830	7800	1.56
Ginna	0.96	0.19	1.38	0.069	154	210	0.042
H. B. Robinson	0.736	0.147	11.5	0.57	118.3	1860	0.372
Point Beach	0.15	0.03	0.27	0.014	266	450	0.09
Boiling-Water Reactors							
Oyster Creek	12.1	2.4	11.3	0.56	21.5	78	0.016
Nine Mile Point	32.2	6.4	69	3.45	12.4	27	0.0054
Dresden 1	6.15	1.2	21	1.05	8.7	30	0.006
Dresden 2 and 3	23.2	4.6	17	0.85	8.5	30	0.006
Humboldt Bay	1.84	0.37	11.4	0.57			
Big Rock Point	3.46	0.79	34	1.7	10.3	60	0.012
Millstone	19.65	3.9	26	1.3	12.7	18	0.0036
Monticello	0.014	0.0028	0.054	0.0027	0.59	24	0.0048

*Numerical guides for liquid-effluent design objectives in proposed Appendix I to 10 CFR 50 are: for radioactive material except tritium, 5 Ci annually and an average concentration of 20 pCi/liter, and, for tritium, an average concentration of 5000 pCi/liter.

Table 2 Comparison of Releases in Effluents for 1969 to 1971

	Releases in liquid effluents						Releases in gaseous effluents					
	Total, Ci (less ^{3}H and dissolved gases)			Tritium, Ci			Noble gases, 10^3 Ci			Halogens and particulates with half-lives >3 days, Ci		
Facility	1969	1970	1971	1969	1970	1971	1969	1970	1971	1969	1970	1971
Pressurized-Water Reactors												
Indian Point 1	28.0	7.8	81.1	1100	410	725	0.60	1.7	0.36	0.025	0.08	0.21
Yankee Rowe	0.02	0.03	0.01	1200	1500	1680	0.004	0.017	0.0128	<0.001	<0.001	<0.0001
San Onofre	8.0	7.[illegible]	1.54	3500	4800	4570	0.26	4.2	7.67	0.001	0.001	<0.0001
Connecticut Yankee	12.0	6.7	5.9	5200	7400	5830	0.19	0.7	3.25	0.001	0.002	0.03
R. E. Ginna	0.02	10.0	0.96	<1	110	154	<0.001	10	31.8	<0.001	0.05	0.17
H. B. Robinson			0.74			118			0.018			None detected
Point Beach 1			0.15			266			0.838			<0.0001
Boiling-Water Reactors												
Oyster Creek	0.48	18.5	12.1	5	22	21.5	7.0	110	516	0.003	0.32	2.14
Nine Mile Point	0.9	28.0	32.2	<1	20	12.4	0.06	9.5	253	<0.001	<0.09	0.78
Dresden 1	9.5	8.2	6.2	6.0	5	8.7	800	900	753	0.26	3.3	<0.67
Dresden 2 and 3			23.2		31	38.5			580		1.6	8.68
Humboldt Bay	1.5	2.4	1.8	<5	<2	<7.5	490	540	514	0.65	0.35	0.3
Big Rock Point	12.0	4.7	3.5	28	54	10.3	200	280	284	0.2	0.13	0.61
Millstone 1			19.7			12.7			276			4.0
Monticello			0.01			0.6			75.8			0.052

reactor with seawater in the effluent canal, there would be no comparable doses due to the drinking of the water, and the annual whole-body dose due to the eating of seafoods taken from the canal would be about 3.6 mrems (Appendix A of Ref. 7).

By comparison, if this hypothetical individual's source of intake comes from effluents with the highest concentration of radioactive materials (except tritium) thus far reported, his annual whole-body dose might be as much as 16 mrems. It is most unlikely, however, that any such prolonged exposure to these sources of intake would actually occur, and it is a reasonable expectation that meeting the design-objective release concentrations will assure that even those few individuals with the highest exposures (that might be obtained in practice) will not receive annual whole-body doses in excess of 5 mrems.

The populations using drinking water from the natural bodies of water into which the liquid effluents from currently operating reactors flow are small, and, with the additional dilutions provided by the water body, the average dose per person is reduced to less than 0.01 mrem. Populations near some of the reactors now being built or planned will in some cases be considerably larger, and, if they obtain their drinking water from the water bodies into which the liquid effluents flow, the total population dose would be larger. The average annual whole-body dose to individuals in a large population is not expected to be any larger than about 0.1 mrem for individual reactors operated within the proposed design objectives.[3,8]

Design Objectives: Gaseous Effluents

The proposed design-objective guide for the release of noble gases is that the total annual release from all reactors at a given site should not result in an average dose rate greater than 10 mrems/year in the plant-boundary environs.* The design objective for the gaseous releases of iodine isotopes and particulates with half-lives greater than 8 days is that the annual average concentrations at any location on the boundary of the site or in the nearby environment should not be in excess of the currently specified maximum permissible concentrations in air, divided by 100,000. This takes into account the possible concentration of iodine via the grass–cow–milk chain to human ingestion or other comparable chains.

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*However, it must be shown that the annual dose to any organ of any individual will not exceed 5 mrems as a consequence of gaseous effluents.

Operating Experience and Estimated Doses to People

The quantities of noble gases released from the major light-water-cooled nuclear reactors operated during 1971 and the calculated annual doses at the plant boundary and to the population within 50 miles of the reactor sites are given in Table 3. The calculated annual whole-body doses that could have resulted at the boundaries from the measured gaseous releases range from a minimum of 0.035 mrem to a maximum of 160 mrems. The average doses for people residing within a 50-mile radius range from 0.00002 to 0.5 mrem. Release data and comparison for 1969 to 1971 are given in Table 2.

The quantities of iodines and particulates released in gaseous effluents for 1971 are given in Table 4. The total annual releases of iodines and particulates in gaseous effluents range from a minimum of less than 0.0001 Ci to a maximum of 4.3 Ci. Release data for 1969 to 1971 are given in Table 2.

Quantities and concentrations higher than those discussed above may be deemed to meet the requirement for keeping levels of radioactivity in effluents as low as practicable if the applicant provides reasonable assurance that proposed higher quantities and/or concentrations will not result in annual exposures to any organ of an individual in excess of 5 mrems from liquid or gaseous effluents. The Commission may specify lower quantities and concentrations than those discussed above if it appears that the use of the design objectives is likely to cause an annual exposure in excess of 5 mrems to the whole body or organ of an individual from liquid or gaseous effluents.

Applicable Technology for Effluent and Dose Reduction

On the basis of data from currently operating LWR stations, it appears to be well within the capability of currently available technology to maintain LWR gaseous and liquid effluent releases at levels that provide assurance that annual radiation doses to the whole body or to any organ of an individual will not be in excess of 5 mrems. In some cases, only relatively minor changes in the equipment and practices currently used will be required. Reductions in the release of radioactive materials can be achieved through the increased

Table 3 Noble Gases Released, Boundary and Average Individual Doses, and Population Doses for 1971

Facility	Noble gases released, Ci	Boundary dose, mrems	Within 50 miles	
			Average individual dose, mrem	Population dose,* man-rems
Pressurized-Water Reactors				
Indian Point	360	0.035	0.00005	0.77
Yankee Rowe	13	0.3	0.0003	0.41
San Onofre	7,670	2.2	0.002	6.3
Connecticut Yankee	3,250	5.6	0.003	11
Ginna	31,800	5.0	0.004	4.5
H. B. Robinson	18	0.05	0.00002	0.015
Point Beach	838	0.2	0.0008	0.15†
Boiling-Water Reactors				
Oyster Creek	516,000	31	0.013	46
Nine Mile Point	253,000	4.8	0.009	8.2
Dresden 1, 2, and 3	1,330,000	32	0.057	420
Humboldt Bay	514,000	160	0.54	61
Big Rock Point	284,000	4.6	0.026	3.1
Millstone	276,000	5.5	0.0056	15
Monticello	76,000	4.4	0.0036	4.4

*The man-rem dose for a group of people is the product of the average dose to those people and the number of people.

†Man-rem dose is for the population within 40 miles for this facility.

Table 4 Releases of Halogens and Particulates for 1971 Compared with Proposed Design Objectives

Facility	Proposed design objective*	Release, Ci/year	Ratio of release to design objective
	Pressurized-Water Reactors		
Indian Point	0.053	0.21	4.0
Yankee Rowe	0.0007	0.0001	0.14
San Onofre	0.0056	0.0001	0.018
Connecticut Yankee	0.0014	0.031	22
Ginna	0.012	0.17	14
Robinson	0.0011	Not detected	
Point Beach		0.0001	
	Boiling-Water Reactors		
Oyster Creek	0.88	2.14	2.4
Nine Mile Point	0.33	0.8	2.4
Dresden 1, 2, and 3	0.52	4.3	18
Humboldt Bay	0.039	0.3	7.7
Big Rock Point	0.27	0.6	2.2
Millstone	0.66	4.0	6.1
Monticello	0.07	0.052	0.74

*Permissible release times 0.007. The permissible release is a site-dependent constant times the effective maximum permissible concentration (MPC) for the radionuclide mixture divided by 700. The proposed design objective is the same constant times the effective MPC divided by 100,000.

use of conventional technology to process previously untreated sources and through the utilization of additional collection and decontamination processes.

Examples of the use of existing technology include the addition of evaporators or demineralizers to treat liquids from floor drains and other sources which are treated with less effective means or which are not treated at all. Complete recycling of water within the power plant is the only available means for tritium effluent control. Extensions of existing practices to reduce radioactivity in gaseous airborne effluents include longer holdup times through the use of greater compression in pressurized storage tanks and the addition of high-efficiency filters and charcoal adsorbers for potentially contaminated plant air sources.

A number of additional processes are available to reduce radioactivity in gaseous releases. One is the previously mentioned additional holdup time through the use of charcoal beds for the decay of short-lived radioisotopes. A variation of this technique is adsorption on charcoal at liquid-nitrogen temperatures for recovery and retention of krypton and xenon. This process was demonstrated at an AEC-operated fuel-reprocessing facility at a gas throughput which was the same as that for plant-scale operations. Other processes for recovery and retention (bottling) of radioactive gases from LWR off-gas systems have been developed or are in advanced stages of development.[9] The installation of equipment for this purpose is planned for several LWRs now being designed.

Specific data relating to the efficiency of radwaste systems for removing specific radionuclides from effluents of power reactors operating at design power levels and over long operating periods are needed to provide firm answers on the feasibility of meeting all of the proposed numerical guides, particularly those for radioiodines. Such definitive data are limited at this time because releases of radioactive material in effluents from operating nuclear power stations generally have been well below the limits specified in 10 CFR 20 and generally are only a few percent of those limits.[10] Licensees have been required to make measurements of the radioactive material in effluents. Since the limits have not been approached, even for the more conservative unidentified radionuclide limits, licensees have not been required to routinely perform detailed analyses to determine concentrations or quantities of *individual* radionuclides in effluents. The Environmental Statement addressed to the proposed numerical guides[11] indicates that some difficulty may be anticipated in achieving some of the proposed guideline values, particularly for radioiodine.

THE YEAR 2000 STUDY

About 2 years ago the AEC[3] undertook a detailed study to ascertain the kinds and amounts of radioactive materials that would be reaching a large segment of the U. S. population from the nuclear industry by the year 2000. The area selected for initial investigation in this pilot study comprises the watersheds of the upper Mississippi River (above its confluence with the Ohio River) and of the lower portion of the Missouri River (below Pierre, S. Dak.). The study area encompasses 303,230 sq miles and includes the entire state of Iowa and portions of Minnesota, Wisconsin, Illinois, Missouri, Kansas, Nebraska, and South Dakota (Fig. 1).

It was recognized that an evaluation would be needed of the effects on radiation dose to the population resulting from the airborne contribution of radionuclides from adjacent areas. To account for this contribution, a peripheral zone some 200 miles wide and surrounding the basic study area was defined and designated as the "air envelope," also shown in Fig. 1.

The study area has a population today of about 18 million, roughly 70% of which may be classified as urban, 10% as farming, and 20% as rural nonfarm. By the year 2000, this population is projected to reach 29 million. Today and in the year 2000, the area accounts for and will continue to account for about 10% of the total electric-energy generation and consumption of the United States. With the air-envelope boundary

Fig. 1 Boundaries of environmental study area for the year 2000.

region added, about 25% of total U. S. generation is represented.

The boundaries of the study area were established along county lines, and the majority of the data were collected at the county level. The 479 counties comprising the study area were combined into 300 environmental and demographic units called centroids. Dose calculations were made in accordance with the centroid structure.[12] The near-site conditions were not considered in dose calculation, since near-site dose is not normally a significant factor in the overall radiation dose. For the purpose of this study, the point chosen to locate an urban centroid was the latitude and longitude of the major city. Rural centroids were defined as being located at or near the geographic center of the area represented by the centroid.

Major factors considered in projecting population dose include eating habits, food-production techniques, recreational habits, and population-growth patterns. A massive data bank containing information pertinent to the population and living patterns of the study area was established and used. Included were data on population distribution by location, age group, and urban–rural classification; dietary habits and work and recreational patterns; drinking-water supply and treatment; food production, consumption, and transport within the study area; and food imports from outside the region. These data were obtained from many cognizant organizations, including the U. S. Geological Survey, the Corps of Engineers, the National Oceanic and Atmospheric Administration, the Bureau of the Census, the Department of Agriculture, state fisheries departments, and regional planning and conservation committees.

Forty-five separate pathways leading to human exposure were considered. These included contributions from direct exposure to radionuclides in air and water and on the ground, air inhalation, ingestion of water, and the ingestion of some 35 separate categories of food. Food-chain relationships of radionuclide concentrations were calculated for each food type for each of the 45 separate fission and activation products included in the study.

Some of the major assumptions made in setting up the model for the "base case" in this study include: (1) the introduction of the liquid-metal-cooled fast breeder reactor (LMFBR) on a commercial scale so that by the year 2000 the installed nuclear capacity would consist of about half LMFBR plants and half LWR plants; (2) all nuclear plants would have equipment needed to conform with the "as-low-as-practicable" guidelines, but only LMFBRs were assumed to have bottling equipment for inert gases; (3) no tritium-removal equipment was assumed for fuel-reprocessing plants, but inert-gas bottling equipment was assumed for these plants.

Regional Dose-Rate Estimates

The results of the study show that, on the average throughout the region, the year 2000 dose rate to a representative individual would be increased by roughly 0.2 mrem/year because of the presence of nuclear facilities. These dose estimates are based on the contributions from nuclear power reactors and spent-fuel-reprocessing plants only when these plants are assumed to be equipped with advanced waste-treatment systems. These estimates do not include the contributions from fuel-fabrication plants, transportation of new and spent fuel, shipment of radioactive wastes, and waste-disposal operations. Also, the estimates do not contain potential contributions from abnormal or accidental releases from any facility or operation. The comparable dose rate from natural-background radiation in the area is about 140 mrems/year (Table 5).

As might be expected over a region as large and diverse as the study area, the spread in estimated exposures is substantial, ranging from 1.1×10^{-3} to 1.2 mrems/year. Nevertheless, 99% of the population was estimated to receive total-body dose rates less than 0.5 mrem/year (Fig. 2). A very small fraction of the population could receive up to 1.2 mrems/year, which is still only about 1% of the natural background. Exposure patterns for the three age groups considered (adult, teenager, and child) varied only slightly from that for the entire population. Note that the average annual dose in the year 2000 (Table 5 and Fig. 2) is the sum of the external radiation received during each month (caused by radionuclides in the environment that month) and the internal radiation received during the subsequent 12 months following each month's exposure history. Also, the 50-year dose commitment is defined here as the radiation dose an individual would be committed to during the following 50 years due to the intake of radionuclides during the year 2000.

A few individuals living near the boundaries of nuclear sites might receive doses higher than those indicated. Proposed AEC regulations would restrict organ and total-body dose rates at the boundaries of nuclear power-plant sites to 5 mrems/year or less. For greater distances, it was estimated in the study that a person living 1 mile from a nuclear power plant might

Table 5 Average Annual Doses and 50-Year Dose Commitments Received from Radionuclide Releases by Population of Study Area

	Average individual			Average of maximum population group*		
Organ	Child	Teenager	Adult	Child	Teenager	Adult
			Annual Dose Rate, mrem			
Total body	0.122	0.119	0.199	0.132	0.125	0.211
G.I. tract	0.034	0.045	0.058	0.036	0.0478	0.061
Thyroid	1.038	0.601	0.889	1.680	0.797	1.090
Bone	0.044	0.031	0.030	0.065	0.040	0.037
Lungs	0.0742	0.071	0.110	0.081	0.075	0.115
Skin	0.038	0.038	0.038	0.038	0.038	0.038
Liver	0.146	0.133	0.206	0.175	0.150	0.223
			50-Year Dose Commitment, mrem			
Total body	0.106	0.101	0.181	0.117	0.109	0.195
G.I. tract	0	0	0	0	0	0
Thyroid	0.940	0.442	0.637	1.580	0.638	0.893
Bone	0.039	0.021	0.017	0.073	0.039	0.030
Lungs	0.183	0.181	0.204	0.190	0.185	0.209
Skin	0	0	0	0	0	0
Liver	0.128	0.115	0.187	0.158	0.132	0.205

*The maximum population group consists of those individuals in each centroid whose dietary habits and patterns of work and recreation tend to maximize their exposure to radionuclides in the environment. This group should not be confused with the few individuals living near the boundaries of nuclear plant sites.

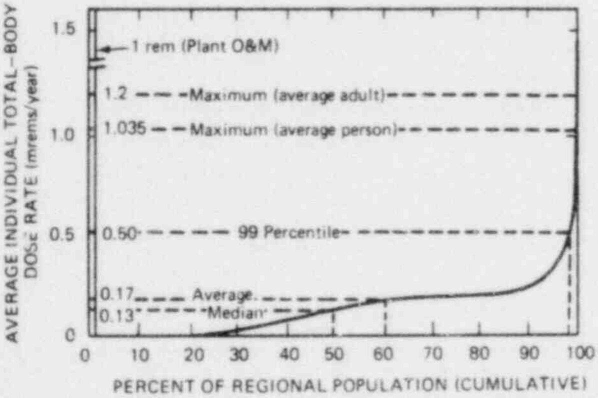

Fig. 2 Average individual total-body dose rate (year 2000 study). Maximum = highest centroid average dose calculated for any of the 300 centroids considered.

receive a total-body dose rate of 0.02 to 0.15 mrem/year from that one installation, depending on the type of plant installed. A person living 1 mile from a nuclear fuel-reprocessing plant could receive a skin dose rate of approximately 7 mrems/year. Only a very few individuals would be expected to live within 1 mile of these plants. In terms of the regional study, these dose contributions are not significant.

The natural-background values include roughly 25 mrems/year due to natural radiation sources within the body (^{14}C, ^{40}K, etc.). The incremental body burden of radionuclides resulting from operation of nuclear facilities is only a very small fraction of this. For a person exposed for 1 year to the average radionuclide concentrations estimated in this study for the year 2000, the total dose commitment to his body, over a 50-year period, resulting from the decay of the added radionuclide burden, would be less than 0.2 mrem—less than 1% of the annual dose from the natural body burden.

Specific Radionuclide Contributions to Dose Rate

Of the 45 radionuclides* considered in the study, isotopes of only three elements contributed the bulk of the radiation dose rate. These three elements (tritium, iodine, and cesium) contribute about 95% of the

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*Transuranic elements were not considered in this study.

total-body dose rate and 80% or more of the dose rate to the organs considered (except for the skin, where krypton and xenon contribute about 50%). The dose-rate breakdown by radionuclide for the various organs considered is given in Fig. 3.

Examination of Fig. 3 reveals tritium to be a major contributor to many of the organs and to the whole body. This is due partly to the fact that no tritium removal from effluents was assumed. The development programs for tritium-removal technology which were in progress at the initiation of this study were not considered, since the state of the art did not comply with the study ground rule of involving presently available technology. However, if the study had assumed treatment systems for removal of 99% of the tritium from fuel-reprocessing-plant effluents, the calculated average dose rate would have been about 0.03 mrem/year instead of the previously stated 0.2 mrem/year. Technology related to tritium removal is being developed.[9]

Effects of "Advanced" Treatment Systems

The following effects on results of the year 2000 study might be expected if the use of alternate types of waste-treatment systems were to be assumed.

1. If the LWRs were assumed to be equipped (as were all other nuclear plants in the study) with systems for bottling noble gases, with an assumed decontamination factor of 300, then average reductions of 20 to 30% in skin dose might occur; negligible changes would be seen in the dose to other organs or to total-body dose.

2. If no reprocessing plants or power plants in the study had bottling systems for noble gases, regional population dose would increase to approximately 0.26 mrem/year (an increase of only about 30%), primarily from the additional ^{85}Kr released from reprocessing plants. A reduction in the release of tritium by a factor of 100 would reduce the total-body dose to the population by about a factor of 5.

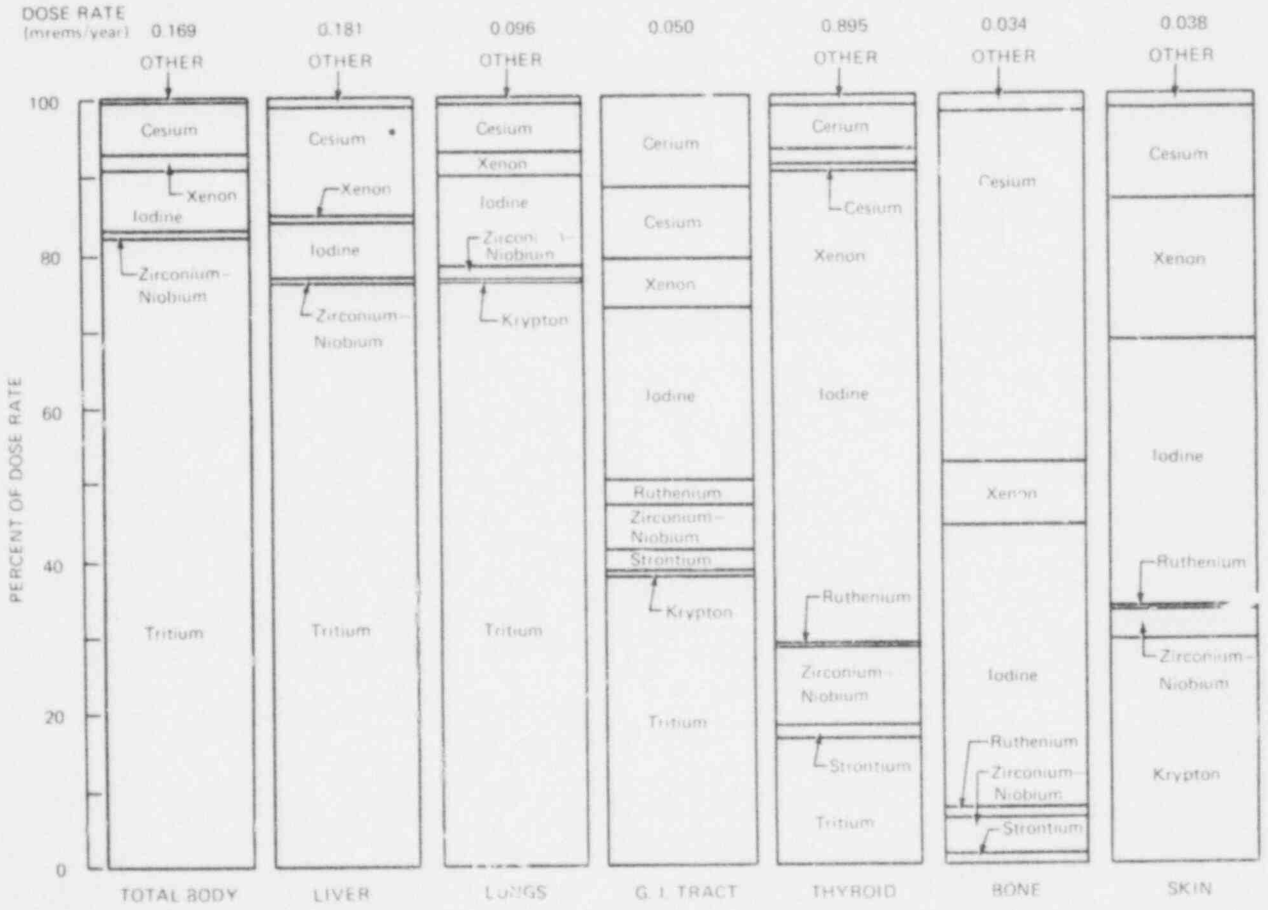

Fig. 3 Percent contribution to dose rate by individual radionuclides (year 2000 study).

CONCLUSIONS

The year 2000 study represents a detailed and thorough analysis of population dose due to nuclear facility effluents, projected to a time when electricity generated by nuclear power plants will exceed the total amount of electricity now generated by all types of plants. The results indicate that, with relatively modest changes in equipment and practices for effluent control, radiation doses from the nuclear industry can be maintained at a very small fraction of the unavoidable natural-background radiation dose. Moreover, the study shows that with more advanced effluent-control technology, which is being developed, radiation doses from the nuclear industry could be held to even lower levels.

Although it is planned to extend the year 2000 study to include other major sectors of the country, the study of other sectors is also expected to indicate a small contribution to background radiation. Thus it appears that radiation doses from the nuclear industry will remain low throughout the country as the industry grows. The fact that the average population dose due to nuclear power will evidently increase from the estimated 0.003 mrem per person per year in 1970 to perhaps as much as 0.2 mrem in 2000 may be of some significance,[13] but it is difficult to ascribe any great significance to this change. After all, this small dose is added to a base of over 200 mrems/year from all other sources (Fig. 4) and can differ by as much as 30 mrems/year for an individual living in a brick house as compared with one living in a wooden house.

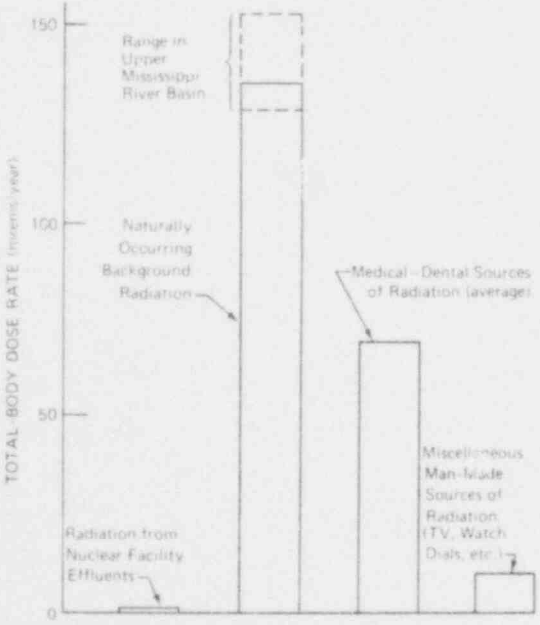

Fig. 4 Sources of total-body dose rate (year 2000 study).

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Natural Background Radiation in the United States

Adapted from NCRP Report 45

Nucl. Safety, 17(**4**): 471–474 (July–August 1976)

Editor's Note: Radiation in the environment from natural sources is the major source of radiation exposure to man. For this reason it is frequently used as a standard of comparison for exposures from medical uses, weapons tests fallout, and nuclear power. To make natural background radiation data more adaptable, the National Council on Radiation Protection and Measurements (NCRP) defined the sources of exposure in explicit detail in a comprehensive report, complete with about 300 pertinent references. This *Nuclear Safety* article contains the Summary from that report and some excerpts from Appendix B of the report. The report is entitled "Natural Background Radiation in the United States" and is available as NCRP Report 45 from NCRP Publications, P. O. Box 30175, Washington, D. C. 20014. An attractive feature in the presentation of the data is that they are expressed in terms of the critical organs which are exposed.

Although the major contribution to radiation dose to humans is from natural background, the greatest portion of man-made radiation dose is due to exposures accrued during medical diagnostic procedures. The estimated annual genetically significant dose contributions from radiographic examinations in the United States in 1970 is approximately 20 mrads (≅20 mrems) (Source: "Gonad Doses and Genetically Significant Dose from Diagnostic Radiology U. S., 1969 and 1970," Bureau of Radiological Health, U. S. Department of Health, Education, and Welfare, April 1976). Also, the contribution from developing nuclear power industry is expected to contribute a population dose of less than 1% of natural background.

The following text (with minor editing added) is the Summary from NCRP Report 45, pages 107 to 111:

Average Values of Dose Equivalent Rate

The previous sections in this report [NCRP Report 45] have described the various exposures of man to natural background radiation. The descriptions were intended to indicate the sources and the various pathways which are of interest, as well as those which are most significant in evaluating human exposure. This section provides summary tables of total dose equivalent rates for the tissues of interest: lung, bone (surface and marrow), gonads, and gastrointestinal tract. Although the thyroid is not specifically listed, the dose equivalent rate would be the same as for the gonads.

It should be pointed out again that many of the basic data for external radiation are in terms of absorbed dose rate in air. This has been converted to absorbed dose rate in tissue by the factors described in the preceding sections. The tissue dose rates from all sources have been converted to dose equivalent rate using a quality factor of 1 for gamma rays, electrons, and muons; a factor of 5 for cosmic-ray neutrons; and a factor of 10 for internal alpha emitters. No weighting factor for dose rate was applied.

A number of the estimated dose equivalents are uniform over the whole body, and these estimated values are applied to all of the organs listed. In other cases the exposures are localized, and calculations have been made to estimate the pertinent dose equivalents. This has been particularly necessary for inhaled radon and its daughter products, where the critical doses are those to the segmental bronchioles. Certain other minor doses described in the text are not included in the summary tables, for example, the skin doses from airborne natural radioactivity.

The data have been aligned in two ways. Table 1 shows the dose equivalents for each of the organs of interest according to the source of the radiation. Table 2 uses the same information, but arranged in order of the radionuclides contributing the dose. In Table 2 the dose equivalents to the lung are separated into those from radionuclides in the body and from inhaled radionuclides.

It is intended, within the limitations of the data, that the information in this report will allow an estimate of the dose equivalent rate from natural background for many segments of the population in the United States. The summary tables merely supply the mean dose to the population, and it is necessary to go to the individual sections of the report to obtain detailed information on variability. The general considerations on variability are described below.

Variability

Cosmic Radiation. The average dose equivalent rate to all important body organs for cosmic radiation is 28 mrems/year. This value takes into account the altitude distribution of the U. S. population and includes a 10% reduction factor to allow for structural shielding. The cosmic radiation is highly penetrating, and the dose equivalent is considered to be uniform throughout the body.

The variations of cosmic radiation with latitude, solar cycles, and the amount of structural shielding within the United States are of the order of 10%. Altitude is a significant factor, with a doubling of the sea-level dose equivalent rate at about 2000 m.

Cosmogenic Radionuclides. The total contribution of cosmogenic radionuclides to the average dose equivalent rate is less than 1 mrem/year, so that variations are not significant.

External Terrestrial Radiation. The overall population-weighted absorbed dose rate in air in the United States from external terrestrial radionuclides is estimated to be

Table 1 Summary of Average Dose Equivalent Rates (mrems/year) from Various Sources of Natural Background Radiation in the United States

Source	Gonads	Lung	Bone Surfaces	Bone Marrow	G.I. tract
Cosmic radiation[a]	28	28	28	28	28
Cosmogenic radionuclides	0.7	0.7	0.8	0.7	0.7
External terrestrial[b]	26	26	26	26	26
Inhaled radionuclides[c]		100[d]			
Radionuclides in the body[e]	27	24	60	24	24[f]
Rounded totals	80	180	120	80	80

[a] "Cosmic radiation" includes 10% reduction to account for structural shielding.

[b] "External terrestrial" includes 20% reduction for shielding by housing and 20% reduction for shielding by the body.

[c] Doses to organs other than lung included in "Radionuclides in the body."

[d] Local dose equivalent rate to segmental bronchioles is 450 mrems/year.

[e] Excluding the cosmogenic contribution shown separately.

[f] This does not include any contribution from radionuclides in the gut contents.

Table 2 Summary of Dose Equivalent Rates (mrems/year) from Various Radionuclides Composing the Natural Background Radioactivity in the United States for External (E), Airborne (A), and Internal (I) Exposures

Radionuclide	Mode of exposure	Gonads	Lung	Bone surfaces	Bone marrow	G.I. tract*
^{14}C	I	0.7	0.7	0.8	0.7	0.7
^{40}K	E	8	8	8	8	8
	I	19	19	15	15	19
^{87}Rb	I	0.3	0.3	0.6	0.6	0.3
Uranium series	E	6	6	6	6	6
^{238}U(^{234}U)	I	0.8	0.8	4.8	0.9	0.8
	A		0.2			
^{226}Ra	I	0.2	0.2	6.6	1.2	0.2
	A		0.2			
^{222}Rn	I	0.4	0.4	0.4	0.4	0.4
	A		2†			
^{218}Po(^{214}Po)	A		90‡			
^{210}Pb(^{210}Po)	I	6	3	24	4.8	3
	A		11			
Thorium series	E	12	12	12	12	12
^{232}Th	I	0.0	0.0	0.7	0.1	0.0
^{228}Ra	I	0.3	0.3	8.0	1.0	0.3
^{212}Pb(^{212}Bi)	A		3			
^{220}Rn	I	0.0	0.0	0.2	0.2	0.0

*Dose equivalent rate to the G.I. tract is considered to be the same as for soft tissue, with no allowance for irradiation by the gut contents.

†Dose equivalent rate to bronchial surfaces.

‡Dose equivalent rate to the segmental bronchioles would be 450 mrems/year.

40 mrads/year. The absorbed dose is corrected by a housing factor of 0.8 and a body screening factor of 0.8 to obtain a dose equivalent rate of 26 mrems/year. This dose is essentially all from gamma rays and X rays, and the dose equivalent is considered to be uniform throughout the body. This is not strictly true for skin and other surface organs; however, it is within ±10% for the organs considered here.

The variability in external terrestrial radiation is larger than that for other natural sources of human exposure. The dose is largely determined by the concentrations of ^{40}K and the members of the uranium and thorium series in the soil. The three general areas described in Section 5.4 [in NCRP Report 45] are characterized by external terrestrial dose equivalent rates to the whole body of 15, 30, and 55 mrems/year for the Atlantic and Gulf Coastal Plains, for the majority of the United States, and for an indeterminate area along the Rocky Mountains, respectively.

Other factors which can influence the terrestrial dose equivalent include the moisture content of the soil, snow cover, shielding by buildings, and the exposure from radiation originating from radionuclides in building materials.

Inhaled Radionuclides. The significant exposures from natural airborne radionuclides are from the alpha-emitting daughters of ^{222}Rn. The short range of alpha radiation means that the doses are delivered locally to the lung tissue, particularly to the bronchial epithelium. The average dose equivalent rate to the total lung is about 90 mrems/year, while segmental bronchioles receive about 450 mrems/year. This latter point is of possible significance since most of the tumors have originated in this region for the uranium miners exposed to high levels of radon daughters.

Variability is dependent on local concentrations of ^{222}Rn. There is some increase in areas with elevated soil radium levels and a decrease in coastal regions during periods of on-shore winds. It should also be noted that dose equivalent rates to the lungs of smokers from the long-lived daughters of ^{222}Rn may be up to three times higher than for nonsmokers.

Radionuclides in the Body. This mode of exposure is dominated by the 20 mrems/year whole-body dose equivalent rate from ^{40}K, which is under homeostatic control in the body. Variations with age and sex were shown in Figure 26 of Section 7 [in NCRP Report 45]. Variations in inhalation and ingestion do not produce large changes in dose equivalent for the air and diet levels existing in the United States for all radionuclides. The greatest variations would occur in the ^{226}Ra contribution from drinking water and in the lung dose from the long-lived daughter products of ^{222}Rn. There is also some contribution of these latter radionuclides from smoking.

Overall Variability. In looking at the possible exposure variability, keep in mind that many differences become blurred in an urbanized society. Most city dwellers have little exposure to bedrock or soil, building materials are rarely of local origin, and diets are frequently based on foods with nationwide distribution. Thus the exposure of the total U. S. population is probably more uniform than would be indicated by comparison of terrestrial gamma radiation levels on a geographic basis.

As a simple example, consider the whole-body dose equivalent rates received by groups at sea level in the three general areas mentioned in Section 8.2.3 [in NCRP Report 45] for external terrestrial background. These areas are characterized by external rates of about 15, 30, and 55 mrems/year. The internal and cosmic-ray dose equivalents to the gonads sum to about 50 mrems/year, so the subtotals would be about 65, 80, and 105 mrems/year, respectively, for the three areas.

The dose equivalent rates for groups living at an altitude of 1.5 km would be increased by about 20 mrems/year from the increased cosmic radiation. The highest whole-body total of 125 mrems/year from all sources essentially represents the situation for the city of Denver, where both the cosmic and terrestrial components are higher than average.

Appendix B [of NCRP Report 45] describes radiation exposures from nuclear weapons tests for comparison with those from natural sources. It must be pointed out that the data on natural radiation are in terms of annual dose equivalent rate, while the fallout data are in terms of dose commitment. This latter concept is discussed in Appendix B.

The following excerpts (with minor editing added) are from Appendix B of NCRP Report 45:

Fallout from Nuclear Weapons Tests

The fallout of radioactive debris from nuclear weapons tests was most significant for atmospheric testing carried out through 1962. Most of the continental testing at the Nevada Test Site took place in the period 1951–1957. These were mostly low-yield nuclear devices, while the high-yield thermonuclear tests were in the Pacific area or in the Soviet Union. Additional atmospheric testing by France and China since 1962 has added several percent to the radioactivity, but this addition is not sufficient to modify our dose estimates significantly. This brief summary is intended to indicate the range of levels of exposure to the population of the United States. Estimates of doses will be included at the end of this Appendix.

. . .

The Dose Commitment Concept. During attempts to evaluate the measured and calculated doses to man from fallout, a number of obvious difficulties have appeared. One is that the annual doses have varied markedly, depending on the test pattern. This made it difficult to make comparisons with more uniform sources of exposure such as natural activity. Another is that an honest evaluation of fallout required inclusion of doses to be received in the future from tests already carried out. These and other problems led to the development of the dose commitment concept, which has been defined by UNSCEAR (1964) as ". . . the integral over infinite time of the average dose rates delivered to the world's population as a result of a specific practice, e.g. a given series of nuclear explosions. The actual exposures may occur over many years after the explosions have taken place and may be received by individuals not yet born at the time of the explosions. . . ."

Dose Commitments. The dose commitments estimated from the data in previous tables are summarized in Table 3.

Table 3 Mean Dose Commitments (mrads) in the United States from Nuclear Testing Through 1970

	Mean dose commitment
External	80
Internal	
^{90}Sr, marrow	45
^{90}Sr, endosteal	65
^{137}Cs, gonads	15
^{239}Pu, lung	2
^{239}Pu, bone	0.2
^{131}I, thyroid	Unknown
^{85}Kr, skin	0.02
^{3}H, gonads	2
^{14}C, gonads	12*
^{55}Fe, gonads	<1
^{55}Fe, red blood cells	3

*This is the dose commitment to the year 2000. The total dose commitment, to be delivered over many lifetimes, is 140 mrad.

It must be noted that these values cannot be added together to give a useful quantity. On the other hand, adding the gonad doses would give an underestimate, since the other radionuclides such as ^{131}I also contribute to the general soft tissue absorbed dose. Since all of the components except plutonium are beta-gamma emitters, the dose commitment in terms of dose equivalent would be the same as in terms of absorbed dose.

Trends in Public Health in the Population Near Nuclear Facilities: A Critical Assessment

C. H. Patrick[*]

Nucl. Safety, **18(5)**: 647–662 (September–October 1977)

Abstract: *Ten studies that have looked specifically at changes in public health in areas near nuclear facilities are critically reviewed. All but one of these studies have been unable to show adverse health effects in the local population that might be related to radiation exposure. The one study that purports to find an adverse effect has severe methodological limitations, which preclude any meaningful interpretation of the data.*

Also presented is an analysis of the indicators of public health in the area of Oak Ridge, Tenn., which shows cancer mortality rates that are not significantly higher than would be expected in the general U. S. population.

Although much more research is needed before all the effects of very low levels of radiation from nuclear reactors will be known, the existing studies suggest that nuclear power plants will not have a significant impact on public health as a result of normal operations.

There are numerous conflicting reports concerning the health hazards from very low levels of radioactivity from releases made during normal operations of nuclear facilities.[1–5] This is due in part to the lack of knowledge of the effects on man of exposure to very low levels of radiation.[6–8] However, if the consequences of low-level releases from a nuclear facility are deleterious, then increases in measures of ill health associated with radiation exposure should be observed in the population living near the facility as compared to a control population.[9–11]

To properly study the public health effects of nuclear facility operations, one must have data on relevant measures of ill health for the nearby geographic areas for periods both before and after the facility begins operations. A preliminary analysis of vital statistics data[†] (such as deaths, illnesses, births, and population sizes), adjusted for demographic variables (such as age, race, and sex) that reveal significant time and geographical trends apparently related to nuclear power-plant operations leads to additional analyses, including the social and economic structure of the population, which must be considered. These additional analyses could include, for example, the abrupt shifts in the socioeconomic composition of the local population due to site construction.[18,19] If the trends of ill health apparently related to power-plant operations persist after correcting for demographic and socioeconomic factors, then, whenever possible, records of radioactive releases into the environment must be obtained, dose to the population must be estimated, and ill health must be correlated with dose.[20] All studies to date that have made these analyses have found no significant trends of ill health related to nuclear power-plant operations.[2, 22]

The purpose of this article is to critically review the studies of trends in public health in areas near several nuclear facilities, some of which have been operating since the mid 1940s. In addition, three topics of research are briefly reviewed: (1) changes in measures of ill health which are related to radiation exposure of the population surrounding nuclear plants, (2) the problems in using vital statistics for such studies, and (3) the types of analyses needed in research and in environmental impact statements.

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[†] Vital statistics data are generally published annually by each state for counties and large cities in a vital statistics series. The data are usually broken down by race, but seldom by other traits.[12] Vital statistics data seldom contain migration data and usually contain morbidity information only on communicable diseases. However, the Bureau of the Census publishes estimates of population change and migration and some morbidity data, which are available through the U. S. Public Health Service.[13–15] The federal government also publishes annual vital statistics and related demographic data through the National Center for Health Statistics and through the Bureau of the Census.[16,17]

The somatic and genetic effects that are believed to be associated with radiation exposure are well documented.[23-28] Both types of effects are of interest to the epidemiologist trying to determine the effects of low-level radiation releases on public health. Clinically, many health effects induced by radiation are little different from those induced by other causative agents.[29] Therefore the presence of a health effect does not ensure that the causative agent has been correctly identified. On the other hand, the absence of the hypothesized effect when the agent is present often is taken to indicate that causation has been disproved. To truly test the hypothesis, one must estimate the expected size of the effect and determine if the population and methodology are adequate to detect the expected effect.

The possible somatic effects of radiation include various types of cancers, most of which have relatively long latent periods. The cancers most often cited as caused by radiation exposure are leukemia and cancers of the thyroid, bone, breast, lung, and gastrointestinal tract. The noncarcinogenic diseases associated with radiation exposure include cataracts, central-nervous-system disorders, premature aging ("life shortening"), fertility impairment, congenital defects, and cardiovascular–renal diseases.

The possible genetic effects of radiation exposure include gene or point mutations and chromosomal aberrations, which may produce increased rates of spontaneous abortion or fetal wastage, neonatal and infant mortality, infertility, and congenital malformations.

The human health effects associated with nuclear facilities have been examined in a wide variety of studies (see Table 1). These studies generally fall into one of two categories, both of which are reviewed in this article. Those in the first category analyze vital statistics for the area near a potential source of radiation exposure, usually a nuclear power plant. These studies look for changes in selected vital statistics of local population groups compared to population groups that are not near the nuclear power plant, and they usually look for a dose-dependent effect. Often the vital statistics before and after the facility starts operation are compared. Studies in the second category compare the vital statistics of the work force in a nuclear facility with the vital statistics of the general population. Mortalities of radiation workers and nonradiation workers have occasionally been compared. In addition, an analysis of mortality in the Oak Ridge, Tenn., area is presented.

SELECTED VITAL STATISTICS OF POPULATIONS NEAR NUCLEAR FACILITIES

The work of Bailar and Young is an example of the first category of study.[30] Their research was undertaken because of a concern over the possible adverse health effects of low-level radioactive releases from the Hanford nuclear reservation near Richland, Wash., which had been raised in an earlier study by Fadeley.[31] Bailar and Young corrected several basic errors in the Fadeley study and specifically tested the hypothesis that the higher observed incidence of cancer mortality (leukemia was considered separately) was related to the presence of the Hanford facilities. The basic errors in the Fadeley study are as follows: (1) several counties in the geographic area being studied were omitted without explanation; (2) basic data (numbers of deaths) were not reported, and statistical variations of rates calculated on small samples were not considered; (3) rates were not adjusted for age or sex even though population structures of the counties varied; (4) urban–rural variations in cancer rates were not considered; and (5) cancer mortality prior to operation of the nuclear facilities was not analyzed.[30]

Bailar and Young analyzed county data from Oregon and Washington and data from the U. S. Bureau of Vital Statistics for groups of counties near or downstream from Hanford in both states for the years 1934 to 1963. These data were corrected for differences in cause-of-death classifications and standardized for age and sex by an indirect method using the 1950 U. S. white population.

In terms of the hypothesis tested, the findings are quite interesting. Although the total cancer mortality rates in the counties of Oregon and Washington that were studied have been consistently lower than in the United States as a whole, the leukemia rates in these areas have been consistently higher. Moreover, these higher death rates from leukemia have persisted since the mid-1930s, a decade before the Hanford nuclear facilities existed. In addition, leukemia rates in the "river counties," including Hanford and downstream areas, have actually decreased since 1950, reversing an earlier upward trend.

Bailar and Young conclude, "No evidence was found that persons living downstream from the Hanford reservation or along the Pacific coast of Oregon had had an excess risk of death from cancer in general or leukemia in particular." It can be argued that migration has not been considered and that less than 20 years of data from the beginning of Hanford

Table 1 Summary Review of Studies of Nuclear Facilities

Study	Nuclear facility	Year(s)	Measures of health effect	Findings and comments
Bailar and Young (Ref. 30)	Hanford Wash. (plutonium production plant; miscellaneous research facilities)	1934–1963	County vital statistics; total cancer rates; leukemia rates	No effect found; control areas employed; standardization used; before and after analysis; migration not considered; latency a potential problem
Tompkins et al. (Ref. 32)	Humboldt Bay Power Plant (boiling-water reactor)	1958–1962; 1964–1967	County vital statistics; infant mortality and rates; neonatal mortality and rates	No effect found; directional quadrants used; regression analysis used but not reported; no racial adjustment
	Dresden Nuclear Power Station (boiling-water reactor)	1955–1959; 1961–1965		
	Big Rock Point Nuclear Plant (boiling-water reactor)	1957–1961; 1963–1967		
DeGroot (Ref. 33)	Dresden Nuclear Power Station (boiling-water reactor)	1950–1967	County vital statistics; infant mortality rates	Linear regression only; overall no effect statistically; one positive result (Brookhaven), one negative result (Shippingport) reported; independent variables: time, radioactive discharges, infant mortality in control areas; no racial adjustments; R^2 (coefficient of determination) not reported
	Shippingport Atomic Power Station (pressurized-water reactor)	1950–1967		
	Indian Point Station (pressurized-water reactor)	1950–1967		
	Brookhaven National Laboratory (research reactors; miscellaneous facilities)	1951–1968		
Sternglass (Ref. 34)	Hanford, Wash. (plutonium production plant; miscellaneous research facilities)	1940–1945; 1946–1949	State and county vital statistics; state and county infant mortality; premature birth rates; leukemia rates	Author interprets each analysis as showing a positive effect; several errors in data presented in tables and figures; no demographic adjustments; questionable interpretation of data, often only two points; weak statistical analyses; omissions and selective inclusions never justified; dubious use of states as units of analysis; see text for further comments
	Dresden Nuclear Power Station (boiling-water reactor)	1955–1968		
	Big Rock Point Nuclear Plant (boiling-water reactor)	1962–1968		
	Humboldt Bay Power Plant (boiling-water reactor)	1958–1969		
	Nuclear Fuel Services, Cattaraugus, N. Y. (fuel-reprocessing plant)	1960–1968		
	Peach Bottom Atomic Power Station (gas-cooled reactor)	1962–1969		
	Indian Point Station (pressurized-water reactor)	1958–1969		
	Brookhaven National Laboratory, Upton, N. Y. (research reactors; miscellaneous facilities)	1955–1967		

(Table continues on the next page.)

Table 1 (Continued)

Study	Nuclear facility	Year(s)	Measures of effect	Findings and comments
Tokuhata et al. (Ref. 35)	Shippingport Atomic Power Station (pressurized-water reactor)	1961–1971	County vital statistics; total and selected cancer rates, fetal deaths, infant deaths, neonatal deaths	No effects found attributable to radiation; demographic adjustments; migration considered; matched communities; fairly thorough discussion of needed adjustments in use of vital statistics; good methodological section
Grahn (Ref. 36)	Big Rock Point Nuclear Plant (boiling-water reactor)	1950–1971	County vital statistics; infant mortality; immature births; cancer mortality	No effects found; male and female rates analyzed; local area rates compared to state rates; demographic factors considered
Moshman and Holland (Ref. 39)	Oak Ridge, Tenn. (gaseous diffusion plant; uranium processing plant; research reactors; miscellaneous facilities)	1948	Cancer morbidity	Significantly lower cancer morbidity in Oak Ridge compared to nation; latency a potential problem; only study of morbidity, limited to 1 year; apparently the first study of population near a nuclear plant
Mason et al. (Ref. 37)	Grand Junction, Colo. (uranium mill tailings)	1950–1971	National Cancer Institute county data; cancer death rates; lung cancer; leukemia	No trend found attributable to mill tailings; demographic adjustments; comparison with other parts of Colorado; latency problem
Larson et al. (Ref. 40)	Oak Ridge, Tenn. (see above)	1950–1971	Actual deaths vs. expected deaths from all causes using man-years	Found 692 deaths, while 992 were expected, based on U. S. 1962 rates man-years analysis; problem of comparability of population
Scott et al. (Ref. 41)	Oak Ridge, Tenn. (see above)	1951–1969	Actual deaths vs. expected deaths; man-years analysis	Uranium workers have lower mortality than non-uranium workers; U. S. 1962 life tables used for relative comparison; demographic adjustments made; death information from Social Security possibly incomplete for either group; uranium group 5 years older on the average, with more males

operations is insufficient to allow for discernible "excess" cases because of long latency periods. Yet, given the data available at the time and the comparison of the pre- and postoperational periods, the research suggests that no apparent carcinogenic effect over the period was due to the Hanford operations.

In 1970 Tompkins et al.,[32] DeGroot,[33] and Sternglass[34] published studies that set out to determine if any adverse health effects on infants in utero were caused by the operation of nuclear power plants. None of the three studies appear to have standardized for maternal age or race. Tompkins et al. examined infant and neonatal mortality rates for the 5 years before and after start of operations at the Humboldt Bay (Eureka, Calif.), Dresden (Morris, Ill.), and Big Rock Point (Big Rock Point, Mich.) power stations.[32] This study was undertaken in response to claims that nuclear power stations expose surrounding populations to radiation which, even at low levels, results in increased infant mortality. For a geographical distribution to be established, county infant mortality data from vital statistics were determined for four concentric bands extending a total of 200 miles from the facility. These bands were then divided into quadrants to allow prevailing wind directions to be taken into consideration. Data from the 1960 U. S. Census were used to determine population, live births, and deaths in each quadrant. Infant mortality rates were based on 5-year aggregates to reduce statistical fluctuations due to small sample size.

No relation between the operations of any of the three plants and changes in infant and neonatal mortality rates was found in the Tompkins et al. analysis. The authors further checked their results, via regression analysis, for sensitivity to either the band width or compass direction from the plants. In both these latter tests, no statistically significant relation was found. This study differs from the Bailar–Young study in (1) its measure of ill health, (2) the use of quadrants of concentric bands, and (3) the use of shorter time periods. Nonetheless, neither study finds a relation between changes in their measures of ill health and the operation of local nuclear facilities.

DeGroot's study[33] of the relation between trends in infant mortality and effluent releases from four nuclear reactors utilizes regression analysis solely. The four reactors he studied were the Dresden reactor (Morris, Ill.), the Shippingport reactor (Shippingport, Pa.), the Indian Point reactor (Indian Point, N. Y.), and the Brookhaven reactor (Upton, N. Y.). He examined the relation using a regression model of the form $M_t = B_0 + B_i X_i$, where M_t is the annual infant mortality rate for a given county of study for the years 1950 to 1967. The independent variables he used vary from case to case and include (1) the year, (2) a measure of liquid discharges, (3) annual infant mortality rates for a control area (state, nation, or other county groups), (4) gaseous discharges, and (5) background radiation (for the Brookhaven reactor).

Although DeGroot fits both linear and semilog models, his results are essentially unchanged by the log transformation of the dependent variable. Unfortunately, he does not report all the slope coefficients in his equations, and so it is difficult to assess how well the independent variables "explain" the trends in infant mortality rates. However, he does report the "*t*" statistics for each variable. The annual infant mortality rates and the measures of radiation effluents he used, in all but two cases, are *not* statistically related at the 95% confidence level. In the two cases in which there is a statistical relation, one was small and positive and one was small and negative.

In the analysis of Suffolk County mortality rates, DeGroot finds a statistically positive correlation (*b* coefficient of +0.015, *t* value of +4.17) between the annual infant mortality rates and the 2-year moving average of tritium discharges from the sand filter beds of the Brookhaven reactor. On the other hand, in the analysis of mortality rates for Allegheny County, Pa., which is southwest of the Shippingport reactor, he finds a negative effect (*b* coefficient of −0.021, *t* value of −2.60). DeGroot states that the differing statistical signs illustrate his contention "that it is not possible to derive strong conclusions about either the existence or nonexistence of an effect from the simple regression models. . . ."

DeGroot's paper emphasizes the limited value derived from testing hypotheses using vital statistics for a large area in conjunction with a single point source of an effluent. Although this method may point out areas for hypothesis testing using more precise epidemiological and statistical methods, it can never be sufficient to prove or disprove a hypothesis because of the inevitable violations of the assumptions of the linear regression method.

Only one author (Sternglass) found a relation between infant mortality and low-level-radiation releases.[34] Sternglass examined the vital statistics for selected years and selected areas and found a rise in infant mortality near nuclear power plants. For the Hanford facilities, several examples showing a positive relation were presented. First, he compared state data on percent change in infant mortality from 1946 to 1949 to the least-squares-fitted trend from 1940 to

1945. Whereas Washington and Oregon showed negative changes (declines) in each year from 1946 to 1949, Sternglass interprets positive increases in infant mortality in Montana and North Dakota for all 4 years and in Idaho for 2 of the 4 years as indicating a positive effect due to Hanford's operations in Washington. He further "confirms" his interpretation of the 4-year data by presenting a bar graph of the percent increase of infant mortality (not mortality rates) in 1945 over the 1943 level—before and after Hanford went into operation—for counties surrounding Hanford and for other distant control counties. He does not note that this increase in the number of infant deaths is related to the population growth in the area as a result of the construction of the Hanford facilities.

Sternglass also studies mortality rates for the areas near the Dresden reactor in Illinois. He finds the infant death rate in Illinois during 1959 to 1968 is consistently higher than that of Ohio. Even though the rates in Illinois were decreasing over the previous year's rates (except during the Illinois rubella epidemic of 1964 and 1965), the difference in the states' rates is correlated (0.865) with radioactive releases from Dresden. He also cites comparisons of Illinois infant mortality with that of North Dakota, Indiana, and Michigan but fails to account for the overall decline in these rates or for demographic differences among the populations.

Sternglass then compares infant mortality rates for 1964 with those for 1966 in six counties surrounding Dresden (including Will County in the Chicago metropolitan area and Grundy County in which Dresden is located) and makes the same comparison in six noncontiguous counties in northern and western Illinois. The infant death rate in the six counties around Dresden increased from 20.8 to 24.3 per 1000 live births, whereas the rates in the six control counties rose from 22.9 to 23.3 in the 2 years. Neither a standardization for demographic variables nor a comparison of data for other years is cited.

Sternglass also compares premature birth rates in his six control counties with those in Grundy County alone. Grundy, with an estimated 1964 population of 23,500, had premature birth rates for 1964 to 1968 of 3.6, 6.3, 8.7, 7.2, and 5.0%, respectively.[34] Among his control counties, the smallest of which had a 1964 estimated population of 39,500, the lowest rates for those years were 5.5, 4.6, 5.1, 5.2, and 6.1% and the highest were 7.5, 5.9, 8.2, 7.3, and 7.7%, respectively. Sternglass cites the large rise in Grundy County in 1966 (the year of peak emissions) as evidence of the adverse effect of the Dresden reactor. However, his control counties also showed evidence of such a peak, which he does not explain.

Sternglass uses similar interpretations of limited data to show that infant mortality has risen in the vicinity of Humboldt, Calif.; Cattaraugus, Westchester, and Suffolk, N. Y.; and York, Pa., as a "result" of radioactive releases, and again he fails to take into account normal statistical fluctuations and other factors associated with differential infant mortality rates.

The Sternglass paper is discussed in detail here because of his gross errors in using vital statistics, not because he claims to see an "effect" due to nuclear power reactors. The paper illustrates a number of methodological pitfalls in using vital statistics and limited quantitative analysis. He adeptly chooses isolated data from selected years and locations and uses various "analyses"; he uses no consistent methodology, nor does he standardize the rates to account for real differentials due to population characteristics. Yet he unfailingly interprets the outcome to show an adverse effect of radiation when the data are inadequate to support such an interpretation. Such studies do little to clarify the true relation between changes in public health and exposure to low levels of radiation.

Two additional studies, by Tokuhata et al.[35] and by Grahn,[36] have examined the public health impact of nuclear facilities. These studies were undertaken in response to claims of increased rates of mortality due to releases from these plants. In 1974, Tokuhata et al. published a study analyzing health hazards to the public living near the Shippingport nuclear reactor in Shippingport, Pa.[35] Using vital statistics and census data for 1961 to 1971 for Aliquippa and communities of similar demographic background without nuclear power plants, they examined fetal and infant mortality rates and those from leukemia and other neoplasms. Additional analyses were also made to determine if geographically distributed radiation-dose-related effects were present. Mortality rates at 5-mile intervals from the reactor and the differences in mortality rates for "on-river" and "off-river" communities downstream from Shippingport were examined.

On the basis of their comprehensive analysis, Tokuhata et al. concluded that "there is no systematic evidence to support the allegation that radioactive releases from the Shippingport plant have had significant effects on the health of the population in the vicinity of the plant . . ." that cannot be explained, at least to some extent, by reporting errors or other known sociological characteristics of the population.

Although the Tokuhata results confirm those of earlier studies, perhaps the major value of the paper lies in its discussion of the problems associated with analyses of this genre, especially the shortcomings of published vital statistics. The paper clearly points out sources of potential error and, more importantly, errors in the public health data. It also attempts to correct for these shortcomings where possible. For example, black infant mortality rates were consistently higher, by a factor of 2, than white rates. Therefore communities that have had a high recent influx of black families or have a relatively high proportion of blacks, as Aliquippa does, compared to the state population will have higher rates of infant mortality. Further analysis by race is then necessary to correct for this source of bias.

Grahn presents another analysis of the Big Rock Point nuclear plant in Michigan.[36] In addition to infant mortality, which was also examined by Tompkins et al., Grahn analyzes cancer mortality and premature birth rates for eight counties surrounding Big Rock Point. The decade prior to 1962, before Big Rock Point began operations, and the following decade ending in 1971 are included in the analysis. In addition, Grahn considers changes since 1950 in the socioeconomic and demographic composition of the population, both in absolute terms and relative to Michigan as a whole.

Overall, Grahn finds no evidence to indicate that releases from the Big Rock Point nuclear station increase ill health in the surrounding population. Specifically, he finds that (1) the rate of premature births is equal to or below the state mean; (2) infant mortality has been above the state averages for the past 20 years, including a decade prior to the reactor startup, but has been declining in recent years; (3) cancer death rates in the area are below state averages, and, for women, have been declining, especially in Charlevoix County where the nuclear power plant is located; and (4) leukemia rates are lower than the state average for females and are about the same as the state rates for males.

Because of concern over the use of uranium mill tailings as construction fill material in western Colorado, a study of the counties surrounding Grand Junction, Colo., was conducted by Mason et al. to determine if higher than normal cancer rates were discernible.[37] Mason et al. examined the age-adjusted cancer mortality rates for white males and females from 1951 to 1967 for leukemia, lung cancer, and all other cancers compared to cancer mortality rates for the 1960 Colorado white population.

In comparing the data for the counties, the investigators could find no carcinogenic effect due to radiation exposure from the mill tailings. Cancer mortality rates for females and for males under 20 years of age showed no statistical difference from the rates in other counties. Leukemia mortality rates for males were no different from those in other counties, but the male mortality rates for lung cancer and for other cancers were higher than those in other counties in the state. However, these rates for males in the one county where tailings were used extensively in construction were consistently below those of counties where tailings were not used. The authors correctly point out that latent periods of 15 years or more may be involved and, if so, that the effects would not yet be observed in the data. Therefore the evidence remains of limited value until it is possible to extend the study over the longer period. In such studies population migration also may be a serious complicating factor, as are personal factors such as smoking history.

Moshman and Holland[38] have studied the population near Oak Ridge, Tenn., although only for the year 1948. Moshman and Holland compared the incidence of cancer morbidity in the Oak Ridge population with the expected incidence to determine if Oak Ridge residents were more susceptible to cancer than the general population. They computed age-standardized cancer incidence rates, based on the 1940 U.S. population age structure by primary site and total cancers for males and females. They found that cancer incidence in Oak Ridge was only 123 per 100,000 compared to the national average for whites of 230 (and the death rate from heart disease was 46 per 100,000 compared to the national rate of 320), reflecting the healthy, highly selected Oak Ridge population. Incidence rates for both males and females were lower than the national norms. On a relative basis the distribution of primary cancer sites in white females in Oak Ridge was not significantly different from the nationally observed distribution. A higher proportion of respiratory cancer was found in white males than would have been expected. The authors feel this was due to the increase in lung-cancer rates over the decades since the 1940 population was analyzed.

Overall, this study of Oak Ridge cancer morbidity is rather a limited use of vital statistics, but it must be considered in perspective. It appears to have been the first study recognizing that nuclear facilities may be potential sources of ill health, and the study set out to test this hypothesis. To my knowledge, it is still the only study using morbidity, or illness, rates as opposed to the more readily available death rates. Given these conditions and recognizing its limitations, the paper is indeed a valuable contribution to the overall picture being formed by studies of vital statistics in areas containing nuclear facilities.

COMPARISON OF VITAL STATISTICS FOR NUCLEAR FACILITY WORKERS AND FOR THE GENERAL POPULATION

As previously noted, the second category of study of the health effects near nuclear facilities compares the vital statistics of the work force in a nuclear facility with the vital statistics of the general population. This type of study was undertaken by Larson et al.[39] and Scott et al.[40] Both studies attempted to determine if working in the Oak Ridge facilities increases the risk of mortality for the employee. The 1966 study by Larson et al. compares the number of employee deaths in the three Oak Ridge nuclear plants from 1950 to 1965 with the number of deaths expected by applying 1962 U. S. sex- and age-specific white mortality rates to the age and sex distribution of the workers.[39] On the basis of 207,204 man-years of cumulative employment, 992 deaths would have been expected, but only 692 deaths had occurred by the end of 1965. Thus workers exposed to the environment of a nuclear facility appear in this analysis to live longer than persons in the general population. This discrepancy probably can be explained by the mortality contributions of institutionalized and unemployable persons in the general U. S. population whose health is poorer than that of workers, such as those at the Oak Ridge facilities, who have on-site medical care and periodic plant physicals.

Scott et al.[40] divided workers from two of the Oak Ridge facilities into two groups, uranium workers and nonuranium workers, based on their work areas at the plants. The uranium workers were predominantly technicians and craftsmen, whereas the nonuranium workers covered a broader spectrum of job classifications. The study covers the years 1951 to 1969 and applies the 1960 U. S. mortality tables to each of the two distributions to determine expected deaths in each group. Scott et al. found the mortality rate for uranium workers to be only 59% as high as the 1960 U. S. control population, whereas the mortality rate for the nonuranium workers was 76% as high. Thus the uranium workers had a lower mortality rate than the nonuranium workers. This result may be even more significant because the average age of the uranium workers is about 5 years greater than that of the nonuranium workers. This potentially gives radiation a longer time to cause an adverse effect if both groups were hired at the same age. Also, the nonuranium worker group contains eight times more female workers, who have lower mortality rates than do males (although the analysis is sex adjusted).

Although there is little doubt that the mortality rate for uranium workers is lower than expected, two critical questions are left unanswered by this study: (1) What are the causes of death, and how do the rates for these causes differ from those in the mortality tables for the general population? (2) How does uranium worker mortality change with radiation dose? These questions should be answered by the Energy Research and Development Administration's (ERDA's) health and mortality study of workers from which only preliminary analyses have appeared to date.[41]

PRELIMINARY ANALYSIS OF MORTALITY IN THE OAK RIDGE, TENN., AREA

Trends in four measures of mortality for the Oak Ridge, Tenn., area from 1929 to 1971 are examined in this section. Included are a 14-year period prior to the existence of the city of Oak Ridge and its three nuclear facilities and the subsequent 29-year period.[42] The analysis has been restricted to the white population for three reasons: (1) the nonwhite population is usually quite small, generally younger, and subject to much larger errors in reporting, especially prior to the 1950s, than is the white population; (2) nonwhite rates of age-specific mortality by cause are approximately twice those of whites; and (3) an effect from a nuclear power plant should show up equally among racial groups.

The crude vital statistics from the city of Oak Ridge were compared with those from the state of Tennessee in an attempt to evaluate the relative shifts in the incidence of mortality from various diseases, which might suggest a hypothesis concerning an effect of radiation.

Fetal and infant deaths and deaths from congenital malformations have been slowly declining in the white population of Oak Ridge and the state of Tennessee. However, cancer in these same populations has been increasing. In Tables 2 to 4, the actual number of deaths from selected causes, the population size, and the death rates are shown.

If only the period from 1949 (when the first vital statistics for Oak Ridge became available) to 1971 is examined, as in Figs. 1 and 2, the trends in deaths for the four causes of death reflect no particular sequence

Table 2 Deaths from Selected Causes in the White Population Proximate to Oak Ridge, Tenn., 1929–1971[a,b]

Year	Anderson County[c]					Roane County[c]					City of Oak Ridge[c]				
	Pop.[d]	(1)	(2)	(3)	(4)	Pop.[d]	(1)	(2)	(3)	(4)	Pop.[d]	(1)	(2)	(3)	(4)
1929	18,971	24	25	7	9	22,571	19	50	12	16					
1930	19,283	15	32	5	15	23,024	29	48	12	17					
1931	19,418	13	31	4	16	23,024	21	31	16	12					
1932	19,554	22	35	1	12	23,024	19	52	11	19					
1933[d]	19,689	21	44	12	24	23,024	20	39	13	14					
1934	19,825	32	31	5	16	23,024	19	27	11	9					
1935	19,960	26	45	9	10	23,024	11	41	20	15					
1936	20,096	22	51	11	21	23,024	11	49	14	18					
1937	20,232	18	35	8	18	23,024	12	47	18	18					
1938	20,367	19	32	14	14	23,024	24	46	11	16					
1939	20,503	8	24	12	11	23,024	13	24	14	7					
1940	26,176	10	29	11	19	26,471	17	41	24	13					
1941	26,851	10	42	9	28	26,807	10	26	9	11					
1942	27,526	2	33	8	13	27,144	9	36	17	12					
1943[e]	28,201	14	26	9	8	27,480	14	28	17	11	Oak Ridge built				
1944	28,876	15	45	12	33	27,816	17	53	25	25					
1945	29,551	23	71	23	43	28,153	23	53	13	22					
1946	30,226	24	64	39	46	28,489	21	43	19	24					
1947	30,901	43	65	30	49	28,825	23	33	29	23	No data before 1949				
1948	31,576	40	58	35	46	29,161	16	38	32	25					
1949	54,997	23	61	36	46[f]	29,852	25	42	22	24[f]	31,199	10	16	9	15[f]
1950	57,518	22	52	37	34	30,190	16	30	37	17	28,864	11	13	17	13
1951	57,594	30	53	40	43	30,608	18	30	34	23	29,027	18	24	11	22
1952	57,594	18	37	34	27	30,983	21	24	37	17	29,027	10	13	15	10
1953	57,594	24	45	39	34	31,358	14	37	29	30	29,027	6	21	11	19
1954	57,594	20	58	48	39	31,734	15	36	45	24	29,027	3	20	17	17
1955	57,594	25	43	48	32	32,109	9	27	33	20	29,027	8	13	13	13
1956	57,594	25	39	45	31	32,484	11	25	35	18	29,027	6	16	20	19
1957	57,594	20	34	44	23	32,859	17	24	33	18	29,027	4	7	12	6
1958	57,594	17	35	42	24	33,234	15	28	38	23	29,027	9	15	22	12
1959	59,641[g]	14	28	50[g]	28[g]	38,432[g]	9	27	37[g]	22[g]	27,250[g]	2	9	19[g]	13[g]
1960	57,973	19	30	53	26	37,512	23	22	40	18	25,782	6	9	14	9
1961	57,973	22	31	50	31	37,512	13	29	34	23	25,782	8	9	23	10
1962	57,915	13	26	61	19	39,074	13	14	45	11	25,782	4	5	20	5
1963	59,537	19	27	48	22	40,211	16	22	46	22	25,782	5	5	19	5
1964	59,578	14	32	55	26	41,655	15	24	36	20	28,166	4	10	22	10
1965	59,048	10	20	60	17	37,634	3	18	40	12	28,166	1	3	28	2
1966	60,969	12	23	71	15	37,612	9	18	40	12	28,340	5	6	25	5
1967	59,659	11	18	59	16	37,861	14	16	48	13	29,473	1	6	20	5
1968	60,062	9	17	82[h]	17	38,335	13	14	56	14	30,244	4	6	29	6
1969	60,281	19	12	87	10	38,504	13	9	58	10	30,927	7	3	41	3
1970	60,300[g]	14	10	86[g]	14[g]	38,881[g]	11	13	62[g]	9[g]	28,319[g]	6	7	34[g]	8[g]
1971	58,977	16	23	71	19	37,846	12	18	57	14	26,603	3	8	29	7

[a] Source: Tennessee Department of Public Health, *Annual Bulletin of Vital Statistics*, 1929–1971, Nashville, Tenn.

[b] Resident population after 1933. Recorded location before 1934.

[c] (1) Stillbirths (fetal deaths). (2) Infant mortality. (3) Cancer deaths. (4) Congenital malformation deaths.

[d] Population totals as recorded in *Annual Bulletin of Vital Statistics*. Lack of intercensal estimation is obvious for Oak Ridge from 1952–1964, for Anderson from 1952–1961, and for Roane from 1931–1939.

[e] Oak Ridge established but, until 1949, omitted from population totals, although not from mortality counts.

[f] After 1948, 6th revision of International Classification of Diseases, Adapted USHEW-PHS, in effect. Not strictly comparable to earlier data. (ICD 750-776.)

[g] Total population data used in the absence of data for white population alone.

[h] Note the increase after 1968 due to changing to the 8th revision of International Classification of Diseases, Adapted USHEW-PHS.

Table 3 Rates of Death from Selected Causes in the White Population Proximate to Oak Ridge, 1929–1971[a,b]

	Anderson County[c]				Roane County[c]				City of Oak Ridge[c]			
Year	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
1929	59.7	62.2	36.9	22.4	31.1	82.0	53.2	26.2	No data available before 1949			
1930	37.5	80.0	25.9	37.5	48.7	80.7	57.1	28.6				
1931	32.7	77.9	20.6	40.2	37.4	55.3	69.5	21.4				
1932	45.6	72.6	5.1	24.9	33.7	92.4	47.8	33.7				
1933	44.5	93.2	60.9	53.8	38.2	74.6	56.5	26.8				
1934	57.2	55.5	25.2	28.6	33.0	47.0	47.8	15.7				
1935	37.7	65.3	45.1	14.5	19.5	72.6	86.9	26.5				
1936	36.5	84.6	54.7	34.8	18.7	83.2	60.8	30.6				
1937	32.9	64.0	39.5	32.9	20.4	79.9	78.2	30.6				
1938	35.1	59.1	68.7	25.9	41.8	80.1	47.8	27.9				
1939	15.1	45.3	58.5	26.8	23.4	43.2	60.8	12.6				
1940	23.6	68.6	42.0	44.5	25.4	59.7	90.7	19.4				
1941	28.0	73.6	33.5	49.0	14.5	37.8	33.6	[illegible]				
1942	3.3	54.9	29.1	21.6	12.4	49.6	62.6	16.5				
1943[d]	20.1	37.3	31.9	11.5	20.4	40.9	61.9	16.1				
1944	17.1	51.3	40.8	37.6	21.5	67.2	89.9	31.7				
1945	14.7	5.3	77.8	27.4	27.8	64.2	46.2	26.6				
1946	12.0	32.0	129.0	23.0	25.2	51.6	66.7	28.8				
1947	21.4	32.3	97.1	24.3	26.2	37.5	100.6	26.2				
1948	22.0	31.9	110.8	25.3	18.9	45.0	109.7	29.6				
1949	13.3	35.2	65.5	83.6[e]	30.9	52.0	73.7	80.3	10.2	16.4	28.8	48.0
1950	13.4	31.6	64.3	59.2	20.3	38.0	122.6	56.1	13.4	15.8	58.9	45.0
1951	17.3	30.5	62.5	73.1	23.1	38.6	111.1	52.2	19.5	26.0	37.9	75.0
1952	10.5	21.5	59.0	47.0	25.1	28.6	119.4	54.7	10.6	13.7	51.7	34.4
1953	14.3	26.7	67.7	58.9	15.6	41.3	92.5	95.8	6.9	24.2	37.9	65.6
1954	10.9	31.7	83.3	67.7	13.9	33.4	141.8	75.7	3.2	21.1	58.6	58.7
1955	14.2	24.4	83.3	55.6	9.3	27.9	102.8	62.3	9.0	14.6	44.8	44.7
1956	15.9	24.7	78.1	53.9	11.9	26.9	107.7	55.5	7.8	20.9	66.2	62.9
1957	13.2	22.5	76.4	40.0	19.0	26.8	100.4	54.7	6.1	10.6	41.3	20.6
1958	11.2	23.0	72.9	41.6	17.0	31.7	114.3	69.3	14.3	23.8	75.8	42.0
1959	10.1	20.8	83.8	47.0	10.3	31.0	96.3[f]	57.2	3.5	16.0	69.7[f]	47.7[f]
1960	13.7	21.6	91.4	44.8	27.3	26.1	106.6	48.0	10.8	16.1	54.3	34.9
1961	16.2	22.8	86.2	53.4	15.8	35.2	90.6	31.4	14.1	15.8	89.2	38.8
1962	10.2	20.3	105.3	32.8	16.0	17.2	115.2	28.2	7.5	9.4	77.6	20.4
1963	15.7	22.3	82.0	37.6	20.7	28.4	114.4	52.3	9.7	9.7	73.7	19.4
1964	11.5	26.2	92.3	43.6	19.8	31.7	86.4	48.0	7.9	19.6	78.1	35.6
1965	9.9	19.8	101.6	28.8	4.7	28.3	106.3	31.9	2.4	7.1	99.4	7.1
1966	12.7	24.3	116.5	24.6	14.3	28.6	106.3	32.0	12.8	15.4	88.2	17.7
1967	12.4	20.2	98.9	26.9	23.1	26.4	126.8	34.4	2.8	16.9	67.9	17.0
1968	10.2	19.3	136.5	28.3	21.8	23.5	146.1	36.5	11.0	16.6	95.9	19.8
1969	21.7	13.7	144.3	16.6	21.4	14.8	150.6	26.0	18.6	8.0	132.6	9.6
1970	15.4	11.0	142.6[f]	23.3[f]	19.0	22.4	159.5[f]	23.1[f]	16.7	19.5	120.1[f]	28.2[f]
1971	17.4	24.9	120.4	32.3	18.2	27.4	150.6	37.0	8.4	22.5	109.0	26.4

[a] Source: Tennessee Department of Public Health, *Annual Bulletin of Vital Statistics*, 1929–1971, Nashville, Tenn.

[b] Resident population after 1933. Recorded location before 1934.

[c] (1) Stillbirths (fetal deaths). (2) Infant mortality. (3) Cancer deaths. (4) Congenital malformation deaths.

[d] Oak Ridge established but, until 1949, omitted from population totals although not from mortality counts.

[e] After 1948, 6th revision of International Classification of Diseases, Adapted USHEW-PHS, in effect. Not strictly comparable to earlier data. (ICD 750-776.)

[f] Total population data used in the absence of data for white population alone.

Table 4 Deaths and Death Rates from Selected Causes in the White Population of the State of Tennessee[a]

Year	White population	Deaths[b]				Death Rates[b]			
		(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
1929	2,155,034	1813	2908	1229	1112	42.3	67.9	57.0	26.0
1930	2,144,781	1827	3016	1297	1192	41.1	67.9	60.5	26.8
1931	2,169,427	1722	2713	1272	1071	38.4	60.5	58.6	23.9
1932	2,194,073	1659	2767	1308	1389	37.4	62.3	[illegible]	26.5
1933	2,218,720	1584	2679	1343	1105	37.5	63.5	60.5	26.2
1934	2,243,366	1602	2924	1447	1159	36.3	66.2	64.5	26.2
1935	2,268,013	1578	2600	1492	1081	35.5	58.4	65.8	24.3
1936	2,292,659	1433	2639	1561	1077	33.8	62.3	68.1	25.4
1937	2,317,306	1460	2371	1601	1072	33.6	54.6	69.1	24.7
1938	2,341,952	1402	2613	1775	1112	30.9	57.6	75.8	24.5
1939	2,366,599	1288	2157	1706	1102	28.7	48.0	72.1	24.5
1940	2,413,698	1236	2411	1830	1129	25.6	49.8	74.1	23.1
1941	2,440,866	1116	2482	1908	1188	22.3	49.5	78.2	23.7
1942	2,468,0[illegible]	1091	2383	1914	1278	20.1	43.9	77.6	23.5
1943	2,495,7[illegible]	1186	2410	2004	1254	20.3	41.3	80.3	21.5
1944	2,522,367	1077	2412	2095	1276	10.1	42.8	83.1	22.6
1945	2,549,536	1075	2398	2141	1245	20.1	44.8	84.0	23.3
1946	2,576,706	1271	2300	2352	1488	19.8	35.8	91.3	23.2
1947	2,603,876	1344	2451	2426	1624	18.7	34.1	93.2	22.6
1948	2,631,041	1247	2393	2549	1622	18.6	35.7	96.9	24.2
1949[c]	2,715,653	1240	2554	2732	1696	18.5	38.1	100.6	62.5[d]
1950	2,758,918	1130	2186	2837	1472	17.5	33.9	102.8	53.4
1951	2,806,084	1172	2095	2994	1562	17.5	31.3	106.7	55.7
1952	2,842,740	1114	2000	2993	1444	17.1	30.6	105.3	50.8
1953	2,879,409	1008	1784	3097	1346	15.4	27.3	107.6	46.8
1954	2,916,072	1048	1859	3180	1423	15.5	27.5	109.1	48.8
1955	2,952,730	998	1728	3228	1311	15.0	25.9	109.3	44.3
1956	2,989,392	1035	1665	3359	1313	15.7	25.2	112.4	43.8
1957	3,026,051	958	1651	3380	1280	14.6	25.2	111.7	42.3
1958[c]	3,062,717	960	1704	3564	1324	14.8	26.2	116.4	43.2
1959	2,988,879	886	1694	3636	1369	13.7	26.2	121.7	45.7
1960	2,977,753	923	1610	3628	1311	14.5	25.3	121.8	43.9
1961	2,977,753	920	1607	3775	1307	14.4	25.2	126.8	43.9
1962	3,032,532	929	1543	3810	1264	14.8	24.5	125.6	41.7
1963	3,081,233	884	1459	4187	1196	14.2	23.5	135.9	38.8
1964	3,168,049	886	1547	4019	1225	14.2	24.7	126.9	38.7
1965	3,210,400	799	1327	4215	1095	14.2	23.5	131.3	34.2
1966	3,246,900	826	1186	4277	993	15.4	22.1	131.7	30.6
1967	3,251,200	728	1107	4535	950	13.7	20.9	139.5	29.1
1968[c]	3,322,600	769	1039	4713	916	14.6	19.7	141.8	26.4
1969	3,294,331	716	1031	4704	863	13.0	18.7	141.2	25.8
1970	3,294,331	765	1061	4964	934	13.5	18.7	150.7	28.4
1971	3,349,611	698	1054	5048	888	12.4	18.8	150.7	[illegible]

[a] Source: Tennessee Department of Public Health, *Annual Bulletin of Vital Statistics*, 1929–1971, Nashville, Tenn.

[b] (1) Stillbirths (fetal deaths). (2) Infant mortality. (3) Cancer deaths. (4) Congenital malformation deaths.

[c] New International Classification of Diseases, Adapted USHEW-PHS, in effect.

[d] Sixth revision of International Classification of Diseases, Adapted USHEW-PHS, in effect; rate per 10^5 population; previously computed per 10^3 live births.

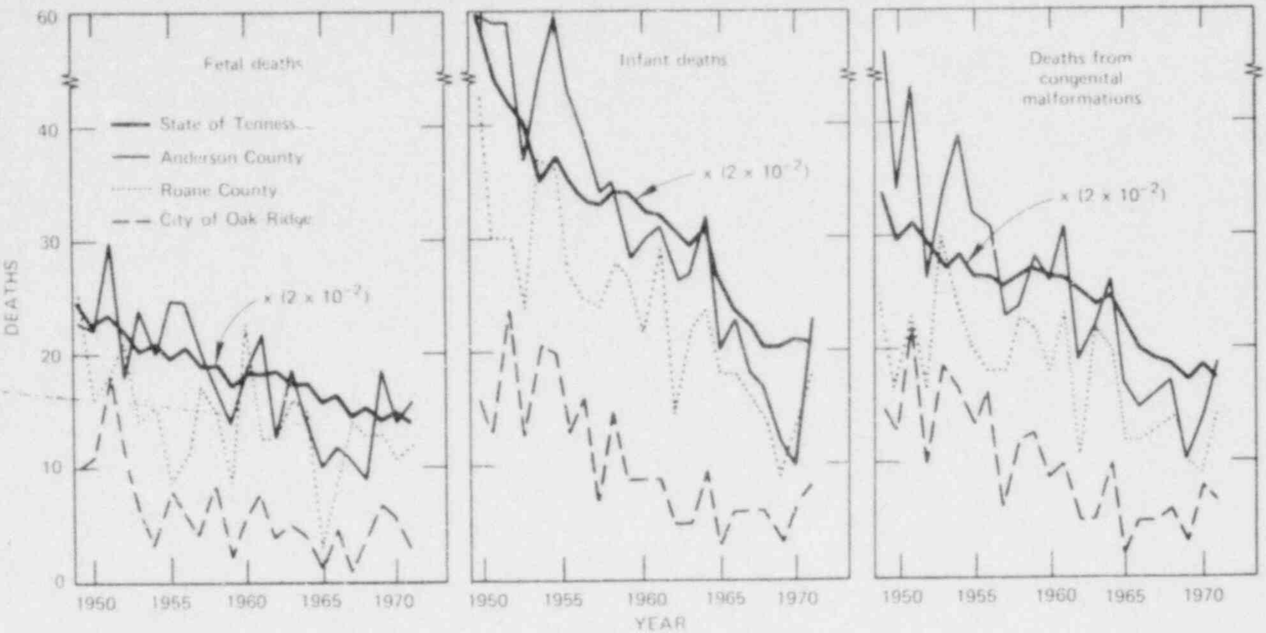

Fig. 1 Trends in fetal, infant, and congenital malformation deaths in the white population in the state of Tennessee and in the Oak Ridge area, 1949–1971. Source: Ref. 42.

which would suggest that the Oak Ridge area has been or is becoming a relatively hazardous locale. Since the number of deaths is small, the statistical fluctuations could be large, but the trends are fairly consistent. The city of Oak Ridge, which is closest to the nuclear facilities, does not show any consistent increases, nor do Anderson County and Roane County. All three areas reflect the general mortality trend indicated for the state of Tennessee.

Although crude annual rates are frequently used, as discussed previously, age-adjusted annual rates are the only appropriate data for comparing the city and state death rates. However, age-adjusted rates are not published for the state of Tennessee. Even those rates which are published may be erroneous. For example, misreporting of a few deaths could introduce a large bias into the smaller reported figures, and misreporting is likely because of changes in death classifications every decade.

A second source of error is obvious in the crude death rates for the Oak Ridge area. The crude death rates are based on the ratio of the number of deaths to the estimated size of the population. As shown in Table 2, these population estimates are unquestionably inaccurate for many, if not most, intercensal years. For example, between 1943 and 1949 Anderson County's base population, upon which the rates are based, did not include Oak Ridge, but the mortalities did. For these reasons the data are only plotted and discussed but not analyzed statistically.

More reliable data—age-adjusted cancer mortality from the National Cancer Institute for the years 1950 to 1969 for Anderson and Roane counties—were analyzed statistically to determine if a geographical pattern could be observed.[43] The city of Oak Ridge is located partly in Anderson County and partly in Roane County; two of the three nuclear facilities are in Roane County, and one is in Anderson County. Figure 3 shows the location of the three facilities and the city of Oak Ridge. Actual deaths from all cancers (including leukemia) were compared with the expected deaths, which were computed using the mortality rate for each cancer and each of four race–sex classes of the population in each county. The results are given in Table 5.

The analysis indicates that for every cancer, the number of actual deaths is statistically no different from the number expected for males of both races and for white females. For black females, actual deaths are no different statistically from expected deaths in all cancers examined with two exceptions. For leukemia and lung cancer in nonwhite females in Anderson County, two deaths occurred, whereas only 0.5 would have been expected based on Tennessee rates. (This

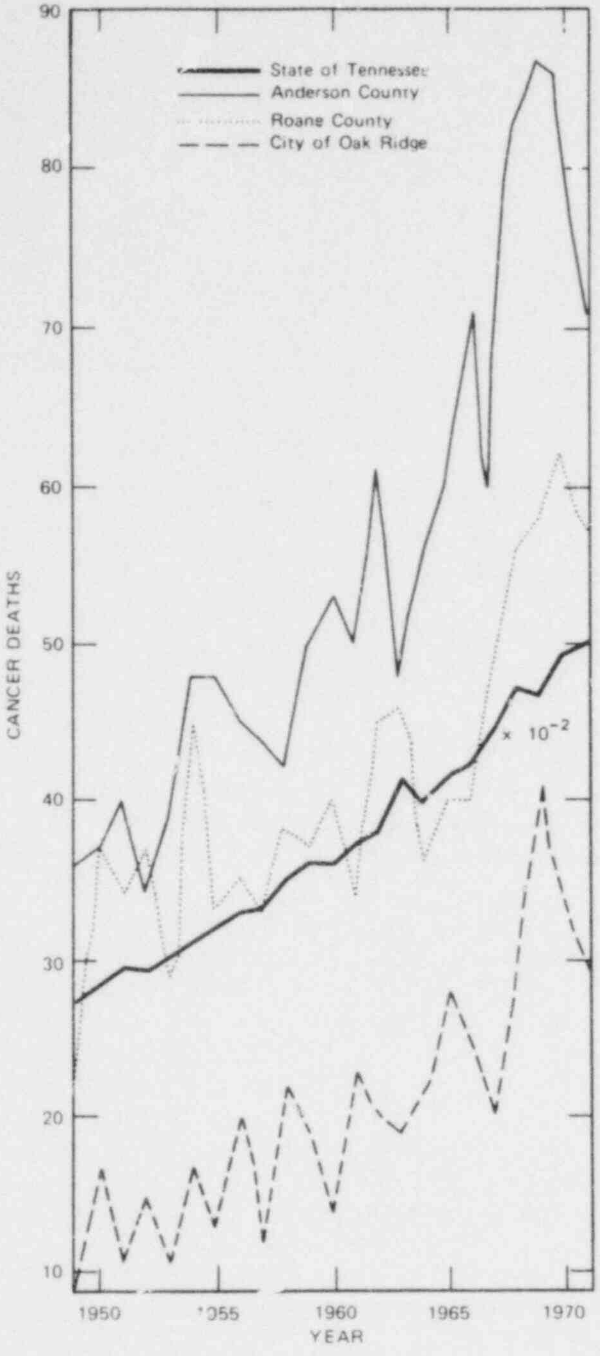

Fig. 2 Cancer deaths in the white population in the state of Tennessee and in the Oak Ridge area, 1949–1971. Source: Ref. 42.

result is not statistically significant at the 0.05 level using the more appropriate Poisson distribution.) The overall results indicate cancer mortality rates that are not significantly higher than would be expected in the general population. Problems in this analysis include (1) no time trends, (2) migration, and (3) socioeconomic factors, as have been mentioned in regard to previous studies.

CONCLUSIONS AND IMPLICATIONS

Although high levels of radiation are a proven threat to man's health, little evidence has yet been found that low levels of radiation such as might result from the normal operation of nuclear facilities are harmful to the general public. Although much more analysis is needed in this area, existing studies using a variety of methods generally have been unable to detect a rise in measures of ill health in populations living near nuclear facilities. Increases that were observed were either representative of general trends for the state or nation or the continuation of trends existing in the area before the nuclear facility went into operation. The results, although tentative because of the limited scope of research in this area, do suggest by their consistency that no correlation between nuclear facilities and increased mortality in the general public can be substantiated.

Since the National Environmental Policy Act of 1969 considers human health impacts as a major portion of overall environmental impacts, more emphasis should be placed on the inclusion of health and mortality data in environmental impact statements.[44] If such data were included, past trends in an area where a power plant, whether nuclear or nonnuclear, is to be located could be used as a baseline against which to measure future changes in health in the area. When widespread utilization of such public health statistics is begun, more meaningful health and mortality statistics will be needed and, hopefully, will be made available. Then trends in various measures of health in areas where power plants are located will allow us to make a more definitive determination of the relative risk of such plants to the public.

Until that time, we must rely on the few studies of public health effects, on results from animal experiments and occupational exposures, and on federal safety regulations as indicators of the safety of power-plant operations to the general public. To date, studies using mortality data from vital statistics have been inadequate for hypothesis testing. These studies should be used solely to indicate the need for more in-depth studies examining hypotheses suggested by trends seen in the vital statistics.

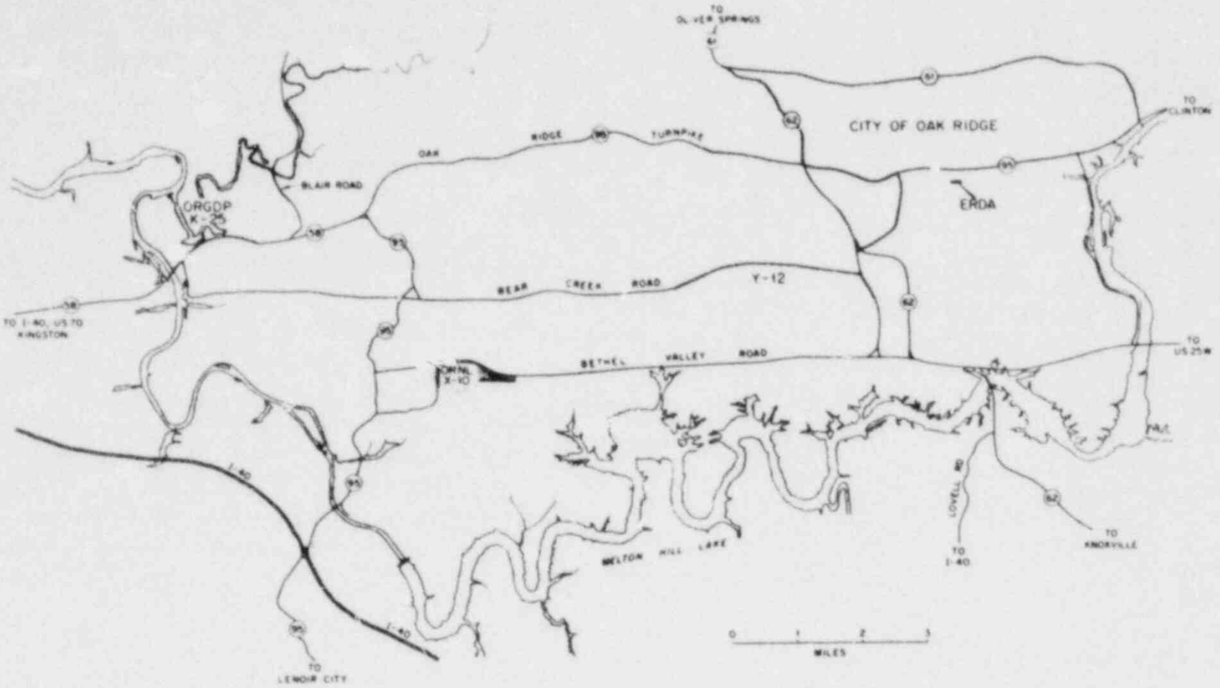

Fig. 3 The city of Oak Ridge, Tenn., and the three nearby nuclear facilities Y-12, X-10, and K-25.

Table 5 Age-Adjusted Mortality Rates, Actual and Expected Deaths for Selected Cancer Sites by Sex and Race in the State of Tennessee, Anderson County, and Roane County, 1950–1969 (Ref. 43)

	Tennessee		Anderson County				Roane County			
Cancer site*	Observed number	Observed rate	Observed number	Observed rate	Expected number	X^2†	Observed number	Observed rate	Expected number	X^2†
All cancers										
WM	38,356	146.3	544	143.8	553.5	0.16	432	154.4	409.3	1.25
WF	35,763	116.0	510	117.4	503.9	0.07	384	120.2	370.6	0.49
NM	7,874	163.8	22	236.[illegible]	15.3	2.99	22	145.3	24.8	0.32
NF	2,268	142.5	22	213.3	14.7	3.63	26	165.8	22.4	0.60
Leukemia										
WM	2,268	8.4	39	8.7	37.7	0.05	20	6.4	26.3	1.49
WF	1,700	5.6	32	6.2	28.9	0.33	20	6.0	18.7	0.10
NM	301	6.0	1	9.6	0.6	0.23	2	12.5	1.0	1.13
NF	222	3.9	2	16.7	0.5	5.03‡				
Lung										
WM	8,885	33.5	151	38.6	131.1	3.04	111	38.7	96.1	2.32
WF	1,673	5.5	23	6.0	21.1	0.17	15	4.7	17.6	0.37
NM	1,387	28.8	6	59.0	2.9	3.22	2	11.7	4.9	1.74
NF	300	5.5	2	20.8	0.5	4.09‡	1	6.0	0.9	0.01
Bone										
WM	371	1.4	8	1.7	6.6	0.30	5	1.4	5.0	0.0
WF	366	1.2	4	0.7	6.9	1.19	6	1.8	4.0	1.00
NM	59	1.2								
NF	43	0.8								
Thyroid										
WM	91	0.3	2	0.6	1.0	1.00				
WF	195	0.6	2	0.6	2.0	0.0	2	0.6	2.0	0.0
NM	12	0.3								
NF	28	0.5								

*WM = white male; WF = white female; NM = nonwhite male; NF = nonwhite female.

†$X^2 = \frac{(\text{observed} - \text{expected})^2}{\text{expected}}$, with one degree of freedom, and with expected based on the state rate applied to local population.

‡Significant at the 0.05 level ($X^2 > 3.84$).

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Radiological Quality of the Environment in the United States, 1977

Adapted from EPA 520/1-009

Nucl. Safety, 19(5): 617–622 (September–October 1977)

[Editor's Note: The following article was adapted by the *Nuclear Safety* Staff from Chap. 1, "Introduction, Summary, and Conclusions," of a report of the same title, which was published in September 1977 by the Environmental Protection Agency as EPA 520/1-009. The report and its summary here provide significant data on dose assessment for evaluating the radiological quality of the environment.]

This article summarizes Report EPA 520/1-009, which is intended to fulfill the Environmental Protection Agency Office of Radiation Program's responsibility for determining individual and total U. S. population doses from all sources of radiation. In addition, the information is used for analysis of radiation trends, identification of radiation problems, and support for establishing standards.

The sources of radiation have been considered in two general categories: (1) ionizing radiation and (2) nonionizing radiation. In the ionizing radiation category, sources were further grouped under the headings of ambient environmental radiation, technologically enhanced natural radiation, fallout, uranium fuel cycle, federal facilities, radiopharmaceuticals, medical, occupational–industrial, and consumer products. The nonionizing radiation category is concerned mainly with the measurement of environmental sources.

Literature searches were conducted for each of these categories, and the data were organized to provide the following information:

1. General information about each source category and the availability of data.

2. Description of data base (includes who reports data to whom, under what authority, and what data are being reported).

3. Status of data-base analyses (to indicate what has been done with the data).

4. A summary of dose data for each source category.

5. Comparison of actual dose data reported with estimates from previous publications.

6. Discussion, evaluation of the adequacy of the data base and needed improvements, and conclusions.

A special effort was made to acquire data supported by direct measurements in contrast to estimates made by extrapolations involving numerous assumptions. Most dose information falls in the latter category because of the difficulty or cost of making direct measurements. Therefore most of the data available represent the product of several calculations involving an understanding of the source term and the interaction of that source term with the environment and man.

Report EPA 520/1-009 tries to include the most current data. For some categories, however, the only available data are for the early 1970s. Because of this time spread of the available data, the latest data available are compiled for each source, regardless of the year for which they were determined. This report, therefore, and those of future years, will represent a compilation of the latest data available at the time of preparation.

The information for Report EPA 502/1-009 was obtained primarily from published reports, such as those appearing in professional society journals and in symposium proceedings, as well as other technical reports. The regional offices of the Environmental Protection Agency (EPA) were instrumental in obtaining reports of the monitoring activities of the states. Operating and environmental surveillance reports from nuclear power reactors were obtained from the Nuclear Regulatory Commission (NRC). Data for Energy Research and Development Administration* facilities were taken from the contractors' annual environmental surveillance reports. Medical X-ray and consumer product information was taken from reports of the Food and Drug Administration's Bureau of Radiological Health.

In addition to the radiation data provided by other agencies, EPA obtains ambient monitoring data from its own national networks. This program is conducted by the Eastern Environmental Radiation Facility (EERF) in Montgomery, Ala., and involves the analyses

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*The functions of the Energy Research and Development Administration have since been transferred to the Department of Energy.

of samples of air, milk, and water. The data from these analyses are published quarterly in an environmental radiation data report. A comprehensive analysis of past Environmental Radiation Ambient Monitoring System (ERAMS) data is being made.

Report EPA 502/1-009 summarizes the individual and population doses in the United States resulting from each category of radiation source, and these data are assessed. When the literature on radiation sources was searched, it became readily apparent that an immense amount of data had been published during the past 15 years. Therefore it was necessary, first, to organize the sources of radiation into the categories described and, second, to summarize, examine, and interpret the data with respect to these categories. In doing so, it was also necessary to assume that the data obtained from the literature were valid. Because the data acquired for this report were generated originally for many different purposes, the results are not only expressed in different units, but also they were accumulated over different time periods and frequently were obtained without quality control. For this reason, many tables of data in Report EPA 502/1-009 carry detailed notes and annotations. Readers are cautioned that before data in the report are used for their purposes, they should read the text and the notes to ensure a correct interpretation.

The data on individual and population doses resulting from the various categories of radiation sources discussed are summarized in Table 1. The information in this table is divided according to whether the primary mode of exposure is external or internal. Exposure to direct radiation from radionuclides in the ground, water, buildings, and air around us, or from radiation-producing machines, such as X-ray equipment and particle accelerators, is considered to be external exposure. Exposures of this type usually result in a radiation dose to the whole body of the person exposed. In contrast, internal exposures occur when radioactive materials are inhaled, ingested, or absorbed through the skin. Internal exposures result in radiation doses to specific organs of the body, such as the lung, gastrointestinal tract, or bone.

As shown in Table 1, there are radiation sources for which data are not available. Consequently the discussion and comments in the report are based on the data that were available at the time of writing. Also, it is worth noting that, although population doses from the different source categories generally can be added together to gain a perspective of overall impact, it does not necessarily follow that individual doses can be added together, since a person in one population group generally does not receive the radiation dose common to another population group. Therefore the data in Table 1 only show totals for population doses in the various source categories.

Dose to the U. S. Population

On the basis of the limited data in Table 1, we see that the source category with the highest population dose is the external dose from cosmic radiation. An overall dose from ambient ionizing radiation is not given because population doses from the worldwide radiation and terrestrial radiation components are not available. If we judge from the figures given for individual doses from these three categories, it would appear that the population doses from terrestrial radiation might be equal to or greater than the dose from cosmic radiation (10 million person-rems per year). The second largest source of population dose is from medical and dental X rays. This dose was estimated to be about 14.8 million person-rems per year to the U. S. population.

The third largest category of population dose for which data are available is radiopharmaceuticals for medical radiation purposes, which are estimated to contribute an internal dose of approximately 3 million person-rems per year to the population dose. The fourth largest category is estimated to be from technologically enhanced natural radiation that contributes approximately 3 million person-rems per year to the population dose. Finally, we note that all the population doses from all other source categories for which data are available are less than 0.1% of the total population dose.

We must mention that the population dose values noted here are based on the data available to us at the time this report was written. It is possible that these values, and thus the relative contributions of population dose from the source categories considered, could change in the future as more information on this subject becomes available.

Dose to Individuals

For individual persons, the largest dose is derived from technologically enhanced natural radiation. This natural radiation contributes internal doses as high as or higher than 100,000 mrems/year to the tracheobronchial surface tissue of the lung as a result of the inhalation of radon daughter products from uranium mill tailings.

Table 1 Summary of Dose Data from All Sources in the United States in 1977

Source	External		Internal	
	Individual dose (mrem/year)	Population dose (person-rem/year)	Individual dose (mrem/year)	Population dose (person-rem/year)
Ambient ionizing radiation				
Cosmic radiation	41–45	9.7×10^6		
Ionizing component	28–35	9.2×10^6		
Neutron component	0.33–6.8	4.9×10^5		
Worldwide radioactivity				
Tritium			0.04	9.2×10^3
Carbon-14			1	
Krypton-85	0.035^{*a}			
Terrestrial radiation	30–95		18–25	
Potassium-40	17		16	
Tritium			4×10^{-3}	
Carbon-14			1	
Rubidium-87			0.6	
Uranium-238 series	13		2–6*	
Thorium-232 series	25		7*	
Technologically enhanced natural radiation				2.73×10^6
Ore mining and milling			100,000*	
Inactive uranium mill tailings piles			$140–14{,}000^b$	$2.5–70{,}000^c$
Phosphate mining and processing (occupational)	10–300*		$6{,}000^{*b}$	
Fertilizer	1.7*			
Thorium mining and milling			$4{,}000^b(1{,}250^d)^*$	
Radon in potable water supplies			$15–54^b$	2.73×10^6
Radon in natural gas			1–4	30,000
Radon in liquefied petroleum gas				
Radon in "health" mines				
Radon daughter exposure in natural caves				
Radon and geothermal energy production				
Radioactivity in construction material				
Airplane travel				
Jet (cosmic), per trip over the Atlantic	2.6 (500 + crew)*			
SST (cosmic), per trip over the Atlantic	2.0 (100 + crew)*			
Coal-fired electric generating station			5–70*	$0.12–2 \times 10^{6}$ *
Oil-fired electric generating station			0.04*	15*
Fallout	$\sim 2^c$			
Uranium fuel cycle		2014		
Mining and milling			4.5×10^{-2f}	2.5
Fuel enrichment	$<0.1^g$	<0.1	0.3^h	0.64^i
Fuel fabrication			2×10^{-4j}	0.66^j
Power reactors (BWR)	76 max^k	1564^m		
Power reactors (PWR)	4 max^k	21^m		
Research reactors				
Transportation: nuclear power industry		$100–9600^n$		
Transportation: radioisotopes		$<170^n$		
Reprocessing and spent-fuel storage	6^p	23^p	$14–257^p$	
Radioactive waste disposal				
Federal facilities		480^q		
ERDA (now Department of Energy)	$<0.1–258^k$	<1–180		
Department of Defense	<0.01			
Accelerators	$0.04–4^k$	0.4–65		
Radiopharmaceuticals		$<0.1^r$		3.3×10^{6s}
Medical radiation				
X rays	103^t	14.8×10^6		
Cardiac pacemakers			<5000	

Occupational and industrial radiation			
At BWRs	1230[u]		
At PWRs	1080[u]		
All occupations	0.80[v]	28 400	
Consumer products			
Timepieces	<0.5*[x]	~6100[y]	
Smoke detectors	0.007*[z]	0.001*	
Artificial teeth			140–1390*[aa]
Television	0.025–0.043[bb]		

	Individual exposure ($\mu W/cm^2$)
Nonionizing electromagnetic radiation	
Broadcast towers and airport radars	10
All sources	0.1–1

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*Indicates new or revised information.

[a] Maximum individual dose to skin surface.

[b] Trachea–bronchial dose.

[c] Lung-rems/year.

[d] Stomach dose.

[e] 50-year dose commitment divided by 50.

[f] Average individual lung dose within an 80-km radius.

[g] Maximum potential exposure per facility.

[h] Maximum potential exposure.

[i] Cumulative exposure per facility within an 80-km radius.

[j] Estimated bone dose within an 80-km radius.

[k] Fence-line boundary dose.

[m] Within a radius of 80 km.

[n] Estimated for the year 1973.

[p] For the Nuclear Fuel Services Reprocessing Plant at West Valley, N. Y.

[q] 1965 data.

[r] Based on data from five institutions.

[s] Estimated 1980 dose.

[t] Estimated mean active bone marrow dose to adults, mrad/year.

[u] Average occupational exposure per year.

[v] Average exposure for all occupations and 3.7 radiation workers per 1000 persons in the United States.

[x] From digital watches.

[y] From timepieces containing tritium or radium-activated dials.

[z] Estimated.

[aa] Dose to the superficial layer of tissue.

[bb] 5 cm from TV set; units of mR/hr.

The second contributor to a high individual dose is medical radiation which contributes internal doses as high as 5000 mrems/year from radioactive cardiac pacemakers. Because of their uranium content, artificial teeth contribute a local-tissue dose as high as 1390 mrems/year to the person wearing them. Occupational and industrial operations contribute a dose of 1230 mrems/year to the individual worker, essentially to maintenance personnel working around boiling-water nuclear power reactors. Finally, the next larger dose is that which might be received by persons at the boundary of federal facilities—258 mrems/year.

As mentioned previously, the relative contributions from each of the source categories are subject to revision as may be required by new data.

Evaluation of the Data Base

Table 1 shows that most of the values on individual and population doses are based on calculations that lead to estimated data. Such doses may be considered to be reliable and conservative estimates if it is understood that, in all probability, the values for the actual doses are appreciably smaller than the estimated values.

In determining individual doses, we need to understand that these doses are for specific categories and are additive only if it is reasonable to expect that the same persons would be exposed to the sources in these categories. For example, in general, the individual dose from uranium mining and milling should not be added to other source categories in the uranium fuel cycle because different persons are involved in these exposures.

In addition to this evaluation of the data base, each chapter in the report contains a more detailed evaluation of the data base pertinent to that chapter.

CONCLUSIONS

1. On the basis of the population dose data in Report EPA 502/1-009, the four major source categories of radiation dose to the population of the United States are ambient ionizing radiation, medical and dental radiation, the use of radiopharmaceuticals

in medicine, and technologically enhanced natural radiation. The relatively high dose values are due to the large populations that are exposed to the sources in these categories.

2. On an individual basis, the largest sources of radiation dose are from technologically enhanced natural radiation, medical radiation, ambient ionizing radiation, consumer products, occupational and industrial operations, and federal facilities. The source responsible for high individual doses in the category of technologically enhanced natural radiation is uranium mill tailings that had been used in the construction of residences. The risk to a person from the dose received from the use of a cardiac pacemaker must be weighed against the benefit derived from this device. It is quite conceivable that, if the dose from other sources in this category were available, additional high individual doses would be observed.

3. There are many gaps in the dose data compiled for this report. For this reason, the observations and comments made here are necessarily restricted to this data base. There is a need to greatly improve the data base for dose assessment in the United States.

Recommendations of the International Commission on Radiological Protection

Adapted from ICRP Publication 26

Nucl. Safety, 20(**3**): 330–342 (May–June 1979)

[Editor's Note: The following adaption by the *Nuclear Safety* Editorial Staff was made from a much longer report of the same name *(ICRP Publication 26)*. The report is an authoritative source of information on risk estimates of ill health associated with ionizing radiation and provides an established basis for radiation protection actions and policies both in this country and elsewhere. A summary is presented here to provide a penetrating insight into this important area.]

As one of the commissions established by the International Congress of Radiology, the International Commission on Radiological Protection (ICRP) has continued its close relationship with succeeding Congresses, and it has also been looked to as the appropriate body to give general guidance on the more widespread use of radiation sources caused by the rapid developments in the field of nuclear energy. The ICRP continues to maintain its traditional contact with medical radiology and the medical profession generally, and it also recognizes its responsibility to other professional groups and its obligation to provide guidance within the field of radiation protection as a whole. Details of the ICRP rules, membership and relationship with other bodies are in the appendix to *ICRP Publication 26*.

In 1966 the ICRP published its recommendations *(ICRP Publication 9)* which had been adopted in 1965; they were amended in 1969 and 1971. During the last decade new information has emerged which has necessitated a review of the Commission's basic recommendations; the present report results from the examination of such new information by the ICRP and its committees and task groups. The recommendations made in this report supersede the former basic recommendations published by the Commission, but not necessarily those of its committees.

As in its previous recommendations, the ICRP deals only with ionizing radiations in this report.

The Commission wishes to reiterate that its policy is to consider the fundamental principles on which appropriate radiation protection measures can be based. Because of the differing conditions that apply in various countries, detailed guidance on the application of its recommendations, either in regulations or in codes of practice, should be elaborated by the various international and national bodies that are familiar with what is best for their needs. The ICRP recognizes that the individual experts responsible for putting radiation protection into practice need guidance that is sufficiently flexible to allow for national, regional, or other variation. For this reason the ICRP recommendations are intended to provide an appropriate degree of flexibility. Because of this, the form in which the recommendations are worded will not necessarily be suitable, and may often be inappropriate, for direct assimilation into regulations or codes of practice.

OBJECTIVES OF RADIATION PROTECTION

Radiation protection is concerned with the protection of individuals, their progeny, and mankind as a whole, while still allowing necessary activities from which radiation exposure might result. The detrimental effects against which protection is required are known as somatic and hereditary; radiation effects are called "somatic" if they become manifest in the exposed individual himself and "hereditary" if they affect his descendants.

"Stochastic" effects are those for which the probability of an effect occurring, rather than its severity, is regarded as a function of dose without threshold. "Nonstochastic" effects are those for which the severity of the effect varies with the dose and for which a threshold may therefore occur. At the dose range involved in radiation protection, hereditary effects are regarded as being stochastic. Some somatic effects are stochastic; of these, carcinogenesis is considered to be the chief somatic risk of irradiation at low doses and is therefore the main problem in radiation protection.

Some nonstochastic somatic effects are specific to particular tissues, as in the case of cataract of the lens, nonmalignant damage to the skin, cell depletion in the bone marrow causing hematological deficiencies, and gonadal cell damage leading to impairment of fertility. Other nonstochastic effects may arise in the blood vessels or connective tissue elements that are common to most organs of the body and therefore require that, as a precautionary measure, a dose-equivalent limit should apply for all body tissues to ensure that nonstochastic effects do not occur in any such tissue.

For all these changes the severity of the effect depends on the magnitude of the dose received, and there is likely to be a clear threshold of dose below which no detrimental effects are seen.

The aim of radiation protection should be to prevent detrimental nonstochastic effects and to limit the probability of stochastic effects to levels deemed to be acceptable. An additional aim is to ensure that practices involving radiation exposure are justified.

The prevention of nonstochastic effects would be achieved by setting dose-equivalent limits at sufficiently low values so that no threshold dose would be reached, even following exposure for the whole of a lifetime or for the total period of working life. The limitation of stochastic effects is achieved by keeping all justifiable exposures as low as is reasonably achievable, economic and social factors being taken into account, subject always to the boundary condition that the appropriate dose-equivalent limits will not be exceeded.

Most decisions about human activities are based on an implicit form of balancing of costs and benefits leading to the conclusion that the conduct of a chosen practice is "worthwhile." Less generally, it is also recognized that the conduct of the chosen practice should be adjusted to maximize the benefit to the individual or to society. In radiation protection it is becoming possible to formalize these broad decision-making procedures, although it is not always possible to quantify them. However, the application of these procedures does not always provide sufficient protection for the individual. It is therefore necessary, for this reason also, to establish dose-equivalent limits in situations where the benefits and detriments are not received by the same members of the population.

For the above reasons the ICRP recommends a system of dose limitation, the main features of which are as follows:

1. No practice shall be adopted unless its introduction produces a positive net benefit.
2. All exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account.
3. The dose equivalent to individuals shall not exceed the limits recommended for the appropriate circumstances by the Commission.

In applying these recommendations, we must recognize that many present practices give rise to dose equivalents that will be received in the future. These dose-equivalent commitments should be taken into account so that necessary developments of present or future practice would not be liable to result in undue exposure of any members of the public.

Although the principal objective of radiation protection is the achievement and maintenance of appropriately safe conditions for activities involving human exposure, the level of safety required for the protection of all human individuals is thought likely to be adequate to protect other species, although not necessarily individual members of those species. Thus the ICRP believes that if man is adequately protected, then other living things are also likely to be sufficiently protected.

BASIC CONCEPTS

Detriment

The deleterious effects of exposure to radiation may be of many kinds. Among the effects on health, there may be both stochastic and nonstochastic effects in the exposed individual and stochastic effects in later generations. In addition there may be deleterious effects not associated with health, such as the need to restrict the use of some areas or products.

The ICRP has introduced the concept of detriment to identify and, where possible, to quantify all these deleterious effects. In general, the detriment in a population is defined as the mathematical "expectation" of the harm incurred from an exposure to radiation, taking into account not only the probability of each type of deleterious effect but also the severity of the effect. These deleterious effects include both the effects on health and the effects not associated with health. On some occasions it is convenient to deal separately with the effects, or the potential effects, on health. These are then characterized by the concept of detriment to health. For effects on health, if p_i, the probability of suffering the effect i, is small and the severity of the effect is expressed by a weighting factor g_i, then the detriment to health, G, in a group of P persons is given by

$$G = P \sum_i p_i g_i$$

Dose Equivalent

The absorbed dose,[1] D, is insufficient by itself to predict either the severity or the probability of the deleterious effects on health resulting from irradiation under unspecified conditions. In radiation protection it is convenient to introduce a further quantity that correlates better with the more important deleterious effects of exposure to radiation, more particularly with the delayed stochastic effects. This quantity, called dose equivalent, is the absorbed dose weighted by the modifying factors Q and N.

The dose equivalent, H, at a point in tissue, is given by the equation

$$H = DQN$$

where D is the absorbed dose, Q is the quality factor, and N is the product of all other modifying factors specified by the ICRP. At the present time the ICRP has assigned the value 1 to N. The special name for the unit of dose equivalent is the sievert (Sv);

$$1\ \text{Sv} = 1\ \text{J kg}^{-1}\ (= 100\ \text{rems})$$

The quality factor, Q, is intended to allow for the effect on the detriment of the microscopic distribution of absorbed energy. The Q factor is defined as a function of the collision stopping power (L_∞) in water at the point of interest. Interpolated values of Q as a function of L_∞ can be obtained by using the values shown in the table below.

L_∞–Q Relationship

L_∞ in water, keV/μm	Q
3.5 (and under)	1
7	2
23	5
53	10
175 (and above)	20

For a spectrum of radiation, an effective value, $\bar{Q}$, of Q at the point of interest can be calculated.[2]

When the distribution of radiation in L_∞ is not known at all points in the volume of interest, it is permissible to use approximate values for $\bar{Q}$ related to the various types of primary radiation. For this purpose the ICRP recommends the following values of $\bar{Q}$ to be used for both external and internal radiation:

X rays, gamma rays, and electrons	1
Neutrons, protons, and singly charged particles of rest mass greater than one atomic mass unit of unknown energy	10
Alpha particles and multiply charged particles (and particles of unknown charge) of unknown energy	20
Thermal neutrons	2.3

Committed Dose Equivalent

Another quantity used in the ICRP recommendations is the "committed dose equivalent," H_{50}, to a given organ or tissue from a single intake of radioactive material into the body. This quantity, which may be considered to be a special case of dose-equivalent commitment, is the dose equivalent that will be accumulated over 50 years, representing a working life, following the intake:

$$H_{50} = \int_{t_0}^{t_0+50\text{y}} \dot{H}(t)\, dt$$

where $\dot{H}(t)$ is the relevant dose-equivalent rate and t_0 is the time of intake.

DOSE–RESPONSE RELATIONSHIPS

The relationship between the dose received by an individual and any particular biological effect induced by irradiation is a complex matter on which much further work is needed. For radiation protection purposes, it is necessary to make certain simplifying assumptions. One such basic assumption underlying the ICRP recommendations is that, regarding stochastic effects, there is, within the range of exposure conditions usually encountered in radiation work, a linear relationship without threshold between dose and the probability of an effect. The simple summation of doses received by a tissue or organ as a measure of the total risk and the calculation of the collective dose equivalent as an index of the total detriment to a population are valid only on the basis of this assumption and that the severity of each type of effect is independent of dose.

The added risk from a given dose increment will depend on the slope of the dose–response relationship. If the dose–response relationship for stochastic processes is in fact highly sigmoid, the risk from low doses could be overestimated by making a linear extrapolation from data obtained at high doses.

There are radiobiological grounds for assuming that the dose–response curve for low-LET* radiation will generally increase in slope with increasing dose and dose rate over the absorbed dose range up to a few gray.† For many effects studied experimentally, the response in this range can be represented by the

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*LET = linear energy transfer.

†1 gray (Gy) = 1 J kg^{-1} (= 100 rads).

expression‡

$$E = aD + bD^2$$

where E denotes the effect, D the dose, and a and b are constants. The quadratic term (bD^2) in this expression predominates at high absorbed doses (generally above 1 Gy) and high absorbed dose rates (of the order of 1 Gy/min); however, the linear term (aD) and the slope that it represents come to predominate as the dose and dose rate are reduced. Although a relationship of this form has been documented for a variety of effects, the relative values of the parameters a and b vary from one observation to another.

For human populations in particular, knowledge of dose–response relationships is too limited to enable confident prediction of the shapes and slopes of the curves at low doses and low dose rates. Nevertheless, in a few instances the risk estimates can be based on the results of irradiation of human populations involving single absorbed doses, of the order of 0.5 Gy or less, or such doses repeated at intervals of a few days or more. In these cases it can be reasonably assumed that the frequency per unit absorbed dose of particular harmful effects resulting from such exposures is not likely to overestimate greatly the frequency of such effects in the dose range of concern in radiation protection, even though the latter may be received at much lower dose rates.

In many instances, however, risk estimates depend on data derived from irradiation involving higher doses delivered at high dose rates. In these cases, it may be appropriate to reduce these estimates by a factor to allow for the probable difference in risk. The risk factors discussed later have therefore been chosen as far as possible to apply in practice for the purposes of radiation protection.

The use of linear extrapolations, from the frequency of effects observed at high doses, leads to an overestimate of the radiation risks, which in turn could result in the choice of alternatives that are more hazardous than practices involving radiation exposures. Thus, in the choice of alternative practices, radiation risk estimates should be used only with great caution and with explicit recognition of the possibility that the actual risk at low doses may be lower than that implied by a deliberately cautious assumption of proportionality.

IMPLICATIONS OF ASSUMPTIONS ABOUT DOSE–RESPONSE RELATIONS

Significant Volumes and Areas

From the assumption about the proportionality between dose and response, it would follow that for stochastic effects it would be justifiable to consider the mean dose* over all cells of uniform sensitivity in a particular tissue or organ. This use of the mean dose has practical advantages in that the significant volume can usually be taken as that of the organ or tissue under consideration.

When the irradiation of a tissue is nonhomogeneous, the use of the mean dose over the tissue ceases to be strictly valid if doses to individual cells differ more widely than the range of doses over which the dose–response relationship for the tissue can be regarded as linear. An example of this may be the irradiation of the lung by radioactive particulates. However, on the basis of theoretical considerations and of available epidemiological evidence, the ICRP believes that, for late stochastic effects, the absorption of a given quantity of radiation energy is ordinarily likely to be less effective when due to a series of "hot spots" than when uniformly distributed because of the effect of high doses in causing the loss of reproductive capacity or the death of cells. Thus, with particulate radioactive sources within a tissue, to assess the risk by assuming a homogeneous dose distribution would probably overestimate the actual risk. Moreover, for nonstochastic effects the limited amount of cell loss that might result at moderate dose levels would be most unlikely to cause any impairment of organ function.

For exposure of the skin, either to external sources or as a result of skin contamination, it is not generally appropriate to average the dose equivalent over the entire skin.

Rate of Dose Accumulation

The ICRP believes that it is sufficient to set annual dose-equivalent limits and does not recommend any

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‡At high doses this expression would have to be modified to take account of the decreased tumor risk caused by cell sterilization. This effect is not significant at the doses encountered in normal exposure conditions. (However, see the discussion of hot spots under Significant Volumes and Areas.)

*Unless specifically qualified, the term "dose equivalent" refers to the mean dose equivalent over the entire organ or tissue.

further restrictions either on the instantaneous rate or on the rate at which the dose equivalent may be accumulated, except in the case of occupational exposure of women of reproductive capacity and pregnant women.

TISSUES AT RISK

For the purposes of radiation protection, it is necessary to specify a number of organs and tissues that have to be considered because of their susceptibility to radiation damage, the seriousness of such damage, and the extent to which this could be treatable.

Some of the quantitative risk factors are clearly age- or sex-dependent, as for example those for the development breast cancer or for the induction of hereditary defects. In addition, the risk factors for the occurrence of malignancies are reduced in older persons because of the long latent periods involved in the development of these effects. For these reasons the total risk from an individual exposure will vary somewhat with age and with sex, although in fact the variations from the average value for all ages and both sexes are not considerable. Thus for protection purposes sufficient accuracy is obtained by using a single dose-equivalent limit for each organ or tissue for all workers regardless of age or sex. These limits, which are discussed under The System of Dose Limitation, are based on the average risk levels listed in Table 1 for the various organs or tissues. The same principle applies also for different members of the general public.

Table 1 Risk Factors for Radiation Protection Purposes

Organ or tissue	Risk factor, Sv^{-1}	Effect
Gonads	10^{-2}	Hereditary ill health within first two generations
Red bone marrow	2×10^{-3}	Leukemia mortality
Bone	5×10^{-4}	Bone cancer mortality
Lung	2×10^{-3}	Lung cancer mortality
Thyroid	5×10^{-4}	Thyroid cancer mortality
Breast	2.5×10^{-3}	Breast cancer mortality
All other tissue	5×10^{-3}	Cancer mortality
Any other single tissue	$\leq 1 \times 10^{-3}$	Cancer mortality
Uniform whole-body irradiation	10^{-2}	Cancer mortality
Uniform whole-body irradiation	4×10^{-3}	Hereditary effects within first two generations
Uniform whole-body irradiation	8×10^{-3}	Hereditary effects in all subsequent generations

The risk factors for different tissues are based on the estimated likelihood of inducing fatal malignant disease, nonstochastic changes, or substantial genetic defects expressed in liveborn descendants. It is recognized that the appropriate basis for quantifying detriment should include the evaluation of all other forms of hurt and suffering that may result from exposure. This problem is the subject of a task group report being prepared for the ICRP. It appears likely that the forms of detriment mentioned above would be regarded as the dominant components of the harm which may be caused by radiation and those on which risk factors should most appropriately be based.

Children and Fetuses

Exposure before birth or during childhood may interfere with subsequent growth and development, depending on such factors as dose and age at irradiation. Susceptibility to the induction of certain malignancies also appears to be higher during the prenatal and childhood periods than during adult life.

Tissues of Low Sensitivity

It is now established that there are various tissues, such as muscle and adipose tissue, in which the development of malignancy following irradiation seems to be very rare, as evidenced by the fact that epidemiological surveys have so far not shown excess rates of malignancy in such tissues. For these tissues. dose limitation is based on the possibility of vascular or other deleterious changes. There may also be some tissues, for example, those containing nonnucleated cells, the irradiation of which can be ignored for the purpose of radiation protection.

Other Effects

Other than the specific effects already discussed, there is no good evidence of impairment of function of organs and tissues at the levels of dose normally encountered in radiation work. The evidence for life-shortening from effects other than tumor induction is inconclusive and cannot be used quantitatively. Moreover, it seems unlikely that any major hazard from irradiation at recommended levels has been overlooked, as judged by the evidence from heavily irradiated populations, observed for periods up to 30 years.

THE SYSTEM OF DOSE LIMITATION

The ICRP recommends a system of dose limitation, the main purposes of which are to ensure (1) that no source of exposure is unjustified in relation to its benefits or those of any available alternative, (2) that any necessary exposures are kept as low as is reasonably achievable, (3) that the dose equivalents received do not exceed certain specified limits, and (4) that allowance is made for future development.

It may thus be necessary to make subjective value judgments in order to compare the relative importance of the costs imposed on human health by radiation exposure with other economic and social factors. In this respect, radiation is not unique, and the same statement could be made in respect to a number of other agents to which mankind is exposed.

Dose-Equivalent Limits: General

The total absorbed dose rate in most human tissues from natural radiation is about one-thousandth of a gray per year, but absorbed dose rates up to one-hundredth of a gray per year or more have been reported from certain limited areas of the world.

Man-made modifications of the environment and man's activities can increase the "normal" exposure to natural radiation. Examples of this include mining, flight at high altitudes, and the use of building materials containing naturally occurring radioactive nuclides. Even living within a house is often sufficient to increase radiation exposure because restricted ventilation tends to lead to an accumulation of radioactive gases and their decay products.

In radiation protection the Commission's recommended dose-equivalent limits have not been regarded as applying to, or including, the "normal" levels of natural radiation, but only as being concerned with those components of natural radiation that result from man-made activities or in special environments.

Moreover, it should be emphasized that, on the premise that the frequency of radiation effects is linearly proportional to the dose received, such harm as may be caused by natural radiation could be regarded as independent of, and simply additive to, the amount of harm that may be caused by any of the man-made practices involving radiation exposure to which the Commission's limits apply. In this sense, regional variations in natural radiation are regarded as involving a corresponding variation in detriment in the same way as, for example, regional variations in meteorological conditions or volcanic activity involve differences in the risk of harm in different areas. On this basis, there is no reason why differences in natural radiation should affect acceptable levels of man-made exposure, any more than differences in other natural risks should do.

Medical Exposures of Patients and Dose-Equivalent Limits

Medical exposure is, in general, subject to most of the ICRP's system of dose limitation, that is, unnecessary exposures should be avoided; necessary exposures should be justifiable in terms of benefits that would not otherwise have been received; and the doses actually administered should be limited to the minimum amount consistent with the medical benefit to the individual patient. The individual receiving the exposure is himself the direct recipient of the benefit resulting from the procedure. For this reason it is not appropriate to apply the quantitative values of the Commission's recommended dose-equivalent limits to medical exposures. With certain medical exposures, a very much higher level of risk may in fact be justified by the benefit derived than by the level judged by the ICRP to be appropriate for occupational exposure or for exposure of members of the public.

Dose-Equivalent Limits for Workers

The ICRP believes that for the foreseeable future a valid method for judging the acceptability of the level of risk in radiation work is by comparing this risk with that for other occupations recognized as having high standards of safety, which are generally considered to be those in which the average annual mortality due to occupational hazards does not exceed 10^{-4} (Ref. 3).

The Commission believes that the calculated rate at which fatal malignancies might be induced by occupational exposure to radiation should not in any case exceed the occupational fatality rate of industries recognized as having high standards of safety.

It should be mentioned that an accidental death appears to involve an average loss of about 30 years of life in many industries and to be associated with an approximately equal total loss of working time from industrial accidents. A fatal malignancy induced by occupational exposure to radiation would be expected to involve the loss of about 10 years of life, owing to the long latency in the development of such a condition, without appreciable associated time loss from accidents.

In many cases of occupational exposure where the Commission's system of dose limitation has been applied, the resultant annual average dose equivalent is no greater than one-tenth of the annual limit.[4] Therefore the application of a dose-equivalent limit provides much better protection for the average worker in the group than that corresponding to the limit. For example, in the case of uniform exposure of the whole body, in circumstances where the ICRP's recommendations, including the annual dose-equivalent limit of 50 mSv, have been applied, the distribution of the annual dose equivalents in large occupational groups has been shown very commonly to fit a lognormal function, with an arithmetic mean of about 5 mSv, and with very few values approaching the limit. The application of the risk factors given in Table 1 to the above mean dose indicates that the average risk in these radiation occupations is comparable with the average risk in other safe industries.

Recommended Dose-Equivalent Limits. The ICRP recommendations given in Table 2 are intended to prevent nonstochastic effects and to limit the occurrence of stochastic effects to an acceptable level. The Commission believes that nonstochastic effects will be prevented by applying a dose-equivalent limit of 0.5 Sv (50 rems) in a year to all tissues except the lens, for which the Commission recommends a limit of 0.3 Sv (30 rems) in a year, as indicated in Table 2. These limits apply irrespective of whether the tissues are exposed singly or together with other organs, and they are intended to constrain any exposure that fulfills the limitation of stochastic effects.

For stochastic effects the ICRP's recommended dose limitation is based on the principle that the risk should be equal whether the whole body is irradiated uniformly or whether there is nonuniform irradiation. This condition will be met if

$$\sum_T W_T H_T \leq H_{wb,L}$$

where W_T is a weighting factor representing the proportion of the stochastic risk resulting from the irradiation of tissue (T) to the total risk when the whole body is irradiated uniformly; H_T is the annual dose equivalent in tissue (T); and $H_{wb,L}$ is the recommended annual dose-equivalent limit for uniform irradiation of the whole body, i.e., 50 mSv (5 rems).

Table 2 Recommended Annual Dose-Equivalent Limits

Recommended limit	Application	Tissue or organ
0.5 Sv (50 rems)	Workers	All tissue except lens of eye
0.3 Sv (30 rems)	Workers	Lens of eye
50 mSv (5 rems)	Workers	Uniform irradiation of whole body
5 mSv (0.5 rem)	Individual members of the public	Whole body
50 mSv (5 rems)		Any one organ or tissue including skin and lens of eye

Table 3 Tissue Weighting Factors

Tissue	Weighting factor (W_T)
Gonads	0.25
Breast	0.15
Red bone marrow	0.12
Lung	0.12
Thyroid	0.03
Bone surfaces	0.03
Remainder	0.30

The values of W_T recommended by the ICRP are given in Table 3. The value of W_T for the remaining tissues requires further clarification. The Commission currently recommends that a value of $W_T = 0.06$ is applicable to each of the five organs or tissues of the remainder receiving the highest dose equivalents and that the exposure of all other remaining tissues can be neglected. (When the gastrointestinal tract is irradiated, the stomach, small intestine, upper large intestine, and lower large intestine are treated as four separate organs.)

Although the ICRP no longer proposes separate annual dose-equivalent limits for individual tissues and organs irradiated singly, the implied values of such limits can be obtained, if required, by dividing the dose-equivalent limit by the relevant value of W_T. Such values would be subject to the limits, based on nonstochastic effects, given in Table 2.

Occupational Exposure of Women of Reproductive Capacity. When women of reproductive capacity are occupationally exposed under the recommended limits and when this exposure is received at an approximately regular rate, it is unlikely that any embryo could receive more than 5 mSv during the first 2 months of pregnancy. Having regard to the circumstances in which such exposures could occur, the ICRP believes that this procedure will provide appropriate protection during the essential period of organogenesis.

Occupational Exposure of Pregnant Women. It is likely that any pregnancy of more than 2 months' duration would have been recognized by the woman herself or by a physician. The ICRP recommends that, when pregnancy has been diagnosed, arrangements should be made to ensure that the woman can continue to work only where it is most unlikely that the annual exposures will exceed three-tenths of the dose-equivalent limits.

Dose-Equivalent Limits for Individual Members of the Public. Radiation risks are a very minor fraction of the total number of environmental hazards to which members of the public are exposed. Thus it seems reasonable to consider the magnitude of radiation risks to the general public in the light of the public acceptance of other risks of everyday life.

An example of such risks is that of using public transport. From a review of available information related to risks regularly accepted in everyday life, it can be concluded that the level of acceptability for fatal risks to the general public is an order of magnitude lower than for occupational risks. On this basis a risk in the range of 10^{-6} to 10^{-5} per year would be likely to be acceptable to any individual member of the public.

The assumption of a total risk of the order of 10^{-2} Sv^{-1} (Table 1) would imply the restriction of the lifetime dose to the individual member of the public to a value that would correspond to 1 mSv per year of lifelong whole-body exposure. Because the application of an annual dose-equivalent limit of 5 mSv to individual members of the public is likely to result in average dose equivalents of less than 0.5 mSv, provided that the practices exposing the public are few and cause little exposure outside the critical groups, the ICRP's recommended whole-body dose-equivalent limit of 5 mSv (0.5 rem) in a year, as applied to critical groups, has been found to provide this degree of safety, and the Commission recommends its continued use under the conditions specified in *ICRP Publication 26*.

In the calculation of the dose equivalent incurred by members of the public from intake of radionuclides, account must be taken of differences in organ size or metabolic characteristics of children. Data on such differences are in the report of the task group on Reference Man *(ICRP Publication 23)*.

As with workers, an increase in the average dose to members of the public could result from any large increase in the number of sources of exposure, even though each satisfactorily met the criteria of justification and optimization and caused no exposures above the recommended limits. National and regional authorities should therefore keep under surveillance the separate contributions from all practices to the average exposure of the whole population so as to ensure that no single source or practice contributes an unjustified amount to the total exposure and that no individual receives undue exposure as a result of membership in a number of critical groups.

Exposure of Populations

In these recommendations the ICRP does not propose dose limits for populations. Instead, the Commission wishes to emphasize that each man-made contribution to population exposure has to be justified by its benefits, and that limits for individual members of the public refer to the total dose equivalent received from all sources (except as already noted). The limit for irradiation of a whole population is thus clearly seen as the total reached by a summation of minimum necessary contributions and not as a permissible total apparently available for apportionment. Thus the Commission's system of dose limitation is likely to ensure that the average dose equivalent to the population will not exceed 0.5 mSv per year.

Accidents and Emergencies

Under conditions in which accidental exposures occur, questions arise as to what remedial actions may be available to limit the subsequent dose. In such cases the hazard or social cost involved in any remedial measure must be justified by the reduction of risk that will result. Because of the great variability of the circumstances in which remedial action might be considered, it is not possible for the ICRP to recommend "intervention levels" that would be appropriate for all occasions. The setting of such levels for particular circumstances is considered to be the responsibility of the national authorities. However, with certain types of accident that are to some extent foreseeable, it may be possible to gauge, by an analysis of the costs of the accident and of remedial action, levels below which it would not be appropriate to take action. The Commission's recommended limits are set at a level that is thought to be associated with a low degree of risk; thus, unless a limit were to be exceeded by a considerable amount, the risk would still be sufficiently low as not to warrant such countermeasures as would themselves involve significant risks or undue cost. It is therefore clear that it is not obligatory to take remedial action if a dose-equivalent limit has been or might be exceeded.

GENERAL PRINCIPLES OF OPERATIONAL RADIATION PROTECTION

Responsibilities for achieving appropriate radiation protection fall on the employers, the statutory competent authorities, the manufacturers and the users of products giving rise to radiation exposure, and in some cases the exposed persons. The management of an institution must provide all the necessary facilities for the safe conduct of the operations under its control. In particular, it should designate persons with special duties for protection, such as members of radiation protection teams.

It is important to distinguish between distinct types of protection standards, i.e., basic limits (dose-equivalent limits and secondary limits), derived limits, authorized limits, and reference levels.

Limits

The *dose-equivalent limits* apply to the dose equivalent, or, where appropriate, to the committed dose equivalent, in the organs or tissues of the body of an individual or, in the case of exposure of the population, to the average of one of these quantities over a group of individuals.

Secondary limits are given for external irradiation and for internal irradiation. In the case of external irradiation of the whole body, the secondary limit applies to the maximum dose equivalent in the body at depths below 1 cm. The secondary limits for internal exposure are the annual limits of intake by inhalation or ingestion.

In practical radiation protection it is often necessary to provide limits which are associated with quantities other than dose equivalent, committed dose equivalent, or intake, and which relate, for example, to environmental conditions. When these limits are related to the basic limits by a defined model of the situation and are intended to reflect the basic limits, they are called *derived limits*. Derived limits can be set for such quantities as dose-equivalent rate in a workplace, contamination of air, contamination of surfaces, and contamination of environmental materials. The accuracy of the link between derived and basic limits depends on the realism of the model used in the derivation.

Limits laid down by a competent authority or by the management of an institution are called *authorized limits*. In general such limits should be below derived limits, although, exceptionally, they may be equal to them. Where an authorized limit exists, it will always take precedence over a derived limit.

Reference Levels

Reference levels can be established for any of the quantities determined in the course of radiation protection programs, whether or not there are limits for these quantities. A reference level is not a limit and is used to determine a course of action when the value of a quantity exceeds or is predicted to exceed the reference level. The most common forms of reference levels are recording levels, investigation levels, and intervention levels.

APPLICATION TO OCCUPATIONAL EXPOSURE

The main responsibility for the protection of workers rests with the normal chain of management in an institution possessing any radiation source that causes exposure of workers. It is necessary to identify technically competent persons to provide advice on all relevant aspects of radiation protection, both inside and outside the institution, and to provide such technical services as are needed in applying appropriate recommendations for radiation protection.

Conditions of Work

For the purposes of this article, occupational exposure comprises all the dose equivalents and intakes incurred by a worker during periods of work (excluding those due to medical and natural radiation). The scale and form of the problems of radiation protection of workers vary over very wide ranges, and there are practical advantages in introducing a system of classification of conditions of work. Conditions of work can be divided into two classes:

1. *Working Condition A*. This describes conditions where the annual exposures might exceed three-tenths of the dose-equivalent limits.
2. *Working Condition B*. This describes conditions where it is most unlikely that the annual exposures will exceed three-tenths of the dose-equivalent limits.

The value of three-tenths of the basic limits for occupational exposure is thus a reference level used in the organization of protection; it is not a limit.

The main aim of the definition of Working Condition A is to ensure that workers who might otherwise reach or exceed the dose-equivalent limits are subject to individual monitoring so that their exposures can be restricted if necessary. In Working Condition B, individual monitoring is not necessary, although it may sometimes be carried out as a method of confirmation that conditions are satisfactory.

The practical application of this system of classification of working conditions is greatly simplified by introducing a corresponding system of classification of workplaces. The minimum requirement is to define controlled areas where continued operation would give rise to Working Condition A and to which access is limited.

It is sometimes convenient to specify a further class of workplace. It is called a "supervised area" and has a boundary chosen so as to make it most unlikely that the annual dose equivalents outside the supervised area will exceed one-tenth of the limits.

There is no simple parallelism between the classification of areas and the classification of working conditions, because the classification of areas takes no account of the time spent by workers in the area during the course of the year and because conditions are rarely uniform throughout an area.

Individual workers are usually classified to simplify the arrangements for medical supervision and for individual monitoring. In principle, this can be done in terms of the class of working conditions in which they operate, but in practice it almost always must be done in terms of the areas where they work, the type of work done, and the time to be spent in the area, if this can be forecast with sufficient reliability.

Provisions for Restricting Exposure

As far as is reasonably practicable, the arrangements for restricting occupational exposure should be those applied to the source of radiation and to features of the workplace. In general, the use of personal protective equipment should be supplementary to these more fundamental provisions. The emphasis should thus be on intrinsic safety in the workplace and only secondarily on protection that depends on the worker's own actions.

Since there is no ICRP recommendation on individual monitoring in Working Condition B (i.e., where it is most unlikely that the exposure will exceed three-tenths of the appropriate dose equivalent, secondary or derived limits), it is often appropriate to use this figure of three-tenths in setting investigation levels for individual monitoring. However, for an investigation level to be useful, it should be set in relation to a single measurement, not the accumulated dose equivalent or intake in a year. In addition, the investigation level should be based on the fraction of three-tenths of the limit corresponding to the fraction of a year to which the individual monitoring measurement refers. The monitoring is associated with a single event, although not necessarily a unique one, and the choice of an investigation level depends on the expectation of the number of occasions on which similar events will occur during the year. In *ICRP Publication 10* the ICRP recommends that the investigation level should correspond to one-twentieth of the annual dose-equivalent limits, if it is assumed that events requiring a program of special monitoring may occur in relation to a single individual about six times in a year.

Although investigation levels are suitable for initiating investigations into specific situations, it may be convenient to record dose equivalents at somewhat lower levels. The ICRP recommends that the recording levels should be based on an annual dose equivalent or intake of one-tenth of the annual dose-equivalent limit or intake limit.

For the special case of monitoring of skin, two situations occur in routine practice. In one situation, for external radiation, a dose equivalent is measured by one or two dosimeters, and the results are treated as representative of the whole skin or of substantial areas of the skin. No problem of averaging then arises, and the results are related directly to the relevant dose-equivalent limit. In the other situation the irradiation results from surface contamination on the skin. Surface contamination is never uniform and occurs preferentially on certain parts of the body, chiefly the hands. However, surface skin contamination does not persist over many weeks and does not always occur again at exactly the same places. For routine purposes it is adequate to regard the contamination as being averaged over areas of about 100 cm^2. Routine monitoring for skin contamination should therefore be interpreted on this basis and the limit applied to the average dose equivalent over 100 cm^2.

In accidents or suspected accidents, more detailed information should be sought on the distribution of absorbed dose, dose equivalent, or contamination. An estimate should be made of the average dose equivalent over 1 cm^2 in the region of the highest dose equivalent. This dose equivalent should then be compared with the dose-equivalent limit. If the dose distribution is extremely nonuniform, as is that from very small particles in contact with the skin, the local distribution of absorbed dose should be assessed and used to predict possible local skin reactions. It is inappropriate, however, to relate such localized absorbed doses to the absorbed doses corresponding to the dose-equivalent limit.

Medical Surveillance

The medical surveillance of workers exposed to radiation is based on the general principles of occupational medicine. The aims are (1) to assess the health of the worker, (2) to help in ensuring initial and continuing compatibility between the health of the workers and the conditions of their work, and (3) to provide a baseline of information useful in the case of accidental exposure or occupational disease.

Workers designated as operating in Working Condition A should be given a preoperational medical examination before starting this kind of work.

Following a preoperational examination, consideration should be given to the need for a continuing surveillance of the health of workers.

The ICRP considers that, with the present dose-equivalent limits, no special administrative arrangement is appropriate for workers as far as radiation risks are concerned. In particular, no special arrangement is required with respect to working hours and length of vacation.

Intervention in Abnormal Situations

Arrangements should be made for dealing with abnormal situations, not only with respect to their detection and the assessment of dose or intake but also with respect to the form of intervention that may have to be applied. The intervention levels and the appropriate actions for limiting exposure should be the subject of operating instructions. Provision should be made for special medical surveillance and, if necessary, treatment following exposure substantially in excess of the dose-equivalent limits.

APPLICATION TO OTHER EXPOSURES

The various contributions to other exposures may be grouped into broad categories to which the general principles of protection may apply but which call for different technical approaches. These categories are (1) exposure due to the dispersion in the environment of radioactive materials; (2) direct exposure to radiation sources used in industry, medicine, and research; (3) exposure resulting from the use in everyday life of widely distributed products containing sources of ionizing radiation; (4) exposure to natural sources of radiation and to practices in everyday life that cause an increase in the level of dose resulting from the natural background of radiation; and (5) exposure due to the use of radiation sources in teaching.

Assessment of Exposures

Application of the system of dose limitation to any practice involving such exposures requires assessment of both the individual dose equivalents and the collective dose equivalents. For the purpose of comparing individual dose equivalents with the appropriate limits, the doses from the normal natural radiation background are not included.

The dose equivalent to a specified organ or tissue in a given population group will usually be determined on the basis of a representative sample. The spread of the observed values will be an indication of the homogeneity of the sample, and thus of the group, and will provide a statistical basis for judging whether the group has been suitably defined.

It is often possible to identify population groups with characteristics causing them to be exposed at a higher level than the rest of the exposed population from a given practice. The exposure of these groups, known as critical groups, can then be used as a measure of the upper limit of the individual doses resulting from the proposed practice.

In some cases it is also useful to assess the dose-equivalent commitment or the collective dose-equivalent commitment.

These assessments require the use of models of various degrees of complexity, representing the movement of radioactive materials through the environment from the source to man. These models have to take into account the nature and the physical and chemical forms of the radioactive materials, together with their methods of release. The models then have to reflect the characteristics of the environment and of man which influence the consequent exposure of individuals and groups. To make such models detailed and realistic requires extremely complex studies involving a considerable effort, and it is reasonable in practice to adjust the magnitude of this effort to the importance of the particular problem.*

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*This topic is discussed in detail in a report being prepared by ICRP Committee 4.

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Preliminary Dose and Health Impact of the Accident at the Three Mile Island Nuclear Station

The Ad Hoc Population Dose Assessment Group

Nucl. Safety, 20(**5**): 591–594 (September–October 1979)

[Editor's Note: The Ad Hoc Population Dose Assessment Group is composed of members of the Nuclear Regulatory Commission, the Department of Health, Education, and Welfare, and the Environmental Protection Agency. This group has examined the available data for the period following the accident and has concluded that the off-site collective dose associated with the radioactive material represents minimal risks of additional health effects to the off-site population, e.g., an increase of 1 cancer death over the 325,000 which would otherwise be expected. Furthermore, the collective dose will not be significantly increased by extending the period past April 7. The 100-page report of the Ad Hoc Group, dated May 10, 1979, is on sale by the Superintendent of Documents, U. S. Government Printing Office, Washington, D. C. 20402, Stock Number 017-001-00408-1. Presented here is the summary and discussion of findings from that report.]

An interagency team from the Nuclear Regulatory Commission (NRC), the Department of Health, Education, and Welfare, and the Environmental Protection Agency has estimated the collective radiation dose received by the approximately 2 million people residing within 50 miles of the Three Mile Island Nuclear Station resulting from the accident of March 28, 1979. The estimates are for the period from March 28 through April 7, 1979, during which releases occurred that resulted in exposure to the off-site population. The principal dose estimate is based on ground-level radiation measurements from thermoluminescent dosimeters located within 15 miles of the site. These estimates assume that the accumulated exposure recorded by the dosimeters was from gamma radiation (i.e., penetrating radiation that contributes dose to the internal body organs). The data were obtained from dosimeters placed by Metropolitan Edison Company before the accident (as part of their normal environmental surveillance program), from dosimeters placed by Metropolitan Edison after the accident and covering the period to April 6, and from dosimeters placed by NRC from noon of March 31 through the afternoon of April 7, 1979. These measurement programs are continuing. The results for the period beyond April 7, 1979, have not been fully examined. An additional dose estimate developed by the Department of Energy (DOE) using aerial monitoring that commenced about 4 p.m. on March 28, 1979, is also included. A variety of other data helpful in assessing relatively minor components of collective dose was also reviewed.

The collective dose to the total population within a 50-mile radius of the plant has been estimated to be 3300 person-rems. This is an average of four separate estimates that are 1600, 2800, 3300, and 5300 person-rems. The range of the collective dose values is due to different methods of extrapolating from the limited number of dosimeter measurements. An estimate provided by DOE (2000 person-rems) also falls within this range. The average dose to an individual in this population is 1.5 mrems (using the 3300 person-rems average value).

The projected number of excess fatal cancers due to the accident that could occur over the remaining lifetime of the population within 50 miles is approximately one. Had the accident not occurred, the number of fatal cancers that would be normally expected in a population of this size over its remaining lifetime is estimated to be 325,000. The projected total number of excess health effects, including all cases of cancer (fatal and nonfatal) and genetic ill health to all future generations, is approximately two.

These health-effects estimates were derived from central risk estimates within the ranges presented in the 1972 report of the Advisory Committee on the Biological Effects of Ionizing Radiation (BEIR) of the National Academy of Sciences. Preliminary information on the recently updated version of this report indicates that these estimates will not be significantly changed.

It should be noted that there exist a few members of the scientific community who believe the risk factors may be as much as 2 to 10 times greater than the estimates of the 1972 BEIR report. There also is a minority of the scientific community who believe that the estimates in the 1972 BEIR report are 2 to 10 times larger than they should be for low doses of gamma and beta radiation.

The maximum dose that an individual located off site in a populated area might receive is less than 100 mrems. This estimate is based on the cumulative dose (83 mrems) recorded by an off-site dosimeter at 0.5 mile east-northeast of the site and assumes that the individual remained outdoors at that location for the entire period from March 28 through April 7. The estimated dose applies only to individuals in the immediate vicinity of the dosimeter site. The potential risk of fatal cancer to an individual receiving a dose of 100 mrems is about 1 in 50,000. This should be compared to the normal risk to that individual of fatal cancer from all causes of about 1 in 7.

An individual was identified who had been on an island (Hill Island) 1.1 miles north-northwest of the site during a part of the period of higher exposure. The best estimate of the dose to this individual for the 10-h period he was on Hill Island (March 28 and March 29) is 37 mrems.

A number of questions concerning this analysis are posed and briefly answered below. More detailed discussions are included in the body of the report.

What radionuclides were in the environment?

The principal radionuclides released to the environment were the radioactive xenons and some ^{131}I. Measurements made by DOE in the environment, measurement of the contents of the waste gas tanks, of the gases in the containment building, and the actual gas released to the environment confirmed that the principal radionuclide released was ^{133}Xe. Xenon-133 is a noble gas (which is chemically nonreactive) and does not persist in the environment after it disperses in the air. It has a short half-life of 5.3 days and produces both gamma and beta radiation. The risk to people from ^{133}Xe is primarily from external exposure to the gamma radiation, which penetrates the body and exposes the internal organs.

What were the highest radiation exposures measured outside the plant buildings?

Some of the Metropolitan Edison dosimeters located on or near the Three Mile Island Nuclear Station site during the first day of the accident recorded net cumulative doses as high as 1020 mrems. These recorded exposure readings do not apply directly to individuals located off site. However, the on-site dosimeter readings were included in the procedure for projecting doses to the off-site population. This procedure is described in the report.

What is meant by collective dose (person-rem)?

The collective dose is a measure of the total radiation dose which was received by the entire population within a 50-mile radius of the Three Mile Island site. It is obtained by multiplying the number of people in a given area by the dose estimated for that area and adding all these contributions.

Were the radiation measurements adequate to determine population health effects?

The extensive environmental monitoring and food sampling were adequate to characterize the nature of the radionuclides released and the concentrations of radionuclides in those media. The measurements performed by DOE (aerial survey) and Metropolitan Edison and NRC (ground-level dosimeters) are sufficient to characterize the magnitude of the collective dose and therefore the long-term health effects. However, a single precise value for the collective dose cannot be assigned because of the limited number of fixed ground-level dosimeters deployed during the accident.

How conservative were the collective dose estimates?

In projecting the collective dose from the thermoluminescent dosimeter exposures, several simplifying assumptions were made that ignored factors that are known to reduce exposure. In each case, these assumptions introduced significant overestimates of actual doses to the population. This was done to ensure that the estimates erred on the high side. The three main factors that fall into this category are:

1. No reduction was made to account for shielding by buildings when people remained indoors.

2. No reduction was made to account for the population known to have relocated from areas close to the nuclear power-plant site as recommended by the governor of Pennsylvania, or who otherwise left the area.

3. No reduction was made to account for the fact that the actual dose absorbed by the internal body organs is less than the dose assumed using the net dosimeter exposure.

What is the contribution of beta radiation to the total dose?

Beta radiation contributes to radiation dose by inhalation and skin absorption. The total beta plus gamma radiation dose to the skin from ^{133}Xe is estimated to be about 4 times the dose to the internal body organs from gamma radiation. This additional skin dose could result in a small increase in the total potential health effects (about 0.2 health effect) due to skin cancer. The increase in total fatal cancers over that estimated for external exposure from gamma radiation alone would be about 0.01 fatal skin cancer. This contribution would be considerably decreased by clothing. The dose to the lungs from inhalation of ^{133}Xe for both beta and gamma radiation increases the dose to the lungs by 6% over that received by external exposure.

What radionuclides were found in milk and food and what are their significance?

Iodine-131 was detected in milk samples during the period March 31 through April 4. The maximum concentration measured in milk (41 pCi/liter in goat's milk, 36 pCi/liter in cow's milk) was 300 times lower than the level at which the Food and Drug Administration (FDA) would recommend that cows be removed from contaminated pasture. Cesium-137 was also detected in milk, but at concentrations expected from residual fallout from previous atmospheric weapons testing. No reactor-produced radioactivity has been found in any of the 377 food samples collected between March 29 and April 30 by the FDA.

Why have the estimates of radiation dose changed?

The original Ad Hoc Group estimate of collective dose (1800 person-rems) presented on April 4 at the hearings before the Senate Subcommittee on Health and Scientific Research covered the period from March 28 through April 2. The data used for this estimate were obtained from preliminary results for Metropolitan Edison off-site dosimeters for the period March 28 through March 31 and preliminary results for NRC dosimeters for April 1 and 2. On April 10 the estimate of 2500 person-rems presented to the Senate Subcommittee on Nuclear Regulation by NRC Chairman Hendrie included the time period from March 28 through April 7. The data base for this estimate included additional NRC dosimetry results for April 3 through 7. The Ad Hoc Group's preliminary report of April 15 stated a value of 3500 person-rems for the time period from March 28 through April 7. This value resulted from better information on the dosimeter measurements and an improved procedure for analyzing the measurements.

The current report states an average value of 3300 person-rems (with a range of 1600 to 5300 person-rems) for the time period from March 28 through April 7. Additional dosimeter data were available and better methods were used to determine the collective dose. Also, the on-site dosimeter measurements are all included in the analysis.

The original estimate of maximum dose (80 mrems) to an individual presented on April 4 increased to 85 mrems in the April 15 preliminary report as a consequence of adding the contribution from April 2 to April 7. This estimate has now been revised slightly to 83 mrems, which is presented as less than 100 mrems so as not to imply more precision than this estimate warrants. New information on dosimeter readings on or very near the site was received after the initial analysis. It was also learned that an individual was present on one of the nearby islands (Hill Island) for a total of 10 h during the period March 28 to March 29. The best estimate of the dose that may have been received by the individual is 37 mrems. The text includes a range of dose estimates for that individual.

Will these estimates of dose change again?

The dose and health effects estimates contained in this report are based on the dosimeter results for the period March 28 to April 7, 1979. There still remain some questions concerning interpretation of the dosimeter results. For example, the best values for subtracting background from the NRC dosimeters have not been determined. Recently available data from additional dosimeters exposed during the March 28 to April 7 period have been reviewed briefly but could not be included in the calculations in time for this report. The actual contribution to collective dose from the period after April 7, if any, has not been fully assessed. Therefore the numerical dose values may be subject to some modification.

The Ad Hoc Group feels that these factors represent only minor corrections to the present estimates. In any case, none of the above refinements should cause an increase in any of the current estimates that would alter the basic conclusion regarding the health impact due to the Three Mile Island accident.

Effects of Low-Level Radiation: A Critical Review

V. E. Archer*

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[Editor's Note: In view of the continuing controversy concerning the biological effects of low-level radiation, the editors asked Dr. Archer to summarize the literature in the field. If the extensive data on mammals taken at high doses and dose rates are extrapolated linearly to dose rates near background levels, the effects are so small as to make statistically meaningful experiments impossible. If, however, low doses are much more effective on a per rem basis, then low-dose effects may be observable. Dr. Archer is of the opinion that he and other investigators have probably observed such effects. Although we have reservations about the validity of that conclusion, we are pleased to publish this comprehensive survey of the literature.]

Abstract: *Both negative and positive reports on the effects on man of low-dose and protracted radiation exposures are reviewed. Such effects are observable only in large populations by epidemiological techniques. Although not conclusive, there is considerable evidence to support the hypothesis that background radiation and artificial radiation in comparable doses probably have detectable effects on man. Certainly this is the prudent conclusion to reach. This [illegible] that nuclear power should be assessed on the basis of ri[illegible]nefit. The same type of assessment should be applied to nonnuclear power sources.*

Public opposition to the siting of nuclear power plants has become an important issue. Such opposition is based in part on a fear that environmental release of radionuclides would lead to cancer and genetic damage in the surrounding population. Is that fear justified? Does it reflect a nebulous fear of a new and unfamiliar hazard, or does it reflect a lack of faith in public officials who state that such facilities are safe? It probably reflects a little of both.

This review relates only to the effects of low-level radiation which might be associated with the normal operation of nuclear facilities, not to the possibility of sabotage, theft, or accidental release of radioactive material.

There is no question that ionizing radiation in sufficient dosage can cause a variety of somatic and genetic effects.[1-5] Many of these same effects are thought to also occur following low-level (below current exposure standards and near background) exposures.[6-8] The principal difference postulated is that, at low levels, the frequency of the effect is so low that it cannot easily be differentiated from normal disease.[8] It is impractical to use a sufficient number of experimental animals for such testing. However, sufficient numbers of people have been exposed at different levels of radiation so that sensitive epidemiological techniques might reveal effects.

Most types of injury which might be caused by low levels of ionizing radiation involve the genetic apparatus of cells.[9] Such injury to somatic cells may result in a variety of malignant diseases (leukemia, carcinoma, or sarcoma of any organ); to germ cells it may result in harmful mutations (congenital malformations and increased neonatal or fetal mortality). One characteristic of such injury to man is the long time between the occurrence of the injury and its manifestation. Induced dominant mutations may be seen in the first generation (but they are rare); the more common recessive mutations may not be evident for many generations; induced cancers may not appear for years or decades.[8] In chronic exposures the lower the exposure rate, the longer is this latent period.[10] Such time delays pose a difficult problem for epidemiology. They may also contribute a false sense of security because negative results are certain to be obtained when studies of exposed populations are made within 10 or 15 years after initiation of exposure. Two approaches—evaluation of chromosome aberrations[11] and watching infant mortality[12,13]—have been proposed as sensitive methods of circumventing the characteristically long latent periods. Their value for this purpose, however, has not yet been proven.

This review does not include results from high exposure studies, since they have been adequately reviewed elsewhere.[1-8] Those studies which sought to observe effects at low levels of exposure are reviewed below by groups.

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STUDIES RELATED TO HANFORD NUCLEAR FACILITIES

A series of analyses have been done on the mortality of employees of the Hanford nuclear installation at Richland, Wash., or nearby residents.[14-25] The first suggested that there were excess deaths downstream on the Columbia River.[14] Another, using superior methods, found that suggestion to be false.[15] Milham,[16] using the crude method of examining death certificates in which Hanford was recorded as the workplace, reported an excess of cancers of the pancreas, lung, bone, and colon. This finding demanded further study. Several studies followed, all of which used proportional mortality methods.[17-23] They were based on deaths at the plant between 1949 and 1971. The earliest study used 841 death certificates, the number increasing to 3365 in the latest study. These studies tended to confirm an excess of deaths due to cancer of reticuloendothelial tissue and the pancreas and hinted that the excess might be associated with increased radiation exposure. The more sophisticated techniques of case-control studies and life table analysis were then used in attempts to determine the relation between radiation exposure and mortality resulting from cancer of those sites where an excess had been observed.[21-25] All of these studies noted a statistically significant association between external radiation and both cancer of the pancreas and multiple myeloma. In addition, one of the case-control studies reported an association between radiation exposure and neoplasms of the lung, pancreas reticuloendothelial system, and all cancers.[21] From this data, doubling doses varying from 0.8 to 6.1 rads were calculated for neoplasms of different sites. A life table analysis that used a regression model calculated the doubling dose as between 15 and 30 rads.[24]

The more sophisticated of these studies have tried to control for, or evaluate, a number of complicating variables such as the age of the individuals or the age at, and time period of, exposure. However, few have been able to adequately assess or control the healthy-worker effect,[26] the influence of cigarette smoking, or other potential carcinogens in the workplace such as solvents or inhaled radioactive materials, medical radiation, radiation received before starting work at Hanford, the fact that cumulative radiation exposure tends to increase with length of employment regardless of cause of death, or the induction–latent period characteristic of radiation-induced cancer. The comparison groups, however, can probably be considered sufficient control for some of these factors.

It is likely that internal radiation, radiation received prior to Hanford work, and unmeasured radiation (such as neutrons) would be correlated with measured external gamma radiation because of the types of skills and activities involved. Such extra radiation would enhance the observed relation between exposure and certain cancers, and it would artificially decrease the doubling doses as calculated by Mancuso et al.[21,22] There is no reason to think that exposure to chemical carcinogens would be greatest among those with highest radiation exposure. The failure to consider the induction–latent period characteristic resulted in a loss of sensitivity in some of the analyses.

Although the results of these different analyses did not differ greatly, the conclusions drawn by the different investigators have been greatly at variance. One group contends that the findings are due to chance or to nonradiation factors (Refs. 17-20, 23, and 25); the other that radiation is almost certainly responsible.[21,22] The latter group has clearly used the more sensitive approach (the case-control study of Gilbert[23] lost sensitivity by matching on job category, which is associated with increased radiation exposure). Criticisms of the statistical techniques initially used by Mancuso et al.[27,28] have some merit but do not completely invalidate the findings.[24,29,30]

The two strongest arguments against regarding the findings as radiation effects are that leukemia has been thought to be the premier manifestation of late radiation injury and that the calculated doubling dose for cancers (0.8 to 6.1 rads) appeared unreasonable since the average exposure received by all people from background radiation is between 3 and 4 rads during the first 30 years of life.[31] This latter observation suggests that the minimum doubling dose for any cancer in adults would be 3 rads or greater. The argument related to leukemia is probably not valid, since multiple myeloma, rather than leukemia, was the principal type of malignant disease that increased among radiologists who started practice between 1940 and 1949 (Ref. 32). Their exposure was similar to that of the Hanford workers—relatively small doses spread over many years. Excess deaths from cancer of the pancreas could not have been predicted from the results of other studies, but they have been found to be associated with radiation. If background radiation causes a substantial fraction of cancer of many sites as suggested recently,[33] then doubling doses between 6 and 30 rads, as indicated by the most recent report,[24] would be reasonable.

OTHER STUDIES RELATED TO NUCLEAR FACILITIES

Several studies examined infant and neonatal mortality rates. Tompkins et al.[12] used quadrants of concentric bands about three nuclear plants to permit consideration of prevailing wind direction. Neonatal mortality rates were determined in 5-year groups. No association was found between operation of the facility and the mortality data. DeGroot[34] sought a relation between annual infant mortality by counties and effluent releases from four nuclear reactors using regression analysis. No association was found between the mortality and the effluent releases. Sternglass,[13] by selecting data from certain years and locations, claimed to demonstrate increased infant mortality in counties or states near nuclear plants. His conclusions, however, are doubtful, since, in addition to his selectivity, he failed to take into account normal statistical fluctuations, demographic variables, growth rates of developing areas, or local trends in infant mortality. Grahn[35] examined cancer mortality in eight counties surrounding a nuclear plant. He considered socioeconomic and demographic changes since 1950 and compared mortality for 10 years before and 9 years after the plant started operating. No associations between cancer mortality and the plant were found. Tokuhata et al.[36] compared death rates for leukemia, other neoplasms, and fetal and infant mortality rates in communities near a nuclear power plant with those in more distant ones. They found no associations between the mortality rates and the nuclear plant. Because of the many factors influencing fetal mortality, it is probably an insensitive indicator of radiation effect in man. Malignant-disease mortality associations in those studies were not only done in an insensitive manner, but were probably premature because of the prolonged latent period for radiation-induced cancer.

There have been four reports on mortality at Oak Ridge, Tenn.[37-40] Moshman and Holland[37] calculated age-standardized cancer-incidence rates that were generally lower than expected, presumably because most residents of Oak Ridge were immigrants who had been selected because they were young, healthy, and had specified skills (healthy-worker effect). Larson et al.[38] calculated expected deaths in three nuclear plants from 1950 to 1965 and compared them to observed deaths. Again, observed deaths were considerably lower than the expected deaths. Scott et al.[39] compared the mortality of those who worked with uranium at Oak Ridge National Laboratory and those who did not. They compared mortality in the two groups from 1941 to 1969 and found that both groups had lower than expected mortality but that the uranium workers had a lower mortality than did the non-uranium workers. It is not clear that those who work with uranium had the higher radiation exposures, although there were more clerical workers in the non-uranium group. Patrick[40] compared expected deaths with various specific age-adjusted causes of deaths occurring in the city of Oak Ridge and the two counties in which the nuclear facilities are located for the 1950 to 1969 period, using two approaches. The first compared mortality for the 14 years prior to establishment of the facility with mortality for the subsequent 29-year period. Several defects in this trend analysis were noted, but no significant differences in mortality trends were found between these three areas and the state of Tennessee. In the second approach, age-adjusted mortality for all cancer and for selected sites for the period 1950 to 1969 was compared to the expected rates for the two counties. The sexes and two racial groupings were analyzed separately. With the exception of leukemia and lung cancer among black females, there were no statistically significant differences between the observed mortality rates and the expected mortality rates in these two counties for total cancer, for leukemia, or for cancer of the lung, bone, or thyroid. The two significant findings were based on only two cases for each of the two cancer sites. It is not known whether these four individuals worked at the nuclear plants.

These four studies are best noted for the insensitive methods employed. Large groups of unexposed persons or recently hired individuals were included with exposed persons when comparisons were made. In some, the healthy-worker effect was ignored. In all but the study by Patrick, there was no attempt to look at specific causes of death. In only one of them was consideration given to the latent period; i.e., the deaths for the years when no excess cancers from radiation could be expected were combined with the deaths for later years when some might be expected.

Voelz et al.[41] compared the expected rates for cancer of selected sites with those observed for white males in Los Alamos County, most of whose residents are associated with the nuclear facility. There was a possible excess of malignant disease of the lymphatic and hematopoietic tissues and of the digestive tract. The radiation exposures of those individuals with malignant disease were not known. This situation is being studied further.

Two studies attempted to determine whether the uranium mill tailings used as fill under dwellings in Grand Junction, Colo., were having an effect on mortality there. Mason et al.[42] compared age-adjusted cancer mortality rates among whites for all cancer and for leukemia and lung cancer for the 1951 to 1967 period and compared the findings to Colorado rates. No excesses were noted. In the second study, Cunningham[43] used a case-control method and investigated the observation that leukemia in Mesa County, Colo. (Grand Junction is the county seat of Mesa County) had increased since the study by Mason et al. was made. He confirmed that the leukemia rate had increased since 1970, but he found no excess of leukemia cases associated with houses built on uranium mill tailings. Najarian and Colton,[44] in a preliminary study of death certificates of men who had worked at a naval shipyard where nuclear submarines were serviced, reported an excess of leukemia. However, this study has been criticized on the grounds of incomplete death data, internal inconsistency, and a failure to quantitate radiation exposure.[45] This situation is being studied further, using both case-control and cohort approaches.[46]

STUDIES OF THE EFFECTS OF BACKGROUND RADIATION ON MAN

Laboratory studies of the effects of very low levels of radiation have encountered a difficult problem: as the exposure rate and the total dose are decreased, larger and larger numbers of animals must be followed for longer and longer periods in order to detect the small effects. Predictably, such experiments at or near background radiation levels have been impractical. However, human populations that have been exposed to differing levels of background radiation may be found which satisfy both the criteria of size and of long-term observation. Such populations have their defects in that they may have uncontrolled exposure to mutagens and carcinogens other than background radiation and many have substantial mobility; but, nevertheless, they have a great potential for the exploration of radiation effects at very low levels. A number of such studies have been done, with about half yielding positive results. The negative ones will be considered first.

Bugher and Mead[47] found no relation between the frequency of bone sarcoma in the United States and their estimates of radiation exposure. An association between leukemia mortality and different measures of background radiation was sought without success by several authors.[48-55] Mason and Miller[53] sought, but failed to find, an association between the rates of all cancer (in addition to leukemia) and their estimate of background radiation based on altitude above sea level. Frigerio and Stowe,[54] used a multiple-correlation technique with groups of malignancies and 40 variables, including background radiation. They found no association with radiation. Grahn and Kratchman[56] found no association between all neonatal deaths and environmental radiation. George et al.,[57] Gopal-Ayengar et al.,[58] Freire-Maia and Krieger,[59] and Gianferrari et al.[60] found no association between possible effects and radiation exposure among populations living in high-background areas of India, Brazil, and Italy, respectively.

Leukemia, total mortality, and total cancer rates were unfortunate choices for seeking such an association. Leukemia was found to have a marked variability and to have an inverse association with aplastic anemia.[61] Its rates are highest in the industrialized nations, suggesting that much leukemia may be due to chemical agents. In addition, Archer[33] found that neither leukemia nor total cancer rates conformed nearly as well to estimated background radiation patterns as did cancer of some other sites. The many variables used by Frigerio and Stowe,[54] which could not be properly evaluated for each variation in radiation exposure, would seem to be an unusually insensitive method. Some of these studies used quantitative estimates of background radiation for each of the states in the United States. These estimates were probably misleading because they minimized the role of high linear-energy-transfer (LET) radiation. They failed to consider that low doses and protraction of high LET radiation probably enhance carcinogenic potency substantially. This point is discussed below. There are apparently too many other carcinogenic agents that contribute heavily to leukemia and total cancer patterns to expect anything but negative results from the above studies.

The study of all neonatal deaths combined, as Grahn and Kratchman[56] and others[34-36,40] have done, is another very insensitive approach, since it is likely that background radiation is associated with only a limited number of neonatal deaths, which comprise only a small proportion of the total number of neonatal deaths.[62-65] The failure of Gopal-Ayengar et al.,[58] Freire-Maia and Krieger,[59] and Gianferrari et al.[60] to find an association between any of their birth-associated parameters and background radiation, when others were able to do so,[62-65] is more likely due to inadequate methodology than to an absence of effect. Probably their most serious problem was in assessing exposure. When the population is mobile, an estimate of cumulative lifetime exposure for parents is likely to be much more important than an estimate of current exposure. Other problems may have been inadequate birth records, inadequate population size, and insensitive measuring parameters such as sex ratio, total congenital anomalies, or total neonatal deaths.

Studies that reported positive association between background radiation and an observable effect are of varying quality and cover several different effects. Kochupillai et al.[64] reported an elevated rate of Down's syndrome and related congenital abnormalities among a population living on thorium sands. Barcinski et al.,[65] Gopal-Ayengar et al.,[66] Kochupillai et al.,[64] and Verma et al.[67] reported increased chromosome aberrations in cultured lymphocytes among human populations or in plants living on thorium sands. Pincet[68] reported a correlation between human mortality due to tumors and natural radioactivity in food and water. Gentry et al.[69] reported an association between the incidence of congenital malformations and geologic formations ranked by their estimated content of radioactive material. Plewa et al.[70] reported a correlation between levels of background radiation and leukemia in Poland. Novak et al.[71] found an association between the incidence of malignant tumors and area measurements of gamma radiation in a Yugoslavian province. Wesley[62] noted a correlation between the incidence of fatal congenital malformations and horizontal geomagnetic flux (HGF).

Since the HGF tends to divert charged particles (primary cosmic radiation) away from the geomagnetic equator toward the geomagnetic poles, where the HGF is weakest, it may be regarded as a surrogate measure of cosmic radiation. Elwood,[72] in a multiple-correlation study, noted strong correlations between both latitude and longitude and the rate of anencephaly in Canadian cities. Archer[63] reanalyzed his data, showing that the primary correlation was probably with HGF and cosmic radiation. Archer[33] also showed a correlation between the cancer rate for a number of organs and HGF. He divided malignancy of various cancer sites into conforming and nonconforming sites. Cancer of the kidney throughout the world was shown to have a strong association with HGF.[33] Since cosmic radiation had been carefully measured at several sites in the United States, Archer calculated total background radiation and showed a strong correlation with the rates for cancer of the kidney and breast, averaged from six adjacent counties. Mortality from congenital abnormalities was similarly associated.[33] Since cosmic radiation increases with altitude above sea level, Archer compared the rates for cancer of several sites in Colorado (the highest state) with the average rate for 10 other states which have about the same HGF but are at lower elevations. The rates for cancer of conforming sites were significantly higher in Colorado than in the other 10 states.[33] Because variations in the gamma component did not seem to be large enough to account for the biological differences noted, Archer postulated that the high LET component (neutrons, pions, and alpha particles) of background radiation might be the most important factor in inducing cancer and congenital anomalies. The reasoning was (1) the efficiency of gamma radiation in inducing effects such as mutations and cancer declines with decreasing dose, whereas the efficiency of high LET radiation does not decrease and may increase at low doses and dose rates[73-75] and (2) the high LET component changes more with geomagnetic latitude than does the low LET component.[76] Since the cosmic-ray component is not the largest component of background radiation and its variation with HGF and latitude is not very great, Archer estimated that a majority of the cancers of conforming sites would have to be caused by background radiation for this effect to be apparent.[33]

Axelson and Edling[77] reported a preliminary case-control study in which persons living in rural stone or brick houses with basements were found to have a higher rate of lung cancer than persons living in wood houses without basements. The difference was attributed to the fact that lower levels of radon were found in the wood houses. Cigarette smoking was not fully investigated, but there was no reason to think that smoking patterns were associated with the type of dwelling. Ujeno[78] found an association between measured background radiation and stomach cancer as well as total cancer in Japan, but not with cancer of the lung, pancreas, large bowel, breast, or uterus. However, he was unable to consider age differences, migration, standards of medical care, or urban–rural differences.

The above studies that found an association between background radiation and a biological effect can be criticized for not having considered all relevant factors. Epidemiological studies rarely can. For instance, the reports on chromosome studies, congenital anomalies, and cancer rates did not consider possible differences in exposure to medical X rays or socioeconomic differences between populations. Gentry used a rather poor index of background radiation; Plewa, Gentry, and Novak used rather insensitive indicators of radiation injury. For the associations of congenital anomalies and cancer deaths with HGF found by Wesley and Archer, it should be noted that there are a number of other environmental factors that also vary in the north–south direction. Mean annual temperature, for instance, varies similarly and was shown by Lea[79] to have a similar correlation with breast cancer. In view of the many uncontrolled variables, which are likely to confuse things and result in negative rather than positive findings, as well as the relatively small differences in radiation exposure, it is surprising that so many of these studies had positive results.

STUDIES OF THE EFFECTS OF DIAGNOSTIC X RAY ON MAN

Because of the relatively large radiation doses involved, it is not surprising that increased rates of malignant disease were found among patients who had received therapeutic doses of X rays[80,81] and among radiologists.[32] However, radiation doses from diagnostic X-ray procedures are much lower, on the order of 0.05 to 5 rads. The relation of these doses to background radiation may be seen by comparing them to the estimate that the average person would receive about 100 mrems from background radiation per year, or about 7 rems during his lifetime.

Increased rates of cancer and leukemia were found among children who received radiation in utero when their mothers had diagnostic X rays for obstetrical reasons.[82] Stewart[83,84] showed that there was not only an increase in cancer rates, but also the cancer rate was directly proportional to the number of X-ray films that had been taken. These observations have been supported by a number of studies which found associations between leukemia and diagnostic X-ray exposure of the fetus[85-94] and among adults.[95-100] Some of them also reported a similar association for preconception exposure of the mother's ovaries.[85,89-91] One reported a change in menstrual problems and pregnancy rates among females when they had been exposed in utero to diagnostic X ray.[101] One reported the identification of a high-risk subgroup.[91] Bross et al.[102] used these subgroups, along with a statistical model, to calculate the risk from exposure to X ray at doses below 5 rads.[89,102] They concluded that previous estimates of risk from diagnostic X ray were low by a factor of 10. This approach has been strongly criticized by Boice and Land[103] on the grounds that estimates were treated as known constants and that "incorrect statistical manipulations" were used in connection with the complex model. Their reanalysis, however, confirmed an association of excess leukemia with diagnostic X-ray exposure of adults.[103]

Four studies either had equivocal results or failed to find an association between leukemia and diagnostic X ray.[104-107] It is likely that the populations in these studies were too small or there was too small a dose to reticuloendothelial tissue to expect positive results.

Increased rates of breast cancer have been repeatedly found among women following fluoroscopic examinations.[106-110] A dose-response relation, which is probably linear, has been shown.[107-110] A number of studies seeking an association between Down's syndrome (mongolism) and diagnostic X ray of patients were reviewed in 1970 by Wald et al.,[111] who concluded that radiation might be an important cause of Down's syndrome, but that more studies were needed. Their principal reservation was due to the fact that an excess of Down's syndrome had not been observed among the offspring of Japanese A-bomb survivors.[112] However, since then, three excellent studies, which considered known variables, have all found the association: Cohen and Lilienfeld[113] found that mothers who had been X-rayed had 1.5 times the usual risk of having a child with Down's. Alberman et al.[114] matched 465 parents of children with Down's with controls on age and time of birth. They found no excess of X-ray exposure among fathers, but there was a statistically significant excess of X-ray exposure among mothers of children with Down's when the X rays were received more than 10 years before conception. They concluded that recent radiation and radiation of fathers had little effect but that distant maternal radiation was quite important—that 2 rads would approximately double the risk of having a child with Down's syndrome. Uchida,[115] using a prospective method, found eight cases of Down's among the children of women who had abdominal X rays vs. one among controls—a statistically significant excess.

Alberman et al.,[116] using a case-control technique, compared the amount of chromosomal aberrations and radiation received by 845 mothers who had spontaneous abortions with matched mothers who had live births. The mothers who had abortions received significantly more diagnostic radiation than the controls. About one-fourth of the aborted fetuses had abnormal chromosomes. Mothers of the fetuses that had abnormal chromosomes received significantly more radiation than the controls.

Changes in the sex ratio of human offspring associated with parental radiation exposure has been reported a number of times,[117-120] but this ratio is considered to be a poor indicator of radiation effect in man because of the many variables (parental age, birth order, etc.) known to affect it.[121] Experimental data from animals have been used to predict genetic effects in man.[8] Generally, all radiation that reaches reproductive tissues is regarded as harmful, and induced mutations are proportional to the dose. One exception is that low LET radiations have a decreased effectiveness at low dose rates.[8] This decreased effectiveness may be the result of DNA repair mechanisms,[121] which seem to be partially effective against damage from low LET radiation but less effective against damage from high LET radiation. Such repair mechanisms, plus evidence from A-bomb survivors and animal experiments, have led some observers to conclude that there is little or no genetic injury to man at or near the usual environmental levels of radiation.[122]

Jablon and Miller[123,124] in two reports compared the cause of mortality of 6560 army radiological technologists with that for other kinds of medical technologists. The radiological technologists during training had practiced radiologic techniques on each other but averaged less than 3 years as such technicians. No statistically significant differences for individual sites of cancer or for deaths from other causes were noted when comparisons were made with the general population, but there was excess respiratory cancer among those exposed to radiation when the two groups were compared in the first report. In the second report this difference had disappeared, but there was a trend toward excess leukemia among the technologists exposed to radiation. Comparative cigarette smoking information on the two groups was not available.

A general life-shortening effect was noted among American roentgenologists, which was only partly due to excess malignant disease.[125,126] This was attributed to occupational exposure to radiation which was poorly quantitated. Other studies have confirmed the excess malignant disease among medical radiation workers.[32,127-130]

OTHER REPORTS ON LOW-LEVEL EFFECTS

Chromosome aberrations in cultured lymphocytes have been found in workers exposed to quite low levels of external radiation[11,131] and to internal radiation substantially below present permissible levels.[132-135] Although the study of chromosome aberration has replaced other blood studies for the detection of low-level-exposure effects, counting binucleated lymphocytes[136-138] and other parameters showed effects at quite low levels.[139] Although chromosome aberrations induced by radiation in blood cells are not harmful in themselves, they almost certainly reflect similar injury in other body cells. This type of injury to nuclear proteins is thought to be the basic mechanism for cancer induction. However, a definite relation between chromosome aberrations in blood cells and subsequent cancer has not been established.

Increased rates of lung cancer have been reported among underground miners exposed to radon daughter levels little above those encountered in many dwellings.[140-144] An increased mortality rate from childhood leukemia has been noted in Utah following exposure to fallout from nuclear weapons.[145] Although there is dispute as to the magnitude of radiation exposures, it appears to have been below 10 rads. Although etiology has not been firmly established, this observation appears to be consistent with the findings from diagnostic X ray noted above.

A biological effect on cell cultures at the surprisingly low dose of 0.3 to 2 mrads/h for 24 to 72 h was found in cultures of *Chlorella.*[146] They lost synchrony of multiplication at these exposures while controls did not. A somewhat similar study noted increased proliferation of *Paramecium* attributed to background radiation.[147] Increased chromosomal nondisjunction was found in aged mice at doses of 5 rads.[148] Two studies have reported findings in wild animals which suggested an effect from naturally occurring radiation exposures.[149,150] In a review, Grahn[151] noted several animal studies in which low-level radiation appeared to have been beneficial.

DISCUSSION

There is a surprisingly large volume of data in the literature on effects of low levels of ionizing radiation in man. However, quantitative effects at low levels are generally obtained by downward extrapolation from atomic bomb survivors or other groups with relatively high exposures.[6] Data from the atomic bomb survivors in Japan have given us much information on radiation effects, but the application of these data to the present subject is limited for two reasons: (1) the dose rate was extremely high—at the opposite extreme from environmental radiation, and (2) the extreme stress on survivors of the blast undoubtedly resulted in many nonradiation deaths and abortions. Such premature nonradiation deaths would almost certainly have an influence on subsequent mortality. Its effect could readily obscure the small radiation effects on the least exposed groups and on children, who could be expected to undergo the greatest stress. The effect of this stress may explain why results of analyses of childhood malignancies, Down's syndrome, and sex ratios in this group differ from other studies, as pointed out by Stewart.[84,152]

Much of the controversy over the effects of low-level radiation has centered about the question of whether linear extrapolation downward from high exposures to zero dose and zero response is a reasonable approach. Some contend that such procedures substantially underestimate the risk at low levels.[102,153,154] There is considerable animal data indicating that at low doses of beta, gamma, or X rays (low LET radiation) most effects per unit of radiation are substantially reduced,[8] leading some observers to conclude that linear extrapolation downward overestimates the risk at low levels. However, this effect may be counteracted to some extent by a protraction effect. There is some evidence that when small doses are administered over long periods of time (as with occupational or background radiation) some effects (including cancer) may be increased per unit of low LET radiation.[155-158] For alpha particles and neutrons (high LET radiation), there is evidence that carcinogenicity per rad is substantially greater both at low doses and with protracted exposure periods than it is at high doses with short exposure.[159-161] Judging from this data, it appears that linear extrapolation of the cancer dose-response curve to zero dose is a reasonable approximation for risk calculation for exposure to low LET radiation, but not to high LET radiation. Risk calculation for exposure to alpha particles and other high LET radiation is quite likely to underestimate the risk when linear extrapolation downward from high levels is used.

The above conclusions are consistent with data on breast cancer in humans which suggests that the linear relation for X ray extends to low fractionated doses;[107,162] on human bone cancer, which demonstrated enhanced carcinogenicity of alpha radiation with protraction of dose;[163] and on lung cancer among miners exposed to alpha radiation from radon daughters, where cancers per rad are increased at low doses and low dose rates.[7]

Using the linear extrapolation technique and other theoretical considerations, up to 50% of observed human cancers might be the result of background radiation.[164] Archer, on the basis of observed correlations between cosmic radiation and cancer rates, suggested that between 30 and 50% of human cancers might be due to background radiation.[33] He also noted that lung cancer among nonsmokers is about what would be expected as a result of normal exposure to radon daughters.[165] There appears to be no inconsistency between theoretical extrapolation of radiation effects to background levels and the natural occurrence of cancer. Other calculations, however, are in substantial disagreement; e.g., the BEIR report[8] estimated that about 1% of human cancers are caused by background radiation. Such calculations appear to have grossly underestimated the role of the high LET component of background radiation as noted above. This underestimate, however, would have little influence on the calculation of population effects from the operation of nuclear power plants, since those effects are predominantly from beta and gamma rays. Fallout from some nuclear explosions, however, would contain substantial amounts of alpha emitters.

Since there is good evidence that effects in large human populations have been observed at average exposures of less than 10 rads, there is every reason to expect that background radiation, which is of the same order of magnitude when considered for a lifetime, will also produce observable effects, as suggested by a number of reports. Although the evidence is not conclusive that background radiation has an effect on man, it is sufficiently strong that the prudent course is to accept it as probably true.

Although data are sparse on genetic effects at low doses of radiation, the subject has been thoroughly reviewed,[166] with the conclusion that the genetic risk from any given whole-body exposure would be about 20 to 40% of the cancer risk. There is no reason to think that this fraction would be greater for low-level, protracted exposure.

Because of the many variables in human society which can affect the rates of malignant disease, birth defects, chromosome aberrations, Down's syndrome, etc., and the many pitfalls in data collection and analysis, it is not surprising that many of the studies noted above reported no observable effects. In this area of research it is probably much easier to obtain negative than positive results because the interfering factors (including inadequate population size) are more likely to obscure the association sought than to give spurious associations. With some exceptions, the positive studies have been the more sophisticated ones—

those which considered more of the pertinent and possibly interfering variables, which used the more sensitive techniques, and which focused on specific effects rather than on broader ones such as total cancer or neonatal mortality rates.

Epidemiological methods appear to be the only way to approach the effects of low-level radiation on man. Such methods can rarely be used to "prove" a cause-and-effect relation because the epidemiologist can never control all possible variables as can be done in animal experiments. However, the large numbers of subjects with which he can deal usually minimize the effects of such variables. If they are varying randomly while the radiation exposure and effects are not, then all the uncontrolled variables do is decrease the sensitivity of the method. However, there is always the possibility that some uncontrolled variable will not vary randomly but will vary with the parameter one is measuring. This could result in spurious positive results. It is for this reason that little reliance can be placed on any single positive result. However, since the number of ways in which the problem has been approached has increased and has yielded positive results, one's confidence in the reality of observable effects in man from small exposures to ionizing radiation must increase.

One must realize that all of the earth's animals evolved in a radiation environment. Some of the background radiation effects may have been helpful (such as speeding up evolutionary changes), but most have probably been harmful. It is not likely that harmful radiation effects have appeared only with the onset of the atomic age. They are neither new nor different. We have always lived with them, just as we have always lived with injury from accidents and infectious disease. Just as we have developed immunologic resistance against infectious disease, we have also developed resistance to radiation, as noted above. It is unreasonable to ask that any industry eliminate all accidental injuries or to never allow anyone to develop pneumonia. It is equally unreasonable to ask that all radiation injury be eliminated. It has seemed reasonable to some people only because radiation injury has been recognized recently; it appeared to them to be a new and different plague visited on us by man's new technology. Most health risks are accepted reluctantly, although a few (like those from alcohol, cigarettes, and fast cars) are accepted willingly. Certainly, if the risk to workers in an industry is high and cannot be reduced to reasonable levels, the industry should be prohibited unless its benefits are very great. But when risks from accidents, radiation, etc., can be reduced to low levels, the most that can be asked of any industry is that it exert its best efforts to keep the risks minimal. The public must realize that radiation is not something new and different that should be forbidden, but an old antagonist that we long ago learned to live with—just as we have learned to live with bacteria and viruses.

Some of the studies noted above, especially those of Marks et al.[25] and Sanders,[20] serve to put the hazard from ionizing radiation in perspective. Regardless of whether one agrees with their conclusions, it is apparent that the effect of occupationally acquired ionizing radiation on the Hanford population has been very small. This is true even though more sensitive analytical methods may demonstrate an effect from radiation in that population. It is important that we maintain a reasonable perspective on radiation effects. One way of doing this is to calculate the expected radiation effects from occupational exposure and compare those effects with other commonly recognized hazards.[167–173] Using this approach, Pochin calculated that an exposure of 4 mrems/year (his estimate of the average dose per person from 1 kW of nuclear power) would result in about the same degree of health risk to an individual as that incurred by smoking one cigarette every two years or driving 64 km in a private auto each year.[157] These comparisons may seem absurd, but they do serve to put radiation risks from nuclear power in perspective. The risk of lung cancer from radioactive materials (radium, etc.) released to the atmosphere from a coal-fired power plant has been calculated to be 400 times greater than the risks incurred from using a plutonium breeder reactor of equivalent size.[172] The total health risks incurred from coal-fired power plants was [illegible]lated to be substantially greater than those incu[illegible] from equal amounts of electricity produced by means of nuclear reactors or natural gas.[173]

[illegible]se estimates are based on linear extrapolation d[illegible]d and do not consider possible effects from disasters that might occur from earthquakes, lightning, sabotage, nuclear accidents, theft of fissionable material, nuclear war, or inadequate disposal of radioactive waste. Such possibilities can be minimized by special precautions, but they cannot be eliminated. One can quarrel with the actual quantitative risk estimates obtained by these authors, and the numbers may be changed somewhat with additional quantitative knowledge on reactor emissions, on effects of low levels of radiation, and on the effect of air pollutants from coal burning, but they are most likely correct within an order of magnitude if one ignores the possibility of a large-scale nuclear accident. They serve the purpose of removing radiation hazards from the category of a nebulous unknown danger and putting such hazards in terms that can be understood.

If one considers the risk of large-scale nuclear accidents separately and considers that the published risk estimates are approximately correct, it is apparent that the small release of radioactive materials from the normal operations of nuclear reactors will cause little human injury when compared to the risk from other commonly accepted health risks—such as the risks incurred from automobile driving, cigarette smoking, and the burning of coal for heat or electricity. However, further research is needed on the effects of low levels of radiation as well as on the risk of nuclear accidents.

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Some Observational Bases for Estimating the Oncogenic Effects of Ionizing Radiation

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Abstract: *Data extracted from several studies on human subjects who received partial- or whole-body exposures to ionizing radiation are presented. The use of these data to estimate the expected mortality from whole-body irradiation is discussed. The interpretations of the results from retrospective case-control studies, as exemplified by the Oxford survey of childhood cancers, are critically reviewed. It is found that the Oxford data of 1972 do not support conventional dose–response relations any better than do random numbers with similar ranges and means. Also discussed is a method for analyzing the results of whole-body radiation studies, which relates the number of deaths from cancer to those from all other causes excluding accidents.*

Two kinds of scientific studies are useful in determining the mechanisms and extent of cancer induction by ionizing radiation. One type of study depends on data derived from model experiments on animals exposed under controlled conditions. The other consists of epidemiological studies conducted on groups of people who were accidentally or incidentally exposed under uncontrolled conditions to a variety of radiations of different qualities, dose rates, and spatial distributions and, in addition, on some who were subjected to radiation for diagnostic or therapeutic purposes under (usually) well-defined conditions.

For brevity this review will be limited almost exclusively to the information derived from human studies. Important somatic effects of exposure to ionizing radiation, besides cancer, have been thoroughly reviewed in various documents published by the United Nations Educational, Scientific, and Cultural Organization (UNESCO)[1,2] and in reports of the International Committee on Radiological Protection (ICRP)[3] and National Council on Radiation Protection and Measurements (NCRP).[4] The effects on induction of developmental abnormalities have been discussed in ICRP Publication 27 (Ref. 3) and in the 1977 report to the United Nations General Assembly by the United Nations Scientific Committee on the Sources and Effects of Atomic Radiation [UNSCEAR 1977 (Ref. 1)]. Data on human cataract induced by radiation were reviewed by Merriam and Focht.[5] All somatic effects were most recently reviewed by a committee of the National Academy of Sciences (see the BEIR report[6]).

Selected for review here are a few of the better known epidemiological studies which contain much of the available statistics on radiation-induced cancer in humans. Included are some studies, such as those of Stewart and Kneale,[7] which purport to show extremely high sensitivity as well as some which appear to indicate low sensitivity toward ionizing radiation. For brevity, many important sources of information on some aspects of radiation-induced carcinogenesis in humans are not reviewed.

There are many ways to present the results of epidemiological studies. An attempt was made here to provide a uniform format to facilitate comparisons. Where possible, the observed and expected number of cases are shown as well as the size of population and years at risk. If not given in the original sources, calculations were made to show all results in terms of excess mortality from cancer or incidence of cancer per 10^6 persons at risk per year per rad. There may be objections to this procedure, and it should not be taken as an implicit endorsement of any hypothesis concerning the real nature of a dose–response relationship. It does, however, provide a useful quick indication of the magnitude of the response in different studies. There are differences in what are called latent periods, and there is a likelihood of different response curves for different cancers, qualities of radiation, dose rates, and dose distributions. For these reasons and

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others, complete reciprocity between persons at risk, doses, and time at risk is not to be expected.

No epidemiological studies of any size on radiation-induced carcinogenesis, even those started decades ago, have covered the entire life span of any group containing people of all ages. The estimation of the lifetime risk of cancer from any dose of radiation therefore contains a considerable element of extrapolation into the future. This, together with other difficulties associated with statistical treatment of data, has allowed sufficient scope for claims of population sensitivity to radiation to vary as much as two or three orders of magnitude.

Cancer Mortality in Atomic Bomb Survivors

The largest nearly instantaneous exposures to radiation occurred in August 1945 during World War II when atomic bombs were dropped on Hiroshima and Nagasaki. A selected group of the survivors from both cities has been studied continuously since 1950—at first under the auspices of the National Academy of Sciences of the United States alone [Atomic Bomb Casualty Commission (ABCC)] and more recently as a joint effort with the Japanese Ministry of Health and Welfare [The Radiation Effects Research Foundation (RERF)]

Table 1 Bone Sarcomas in Female Dial Workers with Radium Intake*

Weighted mean dose, rads†	Number of dial workers	Number of bone sarcomas	Person-years at risk	Excess sarcomas per 10^6 person-years at risk per rad
28 396	7	2	169	0.4
15 099	18	11	449	1.6
6 347	26	10	818	1.9
3 749	31	11	1 162	2.5
1 751	32	4	1 172	1.9
132	440	0	20 371	0.0
Total 1 071	554	38	24 141	1.5

*Source: Ref. 8.

†See Ref. 8 for the method of calculation.

SUMMARIES OF DATA AND DISCUSSION

Bone Cancer Induced by Radium

For historical reasons, data on induction of bone cancers by radium are given first. The studies on radium dial painters is the longest study still in progress in the United States on persons who have suffered exposure to internal or external irradiation. According to Rowland, Stehney, and Lucas,[8] about three-fourths of the female population exposed to radium intake in the United States before 1930 have been identified. Table 1 is condensed from Table 7 of their paper and gives data derived from 759 of the 1474 identified subjects. The response appears somewhat erratic, and no simple dose–response relationship seems very convincing.

The radium-dial painters have been the subject of several extensive epidemiological reports (Evans[9] and Finkel, Miller, and Hasterlik[10]) and served as the basis for the development of a radiobiological theory (e.g., Marshall and Groer[11]).

Very extensive reports have been produced by ABCC and RERF. The latest complete report contains data for the period 1950 to 1974, and a condensed version of this report appeared in 1978 (Beebe, Kato, and Land[12]). Much of the data on observed and expected cancers is presented so as to appear independent of the control group. The condensed values given here (in Tables 2 and 3) were recalculated to make the "expected" values conform exactly to the observed rate for the zero-dose group as a "control." For example, from Table 6-10, page A50 of the 1979 RERF report,[12] the 1950 to 1974 observed value for the zero-dose group at Nagasaki is 168, while the expected value is given as 197.5, a value that can be obtained by assuming no radiogenic cancers and prorating the observed cancers according to the size of the groups. All the expected values for the 1950 to 1974 exposed groups were therefore multiplied by 168/197.5 so that the expected values correspond to the observed value for the zero-dose group. Table 2 gives data from the summary tables in the 1978 RERF

Table 2 Cancer Mortality in Persons Exposed to Atomic Radiation (Nagasaki)*

No. of persons† (male and female)	Years	Mean dose, rads		Cancer mortality		Excess cancer mortality per 10^6 person-years at risk per rem‡
		γ ray	Neutron	Observed	Expected	
4 700 (924)	1950–1958	0	0	42		
	1959–1966			49		
	1967–1974			77		
	1950–1974			168		
10 455 (2 273)	1950–1958	10.2	0	124	103.3	
	1959–1966			132	105.0	
	1967–1974			183	154.1	
	1950–1974			439	362.4	34.0
2 705 (507)	1950–1958	108.0	0.8	22	23.5	
	1959–1966			33	27.8	
	1967–1974			57	44.2	
	1950–1974			112	95.5	2.5
1 396 (273)	1950–1958	332.0	5.7	26	10.9	
	1959–1966			23	13.7	
	1967–1974			30	22.3	
	1950–1974			79	46.9	2.9
14 556 (3 053)	Total exposed	59.1	0.69	630	504.8	6.0

Fraction of total deaths due to cancer: exposed group 0.194
zero-dose group 0.169

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*Source: Ref. 12. For a statistical treatment of the data, the original tables should be consulted.

†The weighted mean ages of the four groups were, respectively, 27.25, 28.09, 27.13, and 25.92 in 1945. The values in parentheses are the deaths from all causes excluding accidents.

‡Calculated by adding five times the neutron dose to the γ-ray dose. Numbers in this column cannot be calculated directly from the other data in the table. See Ref. 12.

report[12] for Nagasaki but is aggregated into 8-yr instead of 4-yr periods as well as into three dose groups instead of seven. Doses are given separately for gamma radiation and neutrons or are combined, a quality factor of 5 being used for neutrons. Table 3 gives similar data for Hiroshima.

Cancer Induced by Therapeutic Radiation

A fairly large group of patients suffering from ankylosing spondylitis has been treated with ionizing radiation to the spine. The doses vary and are difficult to calculate. A summary of these data by Court-Brown and Doll[13] is given in Table 4. Tables 5 and 6 show the observed and expected tumors of the breast in female patients following radiation treatment for mastitis[14] (Table 5) and after fluoroscopy[15] (Table 6). Thyroid tumors, which result in a mortality of only a few percent, are also increased by relatively low doses of ionizing radiation. Some data on these are shown in Table 7 (Refs. 16-18).

Numerous other studies on individual cancer sites are available but for reasons discussed below will not be examined here.

Retrospective Case-Control Studies

Many of the epidemiological studies with results that have been interpreted as indicating great sensitivity to radiation are of the retrospective case-control type. This method usually consists of comparing the relative exposures of two mutually exclusive populations, e.g., those who have died of cancer with those who are living and do not have cancer. No method has yet been devised to prove that the comparison group (the "controls") properly represent those members of the total population who eventually contract cancer. To do the exhaustive investigations that would be required to determine to what degree the comparison group may be properly considered a control would probably make the case-control study as expensive and time-consuming as the equivalent prospective-type

Table 3 Cancer Mortality in Persons Exposed to Atomic Radiation (Hiroshima)*

No. of persons† (male and female)	Years	Mean dose, rads		Cancer mortality		Excess cancer mortality per 10^6 person-years at risk per rem‡
		γ ray	Neutron	Observed	Expected	
29 943 (7 13[illegible])	1950–1958	0	0	436		
	1959–1966			527		
	1967–1974			563		
	1950–1974			1 526		
24 557 (5 776)	1950–1958	9.37	2.3	320	360.7	
	1959–1966			480	437.5	
	1967–1974			475	467.9	
	1950–1974			1 275	1 265.6	0.9
4 439 (1 152)	1950–1958	77.00	19.8	77	70.1	
	1959–1966			112	85.4	
	1967–1974			98	89.1	
	1950–1974			287	245.6	2.5
1 531 (394)	1950–1958	266.80	94.1	40	20.2	
	1959–1966			46	25.4	
	1967–1974			60	27.9	
	1950–1974			145	74.4	3.0
30 527 (7 322)	Total exposed	32.1	9.5	1 707	1 584.6	2.4

Fraction of total deaths due to cancer: exposed group 0.219
zero-dose group 0.200

*Source: Ref. 12. For a statistical treatment of the data, the original tables should be consulted.

†The weighted mean ages of the four groups were, respectively, 32.72, 31.74, 34.17, and 31.19 in 1945. The values in parentheses are the deaths from all causes excluding accidents.

‡Calculated by adding 5 times the neutron dose to the γ-ray dose. See note in Table 2.

Table 4 Observed and Expected Deaths in Persons Treated with a Single Course of Ionizing Radiation for Ankylosing Spondylitis (Dose Not Specified)*

	Observed	Expected†
All causes	1759.000	1061.700
All neoplasms	397.000	256.900
Leukemia	31.000	6.500
Cancer of the colon	28.000	17.300
Cancers of heavily irradiated sites	259.000	167.500
Cancers of lightly irradiated sites	79.000	65.600
All other causes	1362.000	804.800
Fraction of all deaths due to neoplasms	0.226	0.242

*Source: Ref. 13. For a statistical treatment of the data, the original source should be consulted.

†From national mortality rates for England and Wales.

study. The Oxford study[7] of childhood cancer is a case in point. The direct observational data available in 1970 from this study are presented in Table 8. The bulk of the material presented in the numerous research papers emanating from this study group before and since the 1970 publication (Stewart and Kneale[7]) seems mostly directed toward justification of the assumption that the "control" group experience is indeed suitable (e.g., Bithell and Stewart[19] and Kneale and Stewart[20]).

Radiation-Induced Cancer in Children

The Oxford study is the most extensive and exhaustive retrospective case-control type yet conducted for the purpose of determining radiation sensitivity. Therefore it will be used here as an example, and the numerous other similar studies (many of which are reviewed by Archer[21] in this issue of *Nuclear Safety*) will not be examined. The data of Table 8 are from Stewart and Kneale.[7] Note that the

Table 5 Breast Cancers Developed in the Interval 10–34 Yr Following Radiation Treatment for Mastitis*

	Mean dose rads	Person-years at risk	Cancers		Excess cancers per 10^6 person-years at risk per rad
			Observed	Expected	
	0	15 767	28	28.00	
	112	2 620	7	4.78	7.6
	193	2 971	12	5.22	11.8
	294	1 804	9	3.09	11.1
	392	683	4	1.27	10.2
	584	974	4	1.79	3.9
Total number of irradiated people	257	9 052	36	16.15	8.3

*Source: Ref. 14. For a statistical treatment of the data, the original source should be consulted.

Table 6 Excess Breast Cancers in Women After Repeated Fluoroscopies 1–44 Yr Following Initiation of Treatment*

Dose range, rads	Dose mean, rads	Person-years at risk	Cancers		Excess cancers per 10^6 person-years at risk per rad
			Observed	Expected	
0		19 025	15	14.1	
1–9	37	10 990	10	9.6	1.0
100–199	147	7 097	12	5.7	6.9
200–299	244	5 584	12	4.8	5.3
300–399	355	2 020	3	1.5	2.1
400+	578	1 735	4	1.1	2.9
Total 1+ (1–44 yr)	150	27 426	41	23.3	4.3
Total 1+ (10–44 yr)	150	18 511	38	20.9	6.2

*Source: Ref. 15. For a statistical treatment of the data, the original source should be consulted.

Table 7 Thyroid Tumor (Benign + Malignant) Incidence Following Irradiation in the Young*

Dose to thyroid, rads	Person-years at risk	Tumors		Excess tumors per 10^6 person-years per rad	Reference number
		Observed	Expected		
155.00	69 401	76	3.59	6.7	16
399.00†	8 088	33	0.04	10.2	16
6.54	96 236	12	2.00	7.8	17
6.00	44 300	6	2.65	12.6	18

*Source: Refs. 16–18. For a statistical treatment of the data, the original sources should be consulted.

†Subgroup C, see Ref. 16.

Table 8 Recalculated Data from Stewart and Kneale (1970)*

Years	Women receiving prenatal X rays	Women receiving no prenatal X rays	Number of films†					Total number of women
			1	2	3	4	>4‡	
					Cases			
1943–1949	212	1610	59	69	39	16.0	29.0	1822
1950–1954	437	2298	144	125	70	47.0	51.0	2735
1955–1959	381	1772	167	108	54	29.0	23.0	2153
1960–1965	111	828	68	26	7	5.0	5.0	939
Total	1141	6508	438	328	170	97.0	108.0	7649
					Controls			
1943–1949	110	1712	54	31	14	8.0	3.0	1822
1950–1954	316	2419	110	112	45	23.0	26.0	2735
1955–1959	248	1905	116	77	27	13.0	15.0	2153
1960–1965	100	839	69	21	7	(3)		939
Total	774	6875	349	241	93	45.5	45.5	7649

*Source: Ref. 7.

†Cases and controls with no record of number of films are distributed proportionately in groups having 1 to >4 films.

‡For population dose calculations, the average number of films in this column was assumed to be 5, which is an underestimate.

cases and controls having an exposure from an undetermined number of films are distributed in the groups (or cells) having 1 to >4 films in proportion to the numbers already there. The "extra" cases presumed to be caused by prenatal irradiation were calculated for each cell pair (the case and the control constitute a pair) by subtracting from the probability of a case receiving prenatal irradiation the probability of a control being irradiated corrected for differences in the numbers of unirradiated cases and controls. The population exposure was calculated from the dose per film times the number of films times the probability of the control being exposed to that number of films.

Stewart and Kneale assume that there is the induction of childhood cancers by radiation and that the radiation sensitivity changed over the 20-yr period of the Oxford study. If there is such an effect, however, it would not be expected to show changes before many generations as a result of selection toward or away from the sensitivity. The assumption adopted here is that, if there are radiation-induced childhood cancers, their number is proportional to population dose and the sensitivity to radiation does not change over the period of the study. On the basis of these suppositions, the data in Table 8 have been analyzed by aggregation of the calculated excess cancers into four groups, first, in order of increasing population dose and, second, in order of increasing extra cancers. The results are shown in Table 9 when the doses per film in the four periods used by Stewart and Kneale[7] were applied to Table 8 and in Table 10 when the doses per film suggested in the 1972 UNSCEAR report[2] were used.

Data in the last column of Tables 9 and 10 show that the number of extra cancers per 10^6 person-years per rad decreases when the data are aggregated by increasing population dose but increases when they are aggregated by increasing excess cancers. Since there is no apparent biological reason for such trends, a statistical examination of the data in search of relevant trends seems called for. (A slightly different value of the mean response per rad per year, 60.2, was obtained by the procedures used here compared with the 57.2 with standard error of the mean of 13.3 found by Stewart and Kneale.[7])

This has been done in Table 11 by regressing either the excess cancer risk ECR = E/P_{cN} used by Stewart and Kneale[7] or the excess cancers per case, E, against the number of films as they did or against average individual dose, D_i. The results show that, in any case-control study of the same nature as the Oxford survey, the use of the relative risk or a similar measure can be very misleading. This appears to be the result, in this study, of the highest exposures being received by

Table 9 Calculated Excess Cancers from Prenatal Irradiation Arranged in Groups of Increasing Population Dose and of Increasing Excess Cancers*

	Total dose, rads/10^6 person-years	Average dose, rads	Calculated excess cancers/10^6 person-years	Calculated excess cancers per 10^6 person-years per rad
		Increasing population dose		
	3 435	0.937	3.73	108.7
	9 149	0.848	6.07	66.3
	14 181	0.389	9.42	66.4
	21 098	0.738	9.59	45.4
Total	47 863	0.602	28.81	60.2
		Increasing excess cancers		
	7 135	0.314	1.15	16.1
	12 907	0.800	4.46	34.5
	13 321	1.520	8.46	63.5
	14 500	0.454	14.78	101.9
Total	47 863	0.602	28.85	60.3

*There are five pairs of corresponding values in each group. Data from Ref. 7.

Table 10 Calculated Excess Cancers from Prenatal Irradiation with Data Arranged in Groups of Increasing Population Dose and of Increasing Excess Cancers*

	Total dose, rads/10^6 person-years	Average dose, rads	Calculated excess cancers/10^6 person-years	Calculated excess cancers per 10^6 person-years at risk per rad
		Increasing population dose		
	5 674	0.726	2.61	46.0
	18 537	0.624	9.32	50.1
	36 529	1.894	9.14	25.0
	58 680	.584	7.80	13.3
Total	119 420	1.502	28.87	24.2
		Increasing excess cancers		
	15 078	0.665	1.15	7.6
	30 377	1.882	4.46	14.7
	37 369	4.276	8.46	22.6
	36 597	1.148	14.78	40.4
Total	119 421	1.502	28.85	24.2

*There are five pairs of corresponding values in each group. Data from Ref. 7, with doses per X-ray film from the 1972 UNSCEAR report, Ref. 2.

the smallest number of persons. Therefore data points with the greatest relative error are multiplied by the reciprocal of the lowest frequency which is itself expected to have a large error. The resulting numbers in an ordinary regression analysis may carry the greatest weight rather than the least weight (they may be the farthest from the origin rather than the nearest). The effect is brought out in Table 11 in which it is seen that the only regressions with small probabilities of occurring by chance are those for which both Y and X contain the factor $1/P_{cN}$, since $N = D_i/(D_fP_{cN})$. The last four entries show that the dose response claimed

Table 11 Relationships Between Extra Cases and Population X-Ray Dosages in the Oxford Childhood Cancer Survey*

Y†	X†	Slope	Intercept	r†	p†
$ECR = E/P_{cN}$	N	0.632	−0.6700	0.465	<0.050
E	D_i	0.280	0.0067	0.266	>0.200
E	D_i/D_f	0.0447	0.0085	0.130	>0.400
E	N	−0.0020	0.0148	−0.296	>0.100
E(reversed)‡/P_{cN}	N	0.6860	−0.7140	0.617	<0.010
"E"(random, normal)§/P_{cN}	N	0.8050	−1.0780	0.642	<0.010
"E"(random, normal)§/P_{cN}	"D_i"/($D_f P_{cN}$)	0.0284	0.5040	0.789	<0.001
"E"(random, uniform)§/P_{cN}	N	1.540	−2.2200	0.563	<0.010
"E"(random, uniform)§/P_{cN}	"D_i"/($D_f P_{cN}$)	0.130	0.9680	0.766	<0.001

*The data from Table 1 of Stewart and Kneale[7] were used, but those falling in the column designated "no record" were distributed in the columns listing one to >five films in numbers proportional to those already there.

†Abbreviations used: N = number of films in exposure; p = probability of radiation occurring by chance; r = correlation coefficient; E = extra cases per case; ECR = excess cancer risk; P_{cN} = probability of control being X-rayed with N film; $D_i = P_{cN} N D_f$ = average dose per individual in the cohort population.

‡In this row the relationship of E to N was reversed; i.e., the E for five films was matched with $N = 1$; for four with $N = 2$; for three with $N = 3$; for two with $N = 4$; and for one with $N = 5$.

§The observed E's and D_i's were replaced by computer-generated and randomly selected numbers from either a uniform or normal distribution, with mean and standard deviation approximately the same as those of the observed values for E and D_i.

by Stewart and Kneale[7] can be duplicated or improved by substituting random numbers in place of the actual numbers derived from Table 8. When the Oxford data are used in the usual way to relate population dose to excess cancers, no significant correlation is obtained. In fact, only a maximum of 7% of the variance can be accounted for by the radiation dose.

These considerations apply chiefly, but not exclusively, to the supposed dose–response calculations. The overall ratio of exposed cases to exposed "controls" remains unexplained. Additional case-control studies do not help because they are all subject to the same uncertainty about applicability of the control experience. Neyman discussed this problem a number of years ago and showed the pitfalls that can occur.[22] Prospective studies such as those of Oppenheim, Griem, and Meier[23] serve to place an upper limit on the possible sensitivity to radiation in utero, which is not restrictive enough to be helpful. The largest prospective-type study was conducted by Jablon and Kato,[24] who examined survivors of the atomic bombings in Japan who were pregnant at the time. They found no excess cancers among the children who were irradiated in utero. The total number of person-rads in the Jablon and Kato study was 17 500, which can be compared with the figures in column 1 of Tables 9 and 10. Numerous ad hoc explanations for the discrepancy between the results of the two studies have been advanced (Morgan,[25] Rotblat,[26] and Stewart[27,28]), suggesting reasons that the Japanese data were unsuitable. They are usually not accompanied by any effort to examine the Oxford study to determine if the interpretation of those data was faulty.

An alternative way of estimating any relationship between childhood cancer and radiation exposure is discussed in the following section.

Hanford Mortality Study

Among the studies that have led to results supporting the claims for extreme sensitivity to radiation, one of great current interest and controversy is the Hanford mortality study reported, among others, by Mancuso, Stewart, and Kneale;[29] Stewart, Kneale, and Mancuso;[30] Gilbert;[31] Raloff;[32] Marks, Gilbert, and Breitenstein;[33] and Brodsky.[34] The data from this study are not summarized here because they are not readily accessible in original form and the reviewer has been unable to examine them in depth. However, some considerations relating to the atomic bomb survivors developed below have a strong bearing on the Hanford studies as well as on the childhood cancer work.

ESTIMATION OF THE LIFETIME RISK

The material presented here in Tables 1 through 10 is sufficient to acquaint the reader with the major problems confronting those who have undertaken the task of deducing the lifetime risk of cancer from the sparse data available on human response to radiation and the overwhelming variety of interpretations already proposed.

The first problem that arises is determining which studies are most relevant to the task. If we examine the breast cancer and thyroid data in Tables 5, 6, and 7, we note that the mortality or incidence data for a single cancer may equal or exceed the total cancers from the bomb survival data. This observation appears to be part of the basis for a belief expressed by some (see Morgan,[25] Rotblat,[26] and Stewart[27,28]) that the bomb survivors are a select group highly resistant to cancer as compared to "normals." Unfortunately for this view, the death rate for the survivors is not significantly different (except for cancer) from the death rate for those not exposed to bomb trauma (Beebe, Kato, and Land[11]). This is really the only accessible test that provides any information concerning the possibility of selection involving relative susceptibility, but it seems adequate for this purpose.

Cancers as causes of death compete with all other causes of death including other cancers. Radiation or any other carcinogenic agent when applied to a specific organ may accelerate the appearance of a cancer in that organ relative to its presumed usual time of occurrence. In a population in which a specific organ or organs had been exposed to radiation, any radiation-accelerated cancers would appear at an earlier age when there are fewer competing causes of death. The mortality from a specific cancer under these conditions could reach a much higher figure than would be expected if it appeared at the usual (later) age or if the population had received whole-body radiation so that all organs were equally exposed and therefore presumably more or less equally affected.

For this reason, the values for cancer incidence or mortality given by partial-body irradiation cannot be summed to provide an estimate for the effect of whole-body exposure, even if they were available for every cancer site. Partial-body irradiation studies are otherwise useful but are good only for loose guidance with respect to responses to whole-body irradiation doses.

We are forced, then, to use the only extensive whole-body exposure studies that are available, whatever their shortcomings may be, namely, the Japanese studies.

The summary of the 1979 BEIR report[6] gives a lower value of 160 for the lifetime excess cancers per 10^6 persons per rad; the upper limit suggested is 820. If we compare these values for the four concordant values of 2.5, 3.0, 2.5, and 3.0 from Tables 2 and 3 for excess cases per 10^6 person-years per rad, we see that the lower figure could be derived by multiplying the average value, 2.73, by 58.6 yr and the upper figure by multiplying by 300.4 yr. In practice, these values are determined by a complicated process involving purported differential sensitivities, latent periods, and plateau periods. It is instructive, however, to make the comparison in this way. The lower figure is reasonably consistent with what would be expected if the Japanese data are considered to be, and to remain, reliably applicable to radiation exposure received in other ways and if we ignore the hint in the Nagasaki data at the lowest dose level that the low figures at other dose levels are not representative of the entire dose response. This apparent discrepancy is examined below. The BEIR upper limit was doubtless strongly affected by consideration of data similar to those in Tables 5, 6, and 7 and by the "model" that was used to estimate the future course of the observed-to-expected cancer ratios as the population ages after exposure.

The low- and zero-dose statistics from the Nagasaki survivors have been the source of some puzzlement and of not a few ad hoc hypotheses offered in explanation. Perhaps the following analysis may indicate why epidemiologists associated with the RERF–ABCC studies have shown little concern over the apparent differences between the two cities.

From Table 2 we see that the value of 34 excess cancers per 10^6 person-years per rad is associated with a zero-dose group which has a low mortality rate when compared with the Hiroshima zero-dose group. As previously noted, the mortality rate over a period of time may be the best way to characterize a population sample—especially with respect to its susceptibility to natural causes of death. Thus the ratio of cancer mortality to all other mortality may provide useful information when regressed against dose. This was done in Fig. 1 with data from Tables 2 and 3 and Ref. 12. The least-squares line gives a slope of 0.00041 and an intercept of 0.23. The line is drawn through the five of the eight points from Tables 2 and 3 that fall on a straight line.

Only the zero-dose groups and the low-dose group from Hiroshima fail to conform to the line. However, an additional correction seems to be indicated because the groups do not have the same mean age; they differ by about 5 yr. As discussed elsewhere (Totter[35]), the "spontaneous" cancer rate can be expressed as the equivalent of a dose of ionizing radiation being continuously received, and the age can be expressed as an accumulated dose. Extrapolation of the line of Fig. 1 to its origin at the x axis gives such an equivalent dose corresponding to the mean age of the two population samples (about 58 yr in 1974).

Any of several procedures can be applied to the data. In this case use was made of the ratio of cancer deaths to deaths from all causes excluding accidents (this procedure seems somewhat preferable to using uncorrected total mortality as in Fig. 1) less cancer deaths after adjusting for mean age. The annual radiation dose equivalent to 1 yr of age came out to be a minimum of 8 to 10 rads. The difference in ages was corrected for by subtracting 24 rads (equivalent to 2.5 yr) from all the Nagasaki points and by adding 24 rads to all Hiroshima groups, and the result is shown in Fig. 2. The final ratio for the zero-dose groups, which will be reached when all persons in the groups have died, is expected to be about 0.20 (Beebe, Kato, and Land[12]). If this corresponds to 74 x 9 rads = 666 rads lifetime dose equivalent, the lifetime excess cancers per 10^6 person-rads would be about 300. A more revealing way of expressing this result is that it implies a life shortening equal to 1/9 yr per rad for the ~16% of the Japanese population who are expected to die of cancer, or a life shortening of 6.5 d per rad of exposure when averaged over the entire population. These values should be taken as maximum since no possible effect of low dose rate has been taken into account. All the calculations are based on high doses of radiation acutely delivered.

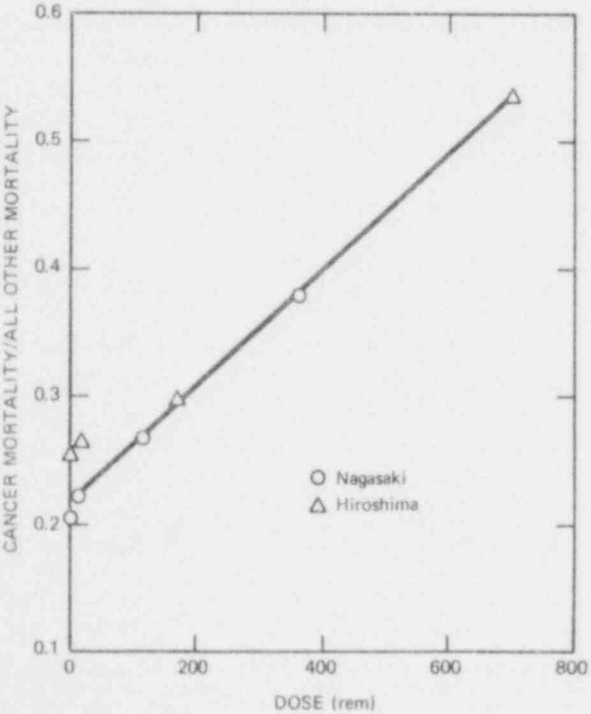

Fig. 1 Regression curve of the ratio of cancer mortality to all other mortality against dose of ionizing radiation, using a relative biological effectiveness of 4.6 for the neutron dose. Data are from Beebe, Kato, and Land (Ref. 12).

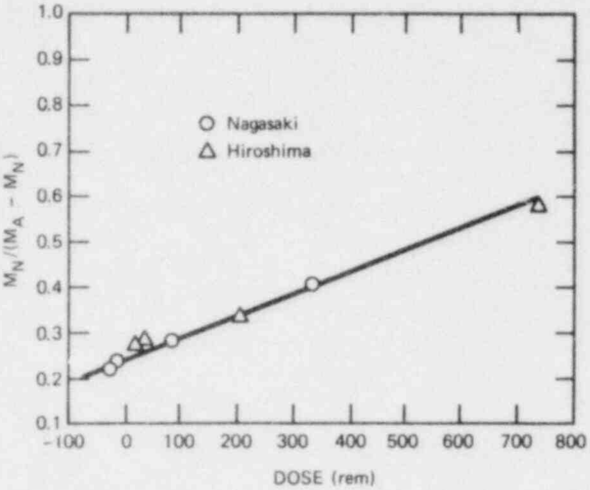

Fig. 2 Regression curve of the ratio of cancer mortality (M_N) to mortality from all causes excluding accidents (M_A) less cancer mortality. The doses are crudely corrected for the difference in weighted mean ages between the Nagasaki and Hiroshima subjects, as described in the text. Data are from Beebe, Kato, and Land (Ref. 12).

THE HUMAN DOSE–RESPONSE CURVE

The procedure previously outlined uses linear extrapolations of a ratio of cancer mortality to mortality from all causes excluding accidents and cancer. The linearity of this ratio, as so far observed, does not imply a similar linearity in the human dose–response relationship. In fact, it results from the age distribution of an aging cohort. With the advance in age, it must eventually deviate from linearity. The implication of the approach used is that the human response to an exposure at the beginning of life would simply be a shift of the curve relating spontaneous cancers to age in a direction giving the population an apparent age older than its actual one. The integral response in a population consisting of all ages at exposure would be governed by its age distribution. For populations with similar age distributions, the lifetime responses would quite possibly have a linear relationship to dose.

If the response in the population is indeed a leftward shift of the spontaneous cancer incidence (or mortality), the procedure already outlined can be followed to set upper limits on the sensitivity (apparent, not real) of the population at any age. For example, there are about 78 childhood cancers per year per 10^6 live births in the studies of Stewart and Kneale.[7] At 9 rads per year owing to age, that means 9×10^6 rads of radiation equivalent dose, or a maximum of 8.7 childhood cancers per 10^6 person-years per rad. This is about 15% of the 57.2 derived by Stewart and Kneale. The real value may be much lower, because the slope of the increase during the first 10 yr of life is much lower than is indicated by this calculation.

Similar calculations need to be made on the Mancuso, Stewart, and Kneale studies.[27,28] The maximum "sensitivity" should appear at 50 to 60 yr of age when the ratio of cancer mortality to all other mortality is highest. Note that the dose could be delivered at any age sufficiently early to allow for growth of the cancer.

In any case, the minimum value of 8 rads per year age equivalent dose, if it proves to be generally applicable, reinforces our experience with the difficulty of actual epidemiological measurements of the effects of doses of the order of 10 rads to human populations.

The method just outlined is, like all other methods, subject to change pending the final outcome of the ratio between observed and expected cancer mortalities. Because more than two-thirds of the population studied were still living in 1975, the uncertainty is large.

CONCLUSION

Data on human radiogenic cancers from several studies were presented in condensed form, and some considerations that apply to the interpretation of the data were discussed. It was concluded that retrospective case-control studies, as represented by the Oxford childhood cancer survey, have not established quantitatively a connection between prenatal irradiation and childhood cancer. A method for treatment of the ABCC data to reconcile Nagasaki and Hiroshima data was suggested. By this method a minimum value for the acute radiation dose equivalent of spontaneous cancers was found to be 8 to 10 rads per year.

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Biological Risks, An Editorial

Alvin M. Weinberg

During the incident at Three Mile Island, Pennsylvania Governor Richard Thornburg ordered the evacuation of pregnant women. Few people realize that this precaution was based on the contention by A. Stewart and G. W. Kneale (*Lancet*, June 6, 1970, pp. 1185-1188) that to double the natural cancer rate in children requires but 2 rads of in utero radiation, some 100- to 400-fold less than is required to double the lifetime cancer risk. The Stewart and Kneale finding is based on a retrospective study of 7649 English children who died of cancer between 1945 and 1960. These children received more prenatal X rays than did a matched group of children who did not die of cancer. According to Stewart and Kneale, this proved that prenatal X rays *caused* the cancers.

The Oxford childhood cancer study (A. Stewart, J. Webb, and D. Hewitt, *British Medical Journal*, 1958, pp. 1495-1508), summarized by Stewart and Kneale, has been controversial ever since it was published almost 20 years ago. The most compelling evidence to the contrary is the experience at Nagasaki and Hiroshima. Several hundred pregnant women received low-level radiation doses (between 1 and 250 rads to the fetus) in these cities. Were the Stewart and Kneale finding correct, about five cancers should have shown up among the children exposed in utero. In fact, only one cancer appeared—about what one would expect from the unirradiated controls. Two attitudes toward this discrepancy have appeared in the literature: (1) assume Stewart and Kneale are correct and explain the atomic bomb data, or (2) assume the atomic bomb data are correct and find the weaknesses in the Stewart and Kneale argument.

In contrast to the retrospective Stewart and Kneale study, the atom bomb cases constitute a *prospective* study—that is, irradiate randomly first and determine the consequences. A priori, one would expect these findings to be more reliable than those of the retrospective study. It is therefore reassuring that H. G. MacPherson and J. Totter at the Institute for Energy Analysis (IEA) have found a basic methodological error in the Stewart and Kneale analysis. For a retrospective radiation study to be sound, the probability that idiopathic cancer cases received radiation must be proved to be the same as the probability that the control population received radiation. In fact, the idiopathic cancer cases in the Stewart and Kneale study may have received more radiation than did the controls. In addition, the entire effect claimed by Stewart and Kneale seems to diminish with date of exposure, there being essentially no effect among children exposed after 1960. These findings cast serious doubt on the often-quoted contention that fetuses or young children are much more sensitive to carcinogenic effects of radiation than are mature individuals.

But the effects of low-level insult are intrinsically uncertain. In the face of such uncertainty, H. Adler of IEA and Oak Ridge National Laboratory has suggested that standards of exposure be set at a minimum level—that is, a level below which damage, if any, can be ignored. The level Adler suggests for ionizing radiation is the standard deviation of the natural background. He presented these views at a meeting in Vienna of the International Atomic Energy Agency. His point of view is now receiving serious attention within the National Council on Radiation Protection and has been used by B. Shleien of the Food and Drug Administration to arrive at standards for exposures in case of emergency.

C. RISK-BENEFIT CONCEPTS

Comparative Risk-Cost-Benefit Study of Alternative Sources of Electrical Energy

Adapted from WASH-1224, Chapter 1

Nucl. Safety, 17(**2**): 171–184 (March–April 1976)

[Editor's Note: The following article is excerpted from a report on the same subject prepared by the U. S. Atomic Energy Commission and issued as WASH-1224; it consists of the "Introduction and Summary" of that report, which the editors believe represents the most comprehensive assessment of the risks, costs, and benefits of coal, oil, natural gas, and nuclear fuel cycles when used to produce electric power. Of the extensive references included in the original document, only the more substantive are included herewith as a bibliography. Persons interested in reading the complete 243-page report and its 51-page appendix, entitled "Energy Expenditures Associated with Electric Power Production by Nuclear and Fossil Fueled Power Plants," may purchase them from the Superintendent of Documents, U. S. Government Printing Office, Washington, D. C. 20402, for $3.20 and $1.20, respectively.]

Abstract: *This study quantifies, normalizes, and compiles conventional and societal costs associated with the production of electrical energy by currently available alternative systems based on coal, gas, nuclear fuels, and hydroenergy. Particular emphasis is placed on examining each energy system in its entirety—both the power plant and its supporting fuel cycle. However, the study is restricted to routine impacts, including routine accidents whose frequencies can be established from historical data. From the available data, which are thoroughly referenced herein, it is concluded that natural gas incurs minimal environmental- and human-impact costs but remaining supplies are small; oil presents considerably greater environmental and human impacts but substantially less than those from coal, which is both the most serious environmental offender and the most abundant domestic fuel source. Nuclear fuels, which are abundant natural resources, have somewhat less environmental and human impacts than gas. The conventional fuel costs of coal and nuclear fuel cycles are comparable and considerably less expensive than gas or oil, but it appears that the cost of abatement and health and safety measures will significantly increase the cost of energy from coal over that from nuclear fuel.*

Reprinted below is Chap. 1, entitled "Introduction and Summary," of WASH-1224.

1.1 INTRODUCTION

The role of energy in sustaining and advancing civilization is fundamental and pervasive. It is difficult to identify a single artifact or activity of modern society which does not involve, either directly or indirectly, an expenditure of energy beyond that associated with man's muscular exertions.

In general, the production of a quantity of useful energy, such as a kilowatt-hour of electricity, involves several dimensions of cost:

(a) the diversion of conventional labor, material, and capital resources, all of which are normally reflected in the market price of energy;

(b) the consumption of a quantity of a nonrenewable fuel resource, thus precluding its use in the future;

(c) degradation of natural and man-made environments, including disruption of natural material, energy, and biological balances, and damage to man-made structures and materials;

(d) impacts on human health and safety.

Recently, popular attention has been drawn to the last two of these cost groupings, as evidenced by the staggering proliferation of energy and environmental studies in the past few years.

Concern over environmental impacts of producing electrical energy has often focused on very narrow aspects of individual electrical energy production systems,* such as thermal effects of discharge heat from power plants, mining impacts, and air pollution. For this reason, the quantitative environmental literature on electrical energy production is, to a large extent, fragmentary and redundant.

A more balanced and coherent view requires that costs and impacts throughout entire fuel cycles be identified, quantified, normalized, and compared on a consistent basis. As part of a continuing analysis of the role of nuclear power in providing the Nation's energy requirements, the Division of Reactor Research and Development of the United States Atomic Energy Commission has undertaken such an assessment—the "Comparative Risk–Cost–Benefit Study of Alternative Sources of Electrical Energy."

Purpose and Scope

The purpose of this study is to provide a quantitative basis for making comparisons of societal costs across and within alternate electrical energy production systems. The principal tasks in achieving this goal are to assign internal and external costs of the alternate systems to a common unit of electrical energy produced (kilowatt-hours) and to express such costs, where possible, in consistent units (dollars). Fuel cycle material balances provide the central format for assembling and normalizing data and provide the quantitative link between an impact or cost anywhere in the system and a corresponding quantity of electrical energy (benefit) produced.

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*The terms "electrical energy production system" and "fuel cycle" are used synonymously in this report.

Such information could provide a preliminary basis for numerous ancillary comparisons and cost–benefit tradeoffs, including: (a) comparisons of total costs (internal plus external) of producing electrical energy from alternate fuels; (b) comparisons of external and internal costs for each process step within each fuel cycle, in order to determine which steps are the most environmentally offending, and in order to measure the cost–effectiveness of abatement measures; (c) comparison of external costs of alternative methods for the same functional step in a given fuel cycle; and (d) comparison of the total costs associated with alternative energy strategies, or mix of fuels, to meet a given energy demand projection over a period of time and (e) coherent judgments regarding abatement measures, which, while reducing an impact at one stage in an energy system, may increase impacts at another.

The following restrictions and assumptions serve to further define the scope of the study.

- The study is confined to *electrical* energy. A more comprehensive assessment would include all forms of end-use energy ("total energy"). Benefits and costs of substituting electrical energy for other forms are not addressed, although the coefficients developed in the course of this study can be useful in such analyses.

- The study is restricted to electrical energy *production* and embraces entire fuel cycles and their residuals. Questions regarding electrical energy use are not addressed, although alternative electrical energy-use patterns may have significant environmental and economic differences.

- Attention is restricted to modern, commercial size, base load power plants and their supporting fuel cycle facilities, and to those systems based on technologies whose commercial application is proven. The analysis includes only those systems expected to make major contributions to base load power production in the near term, i.e., the next ten or fifteen years. Systems considered are those based on coal, residual fuel oil, natural gas, nuclear fission (LWR) [light-water-reactor] fuels, and hydroenergy. Although two types of advanced nuclear fission reactors—the HTGR [high-temperature gas-cooled reactor] and the LMFBR [liquid-metal-cooled fast breeder reactor]—are expected to make significant contributions to base load power by the end of this century, these concepts are not addressed quantitatively in this report. Electricity generation using gasified coal is similarly excluded.

- The study is restricted largely to quantification of the environmental and human impacts of the energy systems under *normal* operating conditions. Certain classes of routine industrial accidents, for which reliable statistics are available, are treated, however. Large, hypothetical accidents at a nuclear power plant are excluded, since other concurrent USAEC studies are addressing this topic.

- "Benefit" in this study is defined as a quantity of electrical energy, e.g., one kilowatt hour. No attempt is made to determine the absolute societal value of electricity. That is, the question addressed is not *whether* a unit of electrical energy should be produced, but instead *how* it should be produced.

- "Risks" are treated as "costs" in this study: the product of the probability of an undesirable event (per unit of electrical energy) times the consequences of the event.

- "Costs" include both "internal" and "external" costs. Internal costs are those costs already borne by electricity consumers. Internal costs are already imbedded in the price of electricity (mills/kWhe) and include the conventional components—labor, materials, and costs of capital. External costs are the environmental and human impacts not accounted for in the price of electricity.

With the definitions of benefit, risk, and cost established above, the study reduces to a comparison of total costs to produce electricity by alternative fuels.

- Much of the information assembled in this report is based on aggregate national data. In this sense, the assessment assumes a national homogeneous model, at the expense of displaying regional variations in unit costs, impacts, engineering and economic constraints, local utility company practice, site-specific considerations, and the like. For example, in order to properly burden a quantity of electrical energy with coal mining impacts, it is necessary to assume production fractions from surface and underground mining techniques. Although the unit impacts of production methods are disaggregated and displayed separately in the body of the report and in other supporting materials,* production fractions representative of the current national pattern (~50% underground, ~50% surface) are assumed for the purpose of constructing summary tables. The same general approach was taken in several other elements of the assessment.

- The bases for normalization of costs and impacts are 1000 MWe of electrical generating capacity, or the annual operation of one 1000-MWe unit at 75% capacity factor (6.57 billion kWhe).† All fuel cycle parameters are normalized to these quantities through *equilibrium* fuel material balances. The resulting evaluation is a static comparison of costs and impacts associated with alternate energy systems. It is recognized, however, that the overall problem of ranking alternatives is a time-dependent one, and that alternatives must be regarded as changing mixes of energy sources or energy strategies rather than as individual, isolated sources. The development of static impact coefficients, the central task of this study, is a prerequisite of the broader assessment of comparing energy strategies.

1.2 SUMMARY AND CONCLUSIONS

Summary

For purposes of making gross comparisons, representative costs and impacts of alternative electrical energy production systems were assembled and normalized to 6.57 billion kilowatt hours (kWhe), the annual energy produced by one 1000-MWe unit operating at 75% capacity factor. Systems considered were those based on coal, oil, natural gas, and nuclear fission fuels.‡ Attention is restricted to

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*And are available to the reader in substituting his own assumptions.

†Some impacts and costs are related to a unit of electrical energy produced (kWhe), while others are related to power capacity (MWe).

‡The hydroenergy system is discussed qualitatively in Chapter 3. Little quantitative information is developed, since relatively little additional hydro capacity is expected to be installed.

modern, commercial size, base load power plants and their supporting fuel cycle facilities, and to those systems based on technologies whose commercial application are proven. Although two advanced reactor types, the HTGR and the LMFBR, are expected to make significant contributions to base load power production by the end of the century, this study includes a quantitative appraisal only of the current generation of power reactors—the LWRs. Emphasis of the report is on quantifying effects throughout the respective fuel cycles, from fuel extraction to power generation, as conceptualized in Fig. 1. Where possible, nonconventional costs were reduced to a common basis (same unit of electrical energy produced) and to common units (dollars), thus rendering them comparable and, perhaps, additive.

The information assembled and normalized in this report emerged from an extensive literature survey aimed at quantifying numerous individual impacts and costs. In most cases, the individual impacts and costs displayed in this report are *derived* quantities. Individual items of data were rarely found in the desired format, that is, restricted to the particular impact or cost under consideration *and* normalized to a unit of electrical energy produced or to a unit of production capacity. For each item addressed, considerable manipulation—disaggregation, interpretation, averaging, normalization—was necessary to reduce the quantity to consistent and meaningful information. In several cases, only source terms, e.g., pollutant emission rates, are presented. Ideally, one would reduce all such quantities to ultimate impacts in consistent damage units to permit their display as added costs.

Table 1 summarizes comparative data for the alternate fuel cycles normalized to production of 6.57 billion kWhe or to a generating capacity of 1000 MWe.* The format of Table 1 warrants some explanation. First, much of the data represents sums over the individual fuel cycle process steps. Chapters 3 and 5 give similar data for each process step, permitting the reader to make comparisons among process steps of individual fuel cycles or among similar process steps (e.g., mining) across competing fuel cycles. Further, it is recognized that the organization of a table such as Table 1 can prejudice and distort a comparative assessment, e.g., the grouping of data under descriptive headings, the selection of "typical" or "representative" parameters, the omission of impacts not quantifiable, etc. In this regard, great care was taken to present an objective set of impacts and costs, assembled in a coherent, but uncontrived, matrix. Entries in Table 1 are arranged to conform roughly to the four conceptual groupings of costs and impacts established in the Introduction: (a) conventional costs; (b) consumption of nonrenewable fuel resources; (c) environmental degradation; and (d) impacts on human health and safety.

The major categories of Table 1 are discussed briefly below.

Power Plant and Energy System Efficiencies

Power plant net thermal efficiencies for the fossil plants are essentially the same—38–39%. The LWRs, PWR [pressurized-water reactor] and BWR [boiling-water reactor], have somewhat lower net thermal efficiencies, ~32%, owing to their coolant temperature limitations.

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*Some impacts and costs are related to a unit of production, while others are related to system capacity.

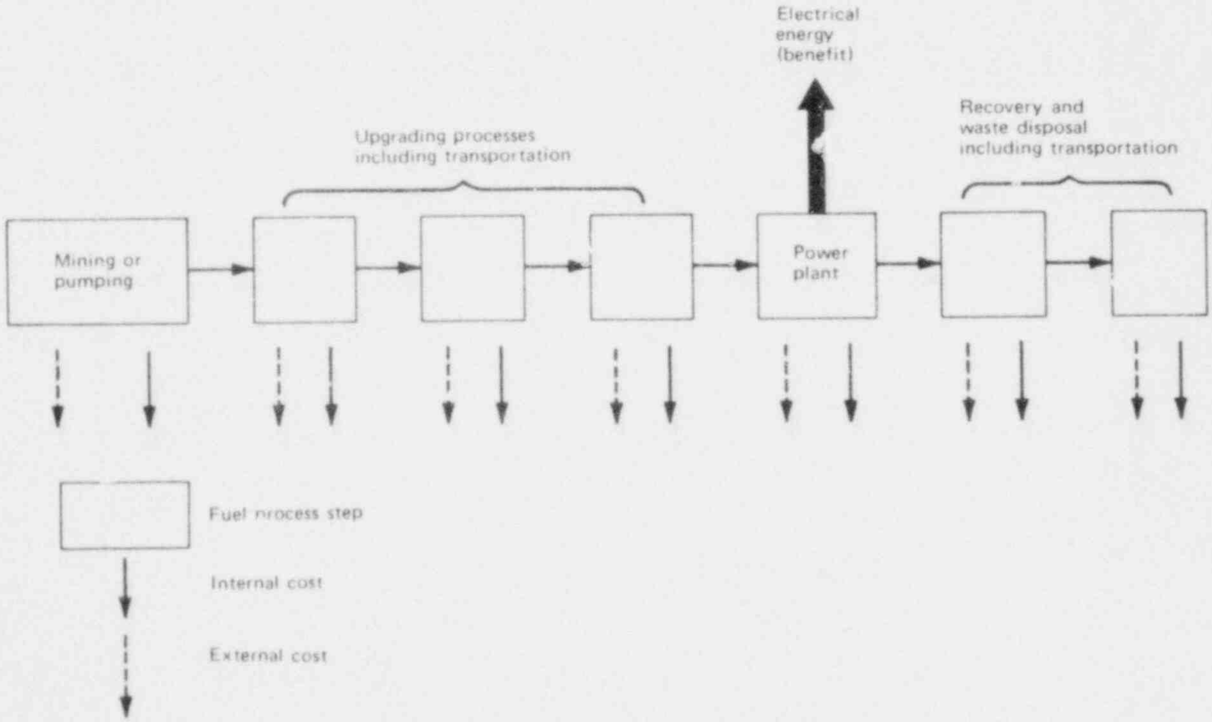

Fig. 1 Schematic of a fuel cycle (energy production system). From WASH-1224.

Table 1 Comparison of Costs and Impacts of Alternate Electrical Energy Production Systems*

Basis: 1000-MWe Power Plant, 75% CF, 6.57 × 10^9 kWhe

	Coal	Oil	Gas	LWR
Power plant and energy system efficiencies				
Electrical energy (billion kWhe/year)	6.57	6.57	6.57	6.57
Power plant heat rate (Btu/kWhe)	8,900	8,830	9,110	10,850
Power plant thermal efficiencies (kWe/kwt, %)	38	39	38	32
Energy system efficiency (kWhe consumer/kWht input, %)	35	35	34	28
Consumption of nonrenewable fuel resources				
Power plant fuel consumption (annual)	2.3 M tons	10 M barrels	64 B cubic ft	~130 M tons U†
Fraction of reserves consumed (annual)	0.000006	0.0001	0.0004	0.0002
Conventional costs (mills/kWhe)‡				
Plant	7.8	7.2	6.4	11.7
O&M	0.8	0.6	0.6	0.8
Fuel	9.8	27.4	36.0	6.0
Total	18.4	35.2	43.0	18.5
Selected abatement costs (mills/kWhe)‡	4.7	2.0	0.6	0.6
Occupational health and safety				
Occupational health (MDL/year)	600	U	U	480
Occupational safety				
Fatalities (deaths/year)	1.1	0.17	0.08	0.1
Nonfatal injuries (number/year)	46.8	13.1	5.3	6.0–7.0
Total man-days lost (MDL/year)	9,250	1,725	780	900–1000
Public health and safety				
Public health				
Routine pollutant release (MDL/year)	U	U	U	180–210
Public safety				
Transportation injuries				
Fatalities (deaths/year)	0.55	U	U	0.009
Nonfatal (injuries/year)	1.2	U	U	0.08
Total man-days lost (MDL/year)	3,500	U	U	60
Environmental degradation				
Land				
Land use, inventory (acres)	22,400	~1,600	~3,600	~1,000
Land use, consumption (acres/year)	740	S	S	12
Air				
SO_2 release, without abatement (tons/year)	120,000	38,600	20	3,600

*The number of digits shown is not generally indicative of precision. In many cases, several digits are retained merely for calculational purposes. U = unevaluated; S = small; M = million; B = billion; T = thousand.

†About 99% of this figure is not irretrievably consumed; rather, it is available in the form of enrichment plant tails for use in breeder reactors.

‡1980 dollars.

Table 1 (Continued)

	Coal	Oil	Gas	LWR
Environmental degradation (continued)				
Air (continued)				
SO_2 release, with abatement (tons/year)	24,000	21,000	0	720
NO_x release, without abatement (tons/year)	27,000	26,000	13,400	810
Particulate releases, without abatement (tons/year)	270,000	26,000	518	8,000
Particulate releases, with abatement (tons/year)	2,000	150	4	60
Trace metals releases (tons/year)	0.5 Hg	1,500 V	U	S
Radioactivity releases (Ci/year)	0.02	0.0005	S	250–500 T
Thermal discharge, power plant stack (billion kWht/year)	1.64	1.71	2.2	0
Water				
Cooling water use (billion gal/year)	263	263	263	424
Process water use (billion gal/year)	1.46	1.75	1.42	0.095
Radioactivity releases (Ci/year)	0	0	0	500–1000
Other impacts (billion gal/year)	16.8	7.9	0	S
Thermal discharge, power plant (billion kWht/year)	9	9	9	14

Overall energy system efficiencies include corrections for process heat and electrical energy requirements of the supporting fuel cycle operations. For all systems, process heat requirements for the supporting fuel cycle are negligible compared to the heat input at the power plant. Fuel cycle electrical energy requirements are also negligible, except for the diffusion-enrichment plant requirements for the LWR systems, which are of the order of 3 to 5% of the power plant output. Transmission losses are assumed the same for all systems.

The fossil fuel cycles have similar systems efficiencies—~35%. The LWRs have lower system efficiencies, ~28%, due both to their lower power plant efficiencies and their enrichment plant power requirements.

More detailed analyses of the overall fuel cycle energy balances are given in Chapter 5 and in the Appendix.

Consumption of Nonrenewable Fuel Resources

The availability of fuel at acceptable cost is a major consideration in selecting a power plant type. For example, fuel shortage offsets the environmental benefits of the natural gas system. Annual fuel consumption of each 1000 MWe plant is expressed in Table 1 as a fraction of reserves available for U. S. electric power production, at current extraction costs and with current extraction technology. Current alternative-use fractions were used to establish the reserve base available to the U. S. electricity production. Residual fuel oil (RFO) assumed to be available from Africa and Venezuela is included in the RFO reserve base.

Coal is seen to be the most abundant fossil fuel resource, natural gas the least. Foreign deposits place the RFO system on a par with the LWR systems.

Fuel resource data are given for each of the mineral fuels in Chapter 3 and reduced to equivalent quantities of electrical energy in Chapter 5.

Conventional Costs

Conventional costs are those definable costs already imbedded in the price of electricity to the consumer—the costs for labor, materials, and use of money. They include the capital cost of power plant amortized over the life of the plant, plant operating and maintenance costs, and fuel costs. Fuel costs include costs incurred throughout the fuel cycle, including capital costs of fuel cycle facilities. These costs are ultimately transferred to the utility company and, together with utility company working capital changes associated with fuel, borne by the consumer.

Representative conventional costs, corrected for escalation to the year 1980, are shown in Table 1. The purposes of including conventional costs in this report are to show roughly the market competitiveness of the alternate energy systems and to provide reference points for comparison of nonconventional costs. Where possible, costs associated with abatement and restoration measures have been separated from the conventional costs.

It should be recognized that conventional costs are quite sensitive to power plant location. Further, a number of factors cause such costs to vary with time—routine inflation, abundance of fuel resources, capacity/throughput effects, legal and regulatory actions, technological maturity, etc.

Abatement Costs

Abatement costs in Table 1 include SO_2 removal from stack gases (coal), desulfurization of residual fuel oil, natural-draft evaporative cooling towers (all plants), near-zero radwaste systems (LWRs), and surface-mined land reclamation. This is not, of course, a complete list.

Abatement costs in the coal cycle are the greatest, due to the large cost projected for SO_2 removal. The desulfurization of residual fuel oil is the dominant abatement cost in the oil cycle. The near-zero radwaste treatment systems add little to the LWR energy costs.

Environmental Degradation

Burden rates on the environmental receptors*—land, air, and water—are displayed in Table 1, with the intent of presenting crude measures of relative environmental impacts of the alternate energy systems. In most cases, these burden rates are merely source terms, i.e., emission rates normalized to a quantity of electrical energy produced. Ideally, these quantities would be reduced to incremental quantities of damage to ultimate receptors, such as natural flora and fauna, structural materials, crops, and the like. Dollar costs could then be assigned to units of damage. Owing largely to the lack of damage-function information for each pollutant–receptor combination, this procedure could not be followed rigorously.

Two aspects of land use are included in Table 1: land tied up or committed by the power plants and their supporting fuel cycle; and the land "consumed" annually, e.g., land disturbed by surface mining, or land inundated by disposal of fuel cycle residuals. The coal fuel cycle has the greatest land impact, owing mainly to its mining operations and waste disposal. Inventory land requirements for the nuclear fuel cycles are magnified by exclusion-area requirements but are still an order of magnitude less than that of the coal cycle.

Annual emissions of sulfur oxides, nitrogen oxides, particulates, radioactivity, heat, mercury, and vanadium to the atmosphere are shown in Table 1. The coal energy system releases greater quantities, per unit energy produced, of SO_2, NO_x, and particulates than do the other fossil systems. For purposes of comparison, electrical energy required for the gaseous diffusion enrichment of LWR fuel is assumed to be provided by a coal-fired plant, and prorated quantities of coal cycle pollutants are, accordingly, assigned to the LWR fuel cycle.† It is interesting to note that on this basis, the LWR cycle "emissions" of SO_2 and particulates are greater than those of the natural gas fuel cycle. Thermal releases to the atmosphere are about 15% of the total heat rejected by fossil power plants. There are, of course, no atmospheric thermal releases at nuclear power plants. Minute quantities of radioactive materials are routinely released from nuclear facilities to the atmosphere. These emissions are of primary concern to public health, and are discussed below, together with fossil pollutants, under the heading "Public Health and Safety."

Light-water reactors, because of practical coolant temperature limitations, operate at lower thermal efficiencies and, therefore, reject more heat than modern fossil fuel plants of the same generating capacity. For this reason and because about 15% of the heat from fossil-fueled plants is discharged into the atmosphere through the stack, LWRs discharge about one-third more waste heat to cooling water than do modern fossil-fueled plants.

Process water use in the LWR fuel cycle is essentially negligible compared to that in fossil fuel cycles, due both to the nature of the processes themselves and to the relatively small masses and volumes of fuel materials involved. Chemical contamination of waterways is similarly small. Chemical contamination in the fossil system includes acid mine drainage in coal fields, black water from coal cleaning plants, and oil spills, ballast discharge, and refinery effluents in the oil system.

As discussed in Chapter 4, damage functions for each pollutant–receptor combination are not well established. Thus, any measure of damage costs, normalized to annual emission rate, must be regarded as a gross preliminary estimate. Section 4.9 gives crude measures of the dollar costs imposed by damage from coal, oil, and natural gas plant SO_2 and particulate emissions. Section 4.10 presents estimates of dollar costs associated with impacts (largely consumptive water use) of waste heat rejection by natural-draft wet cooling towers. Estimates of other damage costs—associated with mine land disruption, oil spills and ballast discharge, and biological oxygen demand of refinery effluents—are given in Section 4.11. All of these damage costs are summarized in Table 2. More detailed discussions are provided in the Appendix.

Occupational Health and Safety

Table 1 displays occupational health effects for coal and nuclear energy systems in units of man-days lost (MDL).

The dominant occupational health effect in the coal fuel cycle is coal workers' pneumoconiosis (CWR), or "black lung," a respiratory disease resulting from the

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*Effects on human health and safety are frequently included in the term "environmental effects." In this study, human health and safety are considered separately. The next two sections deal, respectively, with occupational and public health and safety.

†This is, of course, a purely arbitrary assumption, although the existing diffusion capacity is powered by coal-fire power plants. Notwithstanding recent publicity to the contrary, coal is not uniquely required for the production of enriched nuclear fuel. Some electricity (a few percent of the equivalent electrical energy yield of the nuclear fuel) is required, and any fuel which produces electricity will do.

Table 2 Comparison of Conventional Costs and Some Evaluated Nonconventional Costs of Alternate Energy Systems*

Basis: Annual Operation of One 1000-MWe Power Plant and Supporting Fuel Cycle (6.57 billion kWhe), in 1980 Dollars

		Coal	Oil	Gas	LWR
Conventional costs	($10^6/year)				
Capital plant		51	47	42	77
Fuel cycle		64	180	237	39
O&M		5.4	4.0	3.7	5.2
Rounded totals		120	231	283	121
Abatement costs	($10^6/year)				
Cooling towers		3.6	5.9	7.1	2.4
Sulfur/SO_2 removal		25.9	4.9	NA	NA
Strip-mined land reclamation		0.1	NA	NA	S
Near-zero radwaste		NA	NA	NA	1.2–1.8
Rounded totals		30	11	7	3–4
Conventional and abatement	($10^6/year)	150	242	290	125
Abatement component	(%)	20	5	2	3
Safety	($10^6/year)				
Occupational†		0.46	0.086	0.039	0.05
Public‡		0.18	U	U	0.003
Subtotal		0.64	0.086	>0.039	0.053
Health	($10^6/year)				
Occupational		0.03§	U	U	0.024¶
Public		U	U	U	0.01**
Subtotal		>0.03	U	U	0.034
Total human health and accident costs	($10^6/year)	>0.67	>0.086	>0.039	0.087
Environmental effects	($10^6/year)				
Water base		0.4	0.4	0.4	0.6
Air base		0.8	0.6	0.1	S
Land base		0.2	S	S	S
Subtotal		1.4	1.0	0.5	0.6
Total human and environmental effects	($10^6/year)	2.1	1.1	0.5	0.7
Percent of conventional	(%)	3	1	0.5	0.9

*U = unevaluated; NA = not applicable; S = small.

†Conventional injuries in routine industrial accidents, including fatal and nonfatal injuries; 1 death = 6000 MDL = $300,000.

‡Conventional injuries in accidents in transportation of fuels; 1 death = 6000 MDL = $300,000.

§Coal workers' pneumoconiosis (CWP).

¶Radiological health effects, including lung cancers among uranium miners.

**Radiological health effects from routine emissions.

accumulation of coal dust in the lungs of underground miners. An advanced stage of this disease is progressive massive fibrosis (PMF). Crude estimates of the frequency (normalized to 6.57 billion kWhe) of CWP cases are compared to estimated occupational health effects in the light-water reactor fuel cycles—lung cancers among uranium miners due to inhalation of radon gas, and cancers resulting from occupational exposures to radiation at the reactor and reprocessing plants (6000 MDL is assigned to each malignancy; 1000 MDL is assigned to each case of simple CWP).

It is estimated that on the order of one case of black lung can be attributed to the mining requirements associated with one 1000 MWe coal-fired plant per year.* By comparison, on the order of one malignancy would be expected in the light-water reactor fuel cycles, per 1000 MWe plant, during the life of the plant (~30 years).

Occupational health is addressed in more detail in Sections 4.4, 4.6, 4.7 and in the Appendix.

Occupational injuries due to routine industrial accidents occur throughout the alternate fuel cycles. Table 1 gives injury rates, normalized to the annual operation of a 1000-MWe power plant. Injuries in the coal cycle exceed, by far, those in the other fuel cycles. About one occupational fatality per year can be attributed to each 1000-MW(e) coal-fired plant. The dominant source of coal-cycle injuries is underground mining.† The injury rates in the oil, gas, and LWR fuel cycles are roughly equivalent—an order of magnitude below that of coal. Mining in the nuclear fuel cycles accounts for most of the injuries in these cycles. Because of the high-energy content of nuclear fuels, nuclear fuel mining injury rates are much lower than those in coal mining.

Public Health and Safety

Public health effects of electricity production are extremely difficult to assess. Pollutant emission rates at the power plant or at a fuel process step in the supporting fuel cycle are first estimated. A thorough understanding of the process in question and a careful description of the material flows involved in the process are normally sufficient to yield a fairly accurate emission rate, normalized to a given quantity of electrical energy produced. Transport of the pollutant through various pathways to man, or to alternate fates, must next be analyzed. Factors involved in this step are local meteorology, hydrology, pollutant reconcentration mechanisms, pollutant loss mechanisms, biological uptake mechanisms, population distribution, and the life style, including diet, of the population. Human exposure levels and rates must then be assessed to determine dose. Finally, the health damage corresponding to this dose (using an appropriate dose–response function or coefficient) must be evaluated, and, if warranted, a dollar cost may be assigned to the incremental health damage.

The establishment of dose–response relationships is at present the weakest link in this procedure. The relationships between health effects and pollutant concentrations (or dose levels) are generally established by epidemiological studies on statistical samples of the human population, or laboratory studies on animals. Animal studies require that results be scaled in some manner in order to estimate human effects.

Table 1 contains crude estimates of public health effects (in units of man-days lost) of the routine radioactivity emissions from the nuclear fuel cycles. (A total of 6000 MDL is assigned to each malignancy.) These figures are based on a very conservative dose–response coefficient of the order of ~0.0001 malignancy per rad and the emission rates in curies per ton of fuel processed or per MWhe estimated in the present study. Section 4.4, the Appendix, and the footnotes of Section 3.5 describe these calculations in more detail.

Unfortunately, human health hazards from fossil fuel pollutants are not as well understood and quantified as the health hazards from radiation. There are no dose–response data comparable in quality to therapeutic irradiation and atomic bomb casualty data and no linear dose–response model, both of which are so useful in estimating (however conservatively) radiation effects. Numerous measures of health effect have been investigated but no preeminent measure has emerged which is analogous to malignant neoplasm in the case of radiation. Toxicologic studies on animals have demonstrated that massive doses of specific chemicals such as sulfur dioxide may impair health. Likewise, chronic exposures of animals have demonstrated health effect. Correlations between various measures of human respiratory impairment, including death, and levels of air pollution have been observed during and following episodes of exceptionally high concentration of air pollutants. However, there is no information on the effect of individual exposure to specific pollutants during such episodes, and no dose–response relationship can be formulated. This same lack of exposure information plagues the attempt to establish pollutant–response correlations through study of chronic exposure. Several regression formulas have been developed which relate measures of mortality and morbidity to measures of general air pollution levels, such as sulfur dioxide concentrations and concentrations of particulate matter. These formulas are of no use for the prediction of health effect as a function of pollution level because they have not been based on known and controlled populations, the exposure measures relate to concentrations made at several geographical locations but are not a measure of personal exposure, and the full spectrum of air pollutants is not represented in the equations. Although a quantitative comparison between radiation health effect and fossil air pollution health effect is an essential part of the comparison of nuclear and fossil fuel cycles, no quantitative estimate of fossil air pollution health effect, normalized to a unit of electrical energy produced, can be made at this time.

While it is not feasible, at this time, to normalize public health effects to a unit of energy produced, some perspective can be gained by comparisons of natural background levels, man-made exposures, regulatory standards, and broad ranges of pollutant concentrations known to result in

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*[This] assumes 50% production in the power plant from underground mines. [It] also assumes that future U. S. coal mining health impacts, after implementation of the 1969 Act, will be similar to British experience.

†Occupational injury figures of Table 1 assume 50% production from underground mines, 50% from surface mines.

some health effect. Figure 2 illustrates the comparisons for sulfur dioxide, nitrogen oxides, and whole-body irradiation. The areas labeled "medically perceivable effects" are adapted from a recent University of California study.* Several tentative conclusions may be drawn from Figure 2.

(a) Environmental Protection Agency standards for SO_2 and NO_2, applicable to fossil-fired power plants and other man-made sources of these pollutants, are above natural background levels of these pollutants. Current USAEC regulations (10 CFR 20) for radiation exposure are about equivalent to doses from natural background sources. However, the new proposed "as low as practicable" guidelines (10 CFR 50, Appendix I), applicable to light-water reactors, would restrict individual doses to orders of magnitude below that from natural sources.

When man-made and natural sources are added, the total levels permitted by regulations or guidelines are:

- about a factor of 100 over natural background for SO_2;
- about a factor of 4 over natural background for NO_2; and
- about a factor of 2 over natural background (10 CFR 20) or about a factor of 1.01 over natural background (10 CFR 50, Appendix I)† for radiation.

(b) As expected, ranges of medically perceivable effects are well above natural background levels for all three pollutants.

(c) With the exception of SO_2, the standards are well below the range of medically perceivable effects.

(d) Actual average annual radiation whole-body exposures from nuclear power facilities in 1970 were several orders of magnitude below the existing standards (10 CFR 20) and natural background. Concentrations of fossil pollutants (together with background) were substantially above background levels in 1970.

The discussion above was restricted to effects on public health of routine pollutant releases from the energy system. Of concern also is public safety, more specifically, the hazards to the public from conventional accidents in transporting fuels.‡ Of the various process steps in the

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*D. Hausknecht, *Public Health Risks of Thermal Power Plants*, University of California, May 1972.

†Proposed.

‡Hypothetical, large scale–low probability accidents at power plants and supporting facilities are not addressed in this study.

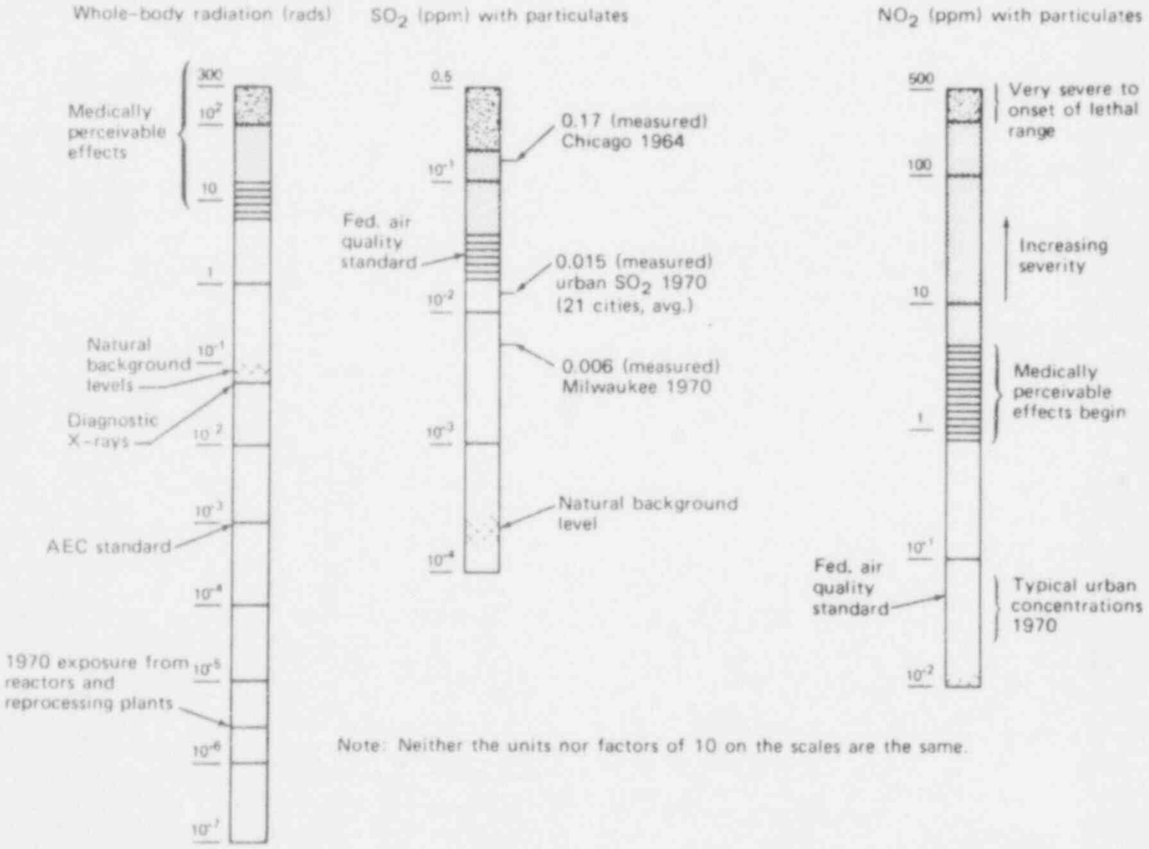

Fig. 2 Comparison of pollutant standards, background levels, man-made exposures, and health effects. From WASH-1224.

electricity production systems, fuel transportation is the dominant source of accident risk to the public since it is in the transportation of fuel that the public comes in closest contact with the energy production system. Routine industrial accidents at power plants and fuel processing facilities usually affect only occupational personnel. Table 1 compares public injury rates associated with transporting fuel required for 1000-MWe coal-fired and LWR power plants.

Radiological and chemical risks associated with transporting fuels, which are orders of magnitude below risks of conventional impact-injury,* have been excluded.

Because of the large masses and volumes of fuel involved, coal transportation imposes a much more severe public safety hazard than transportation of nuclear fuels. Public injury rates in coal transportation are, in fact, comparable to occupational injury rates in coal mining. The transportation of coal for a 1000-MWe plant results in a statistical public death about every two years—this almost entirely due to accidents at railroad grade crossings. Thus, about one-third of the total fatalities attributable to the coal fuel cycle are public fatalities, the other two-thirds being occupational fatalities largely in underground mining.

A more detailed treatment of conventional injury rates in fuel transportation is given in the Appendix.

Nonconventional Costs in Perspective

Although normalized to the same quantity of electrical energy produced or production capacity, the quantities in Table 1 are in a variety of physical and nonphysical units. Quantities along a single row are, however, in consistent units, so that comparisons can be made across competing energy systems. Ideally, one wishes to reduce all such quantities to the same dimension, e.g., dollars, in order to make dissimilar categories of impact within each energy system comparable, and perhaps, additive, making possible comparisons of total societal costs across competing energy systems. For example, one might wish to compare the occupational radiological health impact in the LWR system to the conventional costs of producing electrical energy in this system.

Efforts to assign dollar values to nonconventional costs are highly preliminary, subjective, and generally imperfect. However, in several specific cases, it *is* possible to make gross assessments useful in making order-of-magnitude comparisons.

Table 2 compares conventional costs of producing electrical energy [by alternate energy systems] and several categories of environmental and human impacts which were reduced to dollar costs [for the same systems]. This table represents the highest degree of summation and condensation considered feasible, useful, and appropriate in this study. The table aggregates numerous quantities derived and presented in a labyrinth of supportive materials in the main report and the appendices. Further condensation could lead to misinterpretation and gradual vitiation through succeeding generation of studies. The limitations and uncertainties of the information displayed in Table 2 warrant further discussion. These qualifications do not, however, invalidate the major conclusions and findings of the study.

Additive Costs

One of the tasks of the study was to reduce numerous quantities to a consistent basis (same unit of electrical energy produced) and to consistent units (dollars) in order to render them comparable and additive. All costs, internal and external, should be summed to obtain a total societal cost.

Adding any set of quantities to obtain a total requires that they not only be in consistent units, but also that they be (a) exhaustive and (b) mutually exclusive. Put another way, this means that one should include *all* of the costs, and that one should avoid counting something twice.

The categories and quantities of Table 2 are not exhaustive. One notable omission is the public health effect of airborne fossil pollutants, which, for reasons discussed in more detail in the text, could not be quantified. For this reason, the health subtotal for the coal system may be low by an order of magnitude.

Neither are the quantities of Table 2 mutually exclusive. For example, the conventional costs displayed may indeed contain components such as workers' compensation and insurance, tending to internalize occupational health and safety impacts. In many such cases an exact separation of costs could not be achieved.

Uncertainties

There are several degrees of uncertainty among the quantities presented in Table 2. Uncertainties increase, generally, as one moves from top to bottom and from left to right in Table 2. In general, it was found that small quantities were attended by the greatest uncertainty. This is understandable, since small quantities are frequently masked by large ones; the hazards of dealing with small differences between large numbers are well known among scientists and engineers. Fortunately, in the context of this report, small quantities are less important than large ones.

Conventional costs, the largest of the quantities presented, are the most accurately known. A band of ±15% is assigned to cover regional and local variances and uncertainties in escalating labor, materials, and money costs to 1980. Abatement costs, because they can be tied to specific equipment and procedures, are roughly as accurate as the conventional costs displayed.

Rates of occupational injuries in the coal cycle are considered quite accurate and representative. For example, statistical fluctuations in fatalities per million miner-hours appear very slight; the gradual reduction in mining injuries from 1955 to 1967 appears systematic, suggesting that such injuries may be regarded for practical purposes as deterministic and accepted. By contrast, injuries in uranium mining, because they are fewer, appear highly random. Accordingly, a broad confidence band of ±50% is assigned to nuclear system injuries. Similar comments apply to public injuries in transporting coal and nuclear fuels.

Accidental injuries can be counted as discrete events and assigned to specific activities, e.g., mining, transporta-

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*USAEC, *Nuclear Fuel Transportation Study* (to be issued).

tion, etc. By contrast, health effects are amorphous, difficult to define, and often impossible to assess quantitatively with current knowledge of dose–response characteristics. For this reason, health damage costs displayed in Table 2 should be regarded only as order-of-magnitude estimates based on the best available information. Radiological health impacts of nuclear power production are considered to be conservative, i.e., overestimated, in that they are based on a linear dose–response extrapolation.

Life Values

Health and injury costs were assessed at $50 per man-day lost, leading to a life value of $300,000 if one assumes 6000 man-days lost per death. These are arbitrary figures, assigned to permit rough comparisons, and carry with them no implied comment on the absolute value of human life. The $300,000 per death figure is, however, in accord with several independent assessments. The reader may adopt his own values by scaling the health and accident costs of Table 2.

Summary of Limitations

To summarize, several limitations and shortcomings of Table 2 were discussed above:

- the costs tabulated do not form a complete set, nor are they mutually exclusive; for this reason, the table does not yield total social costs of producing electricity;
- in several categories, only very crude estimates of nonconventional costs could be made; in general it was found that small quantities are attended by the greatest uncertainty; and
- the unit costs of $50/MDL and $300,000/death, assigned more or less arbitrarily to permit comparisons of health impairment and injury costs with conventional costs, are highly subjective, and may be readily challenged on emotional and moral grounds. None of these shortcomings, however, invalidate the major conclusions and findings of the study, reviewed in the next section. The salient point is that even drastic changes in the very small quantities in question will not propel these quantities to dominant importance.

Choice of life value, if applied consistently, will not distort the relative impacts of the competing energy systems. Further, whatever value is assumed, within reason, the health and injury costs will remain small compared to the conventional costs of producing electricity. Similarly, the large uncertainties in the environmental, health, and injury figures do not alter the conclusion that these costs are small compared to conventional costs. The same general argument could apply to overlaps and omissions in the table.

Conclusions

1. Costs associated with human health and injury effects, both occupational and public, of new power stations and their respective prorated supporting fuel cycles, are small compared to conventional energy costs (less than 1%). This conclusion excludes public health effects of airborne fossil pollutants—SO_2, NO_x, particulates, trace metals—which could not be quantified.

2. Total nonconventional costs—including health, injury, and environmental impacts—are small compared to conventional energy costs (less than 3%).

3. In view of conclusions 1 and 2, ultimate fuel resource availability is apt to have greater influence, in making national choices among energy systems, than environmental considerations. Coal and nuclear fuels are the most abundant domestic fuels for electricity generation. This assumes that greater nuclear fuel utilization is achieved through the conversion of fertile nuclides to fissile nuclides, as in the fast breeder reactor. A host of factors affecting supply of residual fuel oil and natural gas make extensive, long-term base load use of these fuels doubtful.

4. Health and injury impacts are greater for occupational personnel than for the public.

5. Specific judgments concerning the cost–effectiveness of various abatement measures cannot be supported by the data available. Although costs of abatement measures can be estimated with some degree of accuracy, corresponding incremental costs of damage avoided are difficult even to estimate by order of magnitude, owing to the lack of damage function (dose–response function) information.

6. The overall problem of ranking alternatives is a time-dependent one, and alternatives must be regarded as mixes of energy sources through time rather than as individual isolated sources. It is probable that all sources will be welcome to meet the rising demand for electrical energy. For this reason, a quantitative ranking or scoring among individual energy systems, based on static parameters, is unwarranted. However, some qualitative conclusions, based on the quantitative assessment summarized in preceding tables are in order.

- The *natural gas system* enjoys low plant capital costs and incurs minimal environmental and human impacts. However, remaining domestic reserves are small, imports at acceptable costs are uncertain, and there is competition from alternate uses of this fuel, such as commercial and residential heating. Supply problems also face the *residual fuel oil* (RFO) system. Domestic yields of RFO are low (less than 10%) because of the incentive to maximize production of more valuable refinery ends; thus, a preponderant share of RFO consumed in the U. S. is imported, and foreign sources cannot be considered secure and permanent. Environmental and human impacts involved in the RFO system are large compared to those of the natural gas system, but substantially less than those of the coal system. Because of fuel supply related problems and attending conventional costs, RFO and natural gas are expected to have diminishing roles in fueling new generating capacity after 1980.

- Coal, the most abundant of domestic fuel resources, is the most severe environmental offender. This results largely from the sheer quantities—masses and volumes—of materials handled in the fuel cycle. Impacts of the coal energy system are more visible and, to some extent, more easily measured than those of other systems. In almost every category addressed, nonconventional (or external) costs are greatest in the coal system. Quantified external costs of producing electricity from coal are, however, less than 3% of conventional costs. Abatement costs, particularly SO_2 retention systems if proved feasible, may add as much as 20% to internal costs. However, the compelling fact is that coal is an abundant domestic fuel, and its environmental disadvantages are not likely to preclude its continued exploitation as a source of electrical energy.

- Nuclear fuels, including both fissile and fertile nuclides, are abundant domestic resources, and are expected to share, with coal, a major role in electrical energy production from 1980 through the year 2000 and beyond, provided reactors with substantially improved fuel utilization characteristics are introduced on a commercial scale. Gross, direct environmental impacts of extracting, processing, and transporting fuel—so visible in the coal fuel cycle—are essentially absent in the nuclear fuel cycles, because of the high energy content (on a mass or volume basis) of nuclear fuels. Similarly, nuclear power plants do not discharge large, visible quantities of airborne pollutants. The current generation of nuclear power plants—the light-water reactors—discharge about one-third more heat to the environment than do modern fossil plants. Though relatively small in mass and volume, material flows and residuals in the nuclear fuel cycles are not without very substantial potential hazard. For this reason, nuclear systems are designed, fabricated, and operated with numerous safeguards, high performance radwaste systems redundancies, and with increasingly vigilant quality-assurance programs and standards.

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Risk-Benefit Evaluation for Large Technological Systems

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Abstract: *The related topics of risk–benefit analysis, risk analysis, and risk–acceptance criteria (How safe is safe enough?) are of growing importance. An interdisciplinary study on various aspects of these topics, including applications to nuclear power, was recently completed at the University of California, Los Angeles (UCLA), with the support of the National Science Foundation. In addition to more than 30 topical reports and various open-literature publications, a final report (UCLA-ENG-7777) to the study, titled "A Generalized Evaluation Approach to Risk–Benefit for Large Technological Systems and Its Application to Nuclear Power," was issued in early 1978. This article briefly summarizes portions of the final report dealing with general aspects of risk–benefit methodology, societal knowledge and perception of risk, and risk–acceptance criteria.*

The pioneering work of Starr[1] has provided considerable perspective and insight concerning risks in society and has been one of the principal focal points for the developing field of risk–benefit evaluation. In 1971 the National Academy of Engineering (NAE) held a 2-day colloquium, "Perspectives on Benefit–Risk Decision Making," in order (1) to help make the issues of benefit–risk decision making explicit enough for public discussion; (2) to ascertain the current status of benefit–risk decision making as a field of study and in terms of current practice; and (3) to identify promising lines of inquiry that might lead to improvements in methodology and implementation. The proceedings of the NAE colloquium[2] constitute another of the basic references in the field, which is due, in large part, to the insight provided by the diversity of viewpoints and approaches presented by the participants.

Since 1971, activity in risk–benefit assessment has grown substantially. Works that provide a review of much of the field include those by Lowrance,[3] Rowe,[4] and Van Horn and Wilson.[5] A second conference, "Risk–Benefit Methodology and Application," was held at Asilomar in 1975 (Ref. 6); it was sponsored by the Engineering Foundation as part of a study* undertaken at the University of California, Los Angeles (UCLA), which is the subject of this article. And some very thoughtful insights into the regulation of potentially hazardous material are to be found in the proceedings of the National Academy of Sciences Forum, *How Safe Is Safe? The Design of Policy on Drugs and Food Additives.*[7]

The following excerpts from the review by Van Horn and Wilson[5] indicate some of the major concerns that must be addressed.

> Decision makers are faced to an ever increasing extent with evaluating uncertain risks and benefits to human health and to the environment. Without reliable knowledge of the implications and consequences of alternative projects or possible courses of action, their ability to make sound judgments is diminished. However, estimating the magnitude, probability, and distribution of risks and assessing the costs and benefits of projects are fraught with the difficulties of science, the uncertainties of technological and economic forecasting, and the pitfalls of public policy. How then can risks, costs, and benefits be explicitly compared? How should pertinent information be ordered and assimilated to assist in achieving acceptable balances between benefits and risks, both in the short term and in the long run?
>
> The methodologies which are used in "risk–benefit analysis" attempt to make explicit the often hidden trade-offs between lives lost and dollars spent, or between pollution and environmental quality. No magic formulae have been evolved for grappling with these seemingly incommensurable attributes. Nevertheless, the growing difficulties of

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*The UCLA project, titled "A Generalized Evaluation Approach to Risk Benefit for Large Technological Systems and Its Application to Nuclear Power," began in the summer of 1973 and was supported by National Science Foundation grants GI 39416 and OEP75-20318.

regulation, standard setting, legislation, and technological choice have necessitated improved methods for answering risk–benefit questions.

From the 1975 conference [Ref. 6] and from a survey of literature, it is evident that no coherent definition of risk–benefit analysis has emerged, owing to the breadth of subjects under study. Most recent effort has been in the area of risk assessment, less attention has been given to benefit assessment, and even less attention has been devoted to how decision makers should integrate this information into the political process.

Dealing with uncertainty is the central dilemma of all policy choice. Uncertainty occurs in predicting the consequences of actions as well as in valuing the particular outcomes of alternative policies. Reducing uncertainty, defining its bounds and its effects on policy preferences, should be primary goals for risk–benefit analysts.

Even if the risk–benefit analyst is able to quantify risks and benefits how are we to judge the acceptability of a risk? What criteria should apply to our choice among alternatives?

Assessing risk and judging the acceptability of a risk (i.e., determining safety) are independent processes. Much confusion has arisen in public policy disputes over the failure to separate the distinguishable questions:

1. What are the scientific and technological bases for assessing the expected risks and benefits?
2. What are the relative probabilities and uncertainties of particular consequences?
3. Can the risk be reduced and what will it cost?
4. Is the distribution of risks and benefits fair?
5. Is this risk acceptable?

Moral, ethical, and political considerations may all properly take precedence in decisions in our democratic society. Nevertheless, in many situations where ethical or political arguments are not paramount, understanding risks and benefits may be crucial. Fears that risk–benefit analyses will obfuscate the issues seem to imply that decision makers or opponents of particular alternatives are not capable of pointing out the limitations of an analysis. Surely, if decision makers are capable of comprehending the complex scientific and technological decisions to be made, they are capable of recognizing the limitations of analytical methods. Holistic decision making is not precluded by using risk–benefit analysis. Careful risk–benefit studies subjected to open criticism are more likely to rationalize and clarify the decision process than they are to hinder or obscure it.

THE ROLE AND METHODS OF RISK–BENEFIT ANALYSIS AND DECISION ANALYSIS*

In this section we review some of the fundamental concepts and language of risk–benefit analysis and decision analysis and outline a possible philosophy and point of view toward this emerging scientific discipline and its appropriate role in society.

Risks vs. Hazards

We begin first by making the distinction between the notions of "hazard" and "risk," as we shall use these terms. Hazards, in our usage, are things that exist externally; risks are dependent on what we do and what we know. Thus, for example, the ocean is a hazard, and if we attempt to cross in a rowboat, we incur great risk. If we cross in a ship like the *Queen Mary*, the risk is small, although the hazard remains the same.

Quantification of Risk

It is often said that risk is probability *times* consequence, and we may use this definition ourselves in specific applications. However, we may also wish to denote a more general definition, namely, that "risk is probability *and* consequence." Thus, suppose a given action could produce various degrees of undesirable consequence, or "damage," with various likelihoods. Damages might be the number of lives lost or dollars lost, for example. We might present the situation most transparently in the form of an integral probability curve, as shown in Fig. 1, in which the ordinate is the probability that a damage of level x or greater will be produced. Applied to such a situation, the meaning of probability *times* damage would be the expected value of damage; i.e.,

$$E(d) = \int x \frac{d}{dx} p(>x) dx$$

This operation reduces the whole curve to a single number, which is a pronounced loss of information, since many vastly different curves with enormously different significance could have the same expected value. In contrast, the point of view that risk is probability *and* consequence would say that the risk is the whole curve, $p(>x)$, in Fig. 1. In fact, we refer to

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*This discussion of decision analysis was prepared by S. Kaplan.

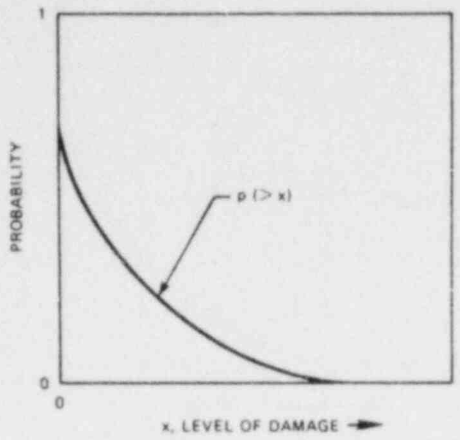


Fig. 1 Risk curve.

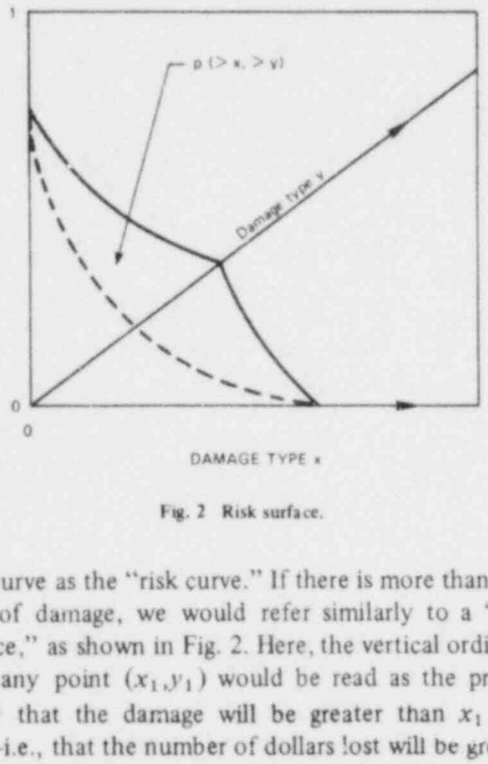


Fig. 2 Risk surface.

this curve as the "risk curve." If there is more than one hint of damage, we would refer similarly to a "risk surface," as shown in Fig. 2. Here, the vertical ordinate over any point (x_1, y_1) would be read as the probability that the damage will be greater than x_1 and y_1—i.e., that the number of dollars lost will be greater than x_1 and the number of lives lost will be greater than y_1.

The risk surface thus tells a more complete story concerning the probability of small consequences *and* the probability of large consequences. For analytical purposes, the risk surface provides a more generalized definition of the risk.

The Purposes of Risk Analysis

In the light of the preceding definitions, we might now say that the purpose of risk analysis is to identify all the hazards and to quantify the risks involved in any proposed action (or inaction). Experience, however, teaches us that in the course of this identification and quantification, there comes about an increased awareness that, by itself, can diminish risk. Actions that can reduce risk may also suggest themselves.

Actions that reduce risk, however, will usually require expenditures of time and resources that could be used elsewhere. Moreover, these actions may bring up new risks and uncertainties of their own. In real life we usually do not get to avoid risks, we only get to choose between them. Thus we must trade off risks, costs, and benefits. To the extent that we can do this explicitly and quantitatively, we may hope not only to make better societal decisions but also to reduce the waste, delay, miscommunication, and bitterness frequently attendant on such decisions. This is one of the real promises of decision theory, which is a formal mathematical framework for optimizing these tradeoffs. Risk analysis may thus be viewed as part of decision theory or as part of the input for a decision analysis.

Decision Theory

The essence of decision theory consists of an idealized model of a decision situation, as diagramed in Fig. 3.

In this diagram the point of decision is shown with various items of information, or indications, feeding into it and various possible decision options emanating from it. Since the outcome of a particular decision option is not known with certainty, the diagram shows a series of possible outcomes emanating from each option, with each outcome having its own assigned probability.

A given outcome will, in general, have many different impacts on people, property, the economy, the environment, etc. These impacts are grouped into a linear list, which is called "the impact vector" in the diagram. The use of the term "vector" here emphasizes the idea that the "impact" of any decision action is a multidimensional, multiattribute quantity.

The decision maker, observing these impact vectors, will be able to say that this set of impacts is more desirable than that set and so on. Thus there is in the mind of the decision maker a notion of preference. We may express this by saying that there exists in the mind of the decision maker a "preference function" or a "utility function" which maps the multidimensional quantity, the impact vector, into a scalar quantity—i.e., a single number, called the "utility" of that vector. The "expected" utility of a decision option may then

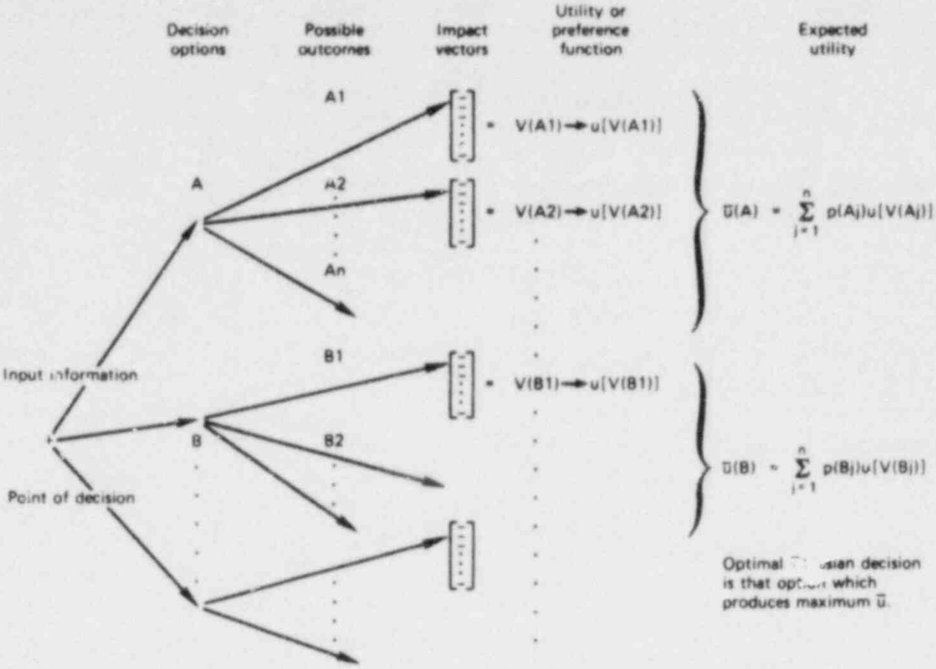


Fig. 3 The anatomy of a decision.

be defined as the sum of the possible outcomes of the utility of each outcome weighted by the probability of that outcome. The optimum decision, then, according to this model of the decision process, is to choose that option which has the maximum expected utility.

Thus, in terms of this model, the steps in a decision process are as follows:

I.
1. Identify options.
2. Identify possible outcomes of each option.
3. Determine the impact vector for each outcome.

II.
4. Assign probabilities to each outcome.

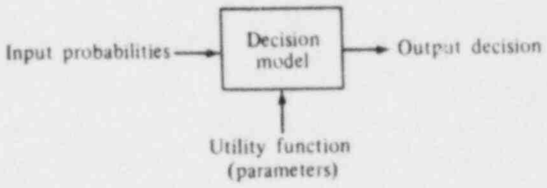
III.
5. Establish a utility function.
6. Compute expected utilities.
7. Decide.

Steps 1 to 3 may be considered to constitute the structural or formal part of the decision analysis. Here we must decide how many options and consequences to consider, how to characterize impacts, whether to use discrete or continuous variables, etc. This part of the job is as much art as science. The same is true of any mathematical modeling effort.

Step 4 may be regarded as the input to the problem. It represents our state of knowledge as of the moment.

Step 5 may be thought of as the setting of the parameters in the model. Here we input our value judgments on the relative desirability of various sets of impacts.

Steps 6 and 7 may be thought of as the operation of the model. Thus, once the structure of the model is established and the judgment inserted, the model operates to convert, or map, a set of input probability distributions into a choice of decision option:



If two parties have the same states of knowledge (i.e., if their input probabilities are the same) and if they have the same preferences (i.e., the same utility functions), then, according to the model, they must reach the same decision. Conversely, if they disagree on the decision, then it must be because they have either different probability functions or different utility functions. Let us now take a closer look at these two aspects of the matter.

Probability

There has been much dispute about various aspects of probability for a long time. An area of particular importance relates to the ability to use probabilistic techniques when very great uncertainties exist. One school of thought says that when there is insufficient data there is nothing else we can do but use probability. However, there is the counter argument that the procedure for using probabilistic techniques exists but that there is no basis for assigning meaningful probabilities.

In the kinds of societal decisions we are concerned with in this study (those relating to power plants, dam failures, liquefied-natural-gas tanks, earthquakes, etc.), we invariably have far less data than we would like. Thus we are always in the realm of probability theory, and therefore it is worth pausing here to give a formal definition of probability. One such definition is that given by Professor E. T. Jaynes in a short course at UCLA:

> Probability theory is an extension of logic, which describes the inductive reasoning of an idealized being who represents degrees of plausibility by real numbers. The numerical value of any probability (A/B) will in general depend not only on A and B, but also on the entire background of other propositions that this being is taking into account. A probability assignment is "subjective" in the sense that it describes a state of knowledge rather than any property of the "real" world, but is completely "objective" in the sense that it is independent of the personality of the user; two beings faced with the same total background of knowledge must assign the same probabilities.

Observe the importance in this definition of the concept of the idealized reasoning being. This is the fundamental premise of probability theory: that any two rational beings, given the same total background of information and experience, will arrive at the same state of confidence. Applied to the nonidealized beings of everyday life, this premise translates thus: To the extent that they are rational and to the extent that they can, through sufficient communication, achieve a commonness of relevant background information, two people will assign similar values of probability to a proposition at hand. Actual experience in this regard is quite variable.

Utility Theory

The basic idea of utility theory is to assign a numerical value to represent another state of mind—this time a state of preference. The idea is most concisely contained in the graph of a typical money–utility curve, Fig. 4. This curve portrays the relative desirability (in arbitrary units) of various quantities of money.

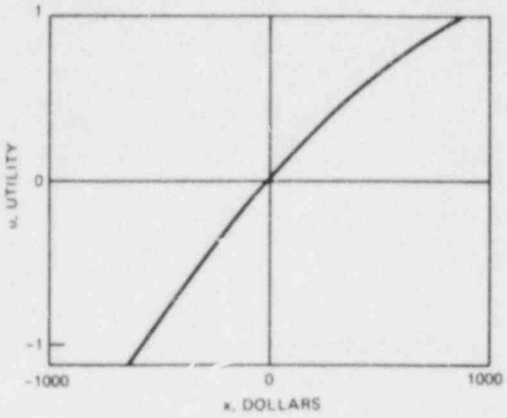


Fig. 4 Money–utility curve.

The concave downward shape of the curve shows that initial increments of money are worth more for this decision maker than later increments. Such a decision maker, or such a curve, is said to be "risk averse." A concave upward curve would be "risk prone," and so on.

Multivariate Utility Theory

The curve shown in Fig. 4 represents a "univariate" utility function. When the impact vector has more than one component, the utility function is said to be a "multivariate" function and must then express the trade-off preferences between the several components, e.g., dollars and lives.

The situation then becomes complex, and dispute more readily arises. People occupying different geographical, social, and economic positions experience the components of the impact vector differently. Also, status aside, people simply have different preferences and values. Sometimes these differences can be adjusted through transfer-payment-type mechanisms; sometimes they are simply irreconcilable. The best that can be hoped for in utility theory is that it can serve as a communications language and as a tool for clarifying attitudes and values. Moreover, the preferences and evaluations of both individuals and groups will change with time, mood, and circumstance. It is important, therefore, that utility theory not be used in an automatic, mechanical way. The best, then, that can be hoped for from utility theory is that it can serve as an aid to judgment, as a tool for clarifying attitudes and values, and for making them consistent, and as a language for communication in these areas.

A Special Case of Multivariate Utility: The Risk–Benefit Formalism

In the general case, the impact vectors in Fig. 3 may have many components covering effects on health, safety, environment, the economy, esthetics, etc. In this section we wish to consider a simplified case in which the vectors are boiled down to two components and in this way to clarify the connections between the model of Fig. 3 and the language of risk–benefit analysis. Suppose therefore that only two components are present: benefit, y, measured in dollars, and damage, x, measured in fatalities. The decision diagram then looks like the diagram in Fig. 5.

If option C is taken (i.e., do not implement the technology), then with probability 1.0 the impact vector is [0,0] (i.e., no benefit and no damage).

If option A is taken, there are various possible outcomes with probabilities $p_1^A p_2^A, \ldots$, etc. All the impact vectors have the same benefit, y_A, but the degree of damage varies along with its associated probability. This probability–damage relationship can be expressed in a risk curve, and the same can be done for option B (see Fig. 6).

Suppose that the risk curve is lower for option B, as shown, and the benefit is also lower, $y_B < y_A$. The decision can then be summarized: Is the reduced risk curve, B, worth the loss in benefit $y_A - y_B$, or is it better to have the risk and no benefit, option C?

Other interesting situations occur; e.g., suppose that $y_A = y_B$, but the risk curves intersect, as shown in Fig. 7.

Now, the question is: Which risk is preferable? Will we trade off the small probability of a large number of fatalities, curve B, for a large or a small number of fatalities as in curve A? To answer these questions, we must put forth a utility function, $u(x,y)$.

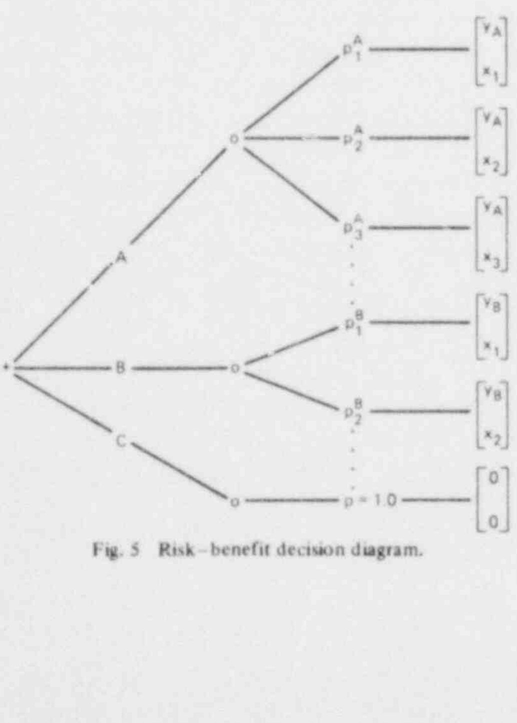


Fig. 5 Risk–benefit decision diagram.

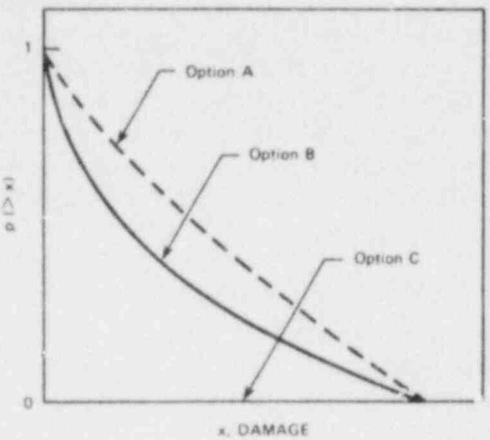


Fig. 6 Risk curves of options.

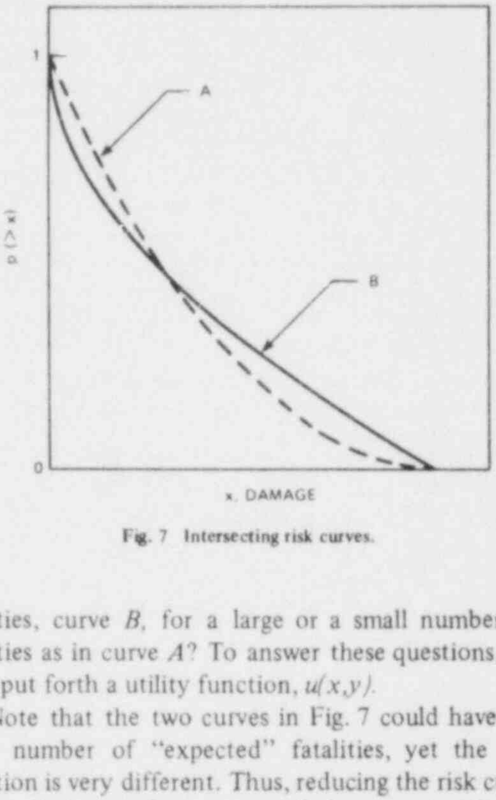


Fig. 7 Intersecting risk curves.

Note that the two curves in Fig. 7 could have the same number of "expected" fatalities, yet the risk situation is very different. Thus, reducing the risk curve for a single number, expected damage, involves a significant loss of information. There is a definite convenience in such a reduction, however, for now the technology or activity in question can be represented as a point in x,y space and plotted along with other technologies and activities.

SOCIETY'S UTILITY FUNCTION

In considering whether to implement a new technological development, we have to ask if the societal benefit is worth the risk—which is a way of asking for society's utility function. How does society perceive the risks and benefits associated with a development? This section reviews some methods and perspectives from past studies in this area, particularly those dealing with the complex question of how society perceives the value of human life.

The Revealed Preference Approach of Starr[1,8,9]

The approach suggested by Starr is to ask: What risks is society accepting in other technologies being used now? In return for what benefits? In this view, what society is doing now and has done in the past reveal its de facto utility function.

Starr found that:

> (i) The indications are that the public is willing to accept "voluntary" risks roughly 1000 times greater than "involuntary" risks.
>
> (ii) The statistical risk of death from disease appears to be a psychological yardstick for establishing the level of acceptability of other risks.
>
> (iii) The acceptability of risk appears to be crudely proportional to the third power of the benefits (real or imagined). . . .

Otway and Cohen,[10] although not questioning the value of Starr's work in general, disagreed with several of his quantified findings, on the basis of their examination of the same data base and using the same basic methodology. Looking at mining wages, Otway and Cohen[10] found that an essentially linear relationship could be derived between risk and benefit, in contrast to the third-power relationship. They found that for voluntary societal activities, the original risk data of Starr could be best fitted by a regression equation indicating risk to be proportional to benefit to the 1.8th power. Looking at involuntary societal activities, and excluding natural hazards, they fitted the original data with a sixth-power relationship.

Several groups, including Starr, Rudman, and Whipple,[11] Wilson,[12] and Slesin and Ferreira,[13] have examined historical data on accidents involving five or more deaths and concluded that, within the available range of data (up to about 1000 fatalities), the frequency of an event of a given size falls off nearly as fast as the cube of the magnitude of the event (measured in fatalities). Slesin and Ferreira[13] suggest that this is, in effect, a *revealed preference*, which society expects man-made hazards to meet, and that it represents a quantitative measure of risk aversion.

However, Raiffa, Schwartz, and Weinstein[14] express a very different opinion, namely, that for the purposes of public policy, the expected number of lost years of life is an appropriate index, provided that we believe in the probabilities.

The Value of Life

Among the papers that contribute significantly to the development of a basic approach to accounting for the value of a human life in risk–benefit decision making are those by Schelling,[15] Zeckhauser,[16,17] Raiffa, Schwartz, and Weinstein,[14] Calabresi,[18] and Bergstrom.[19] As Schelling,[15] among others, points out, rather than the value of life, per se, it is usually the benefit of a small incremental decrease in risk (corresponding to an increase in life expectancy) or the cost of a small incremental increase in risk (with a corresponding decrease in life expectancy) with which we are generally dealing. And Zeckhauser[16] emphasizes that procedures for valuing lives must be developed which appropriately reflect not only considerations of process but also such matters as anxiety, income distribution, and possibilities for compensation.

Nevertheless, it is instructive to examine the "numbers" derived in various value-of-life studies, of which Linnerooth[20] has published one of the more recent surveys of case studies. She divided these case studies into several different categories, as follows.

1. *The human-capital approach.* In a 1958 study prepared for the Federal Aviation Administration (FAA), the discounted value of the average passenger's expected income was considered appropriate.[21] A value of $250,000, obtained by the discounted-earnings approach,[22] was used in a 1962 general aviation study, whereas Fromm[23] obtained a higher figure by allowing for the loss to the person's family, employer, and the government. Rice and Cooper[24,25] have also used the so-called human-capital approach in similar studies for the Social Security Administration, with the dollar values depending on the discount rate chosen and on the person's age and earning capacity.

In 1972 the White House Office of Science and Technology[26] estimated the average cost of a traffic death to be $140,000, whereas the National Highway Traffic Safety Administration obtained a cost of $200,000 (Ref. 27). The Department of Transportation has since used the figure of $200,000 in making cost–benefit evaluations of potential improvements in traffic safety.[28] In a recent study Barrager, Judd, and North[29] have used the value of $300,000 for the life of a [illegible] killed in an accident.

2. *Implicit societal evaluation.* Morlat[30] estimated that, in France, $30,000 is spent per life saved in road

accident prevention and $800,000 to $1 million in aviation accident prevention.

Sinclair, Marstrand, and Newick[31] examined a series of case studies and obtained implicit life valuations for Great Britain, on the basis of expenditures for safety, from $10,000 for an agricultural worker's life to $1 million for a nuclear power plant employee and $20 million for a high-rise-apartment dweller.

Sinclair, Marstrand, and Newick arrived at several main conclusions from their study, including the following:

(i) Risk levels and implicit life valuations differ widely from industry to industry.
(ii) It is possible to demonstrate numerical changes in valuation as they arise from the imposition of social controls—for example, the large increase in valuation caused by the legislative changes made after a disaster.
(iii) Life valuations appear to increase with the technical sophistication of an industry or with the recentness of its foundation.
(iv) Where risk levels can be determined at a national level, for social or technological reasons, valuations tend to be higher.
(v) Where risk levels are set nationally, relatively few individuals appear to be concerned in the technical determination.
(vi) Such risk levels are inconsistently set, even where the level is officially determined.

Conclusion (i) of Sinclair, Marstrand, and Newick[31] is similar to that of Morlat.[30] Comparable conclusions can be drawn about the same inconsistency in implicit life evaluations in the United States, as well as about conclusion (vi) of Sinclair, Marstrand, and Newick, namely, that risk levels are inconsistently set, even where the level is officially determined.

These two inconsistencies are bothersome to the risk–benefit analyst, particularly if they result from the compartmentalization of decision making and from either an absolute absence of knowledge of the facts or a failure to communicate them.

Raiffa, Schwartz, and Weinstein[14] state:

> It is a reasonable governmental goal to "smooth out" the distribution of life-saving investments by equating, at the margin, their net costs per year of life saved. Considerations of equity (that is, interpersonal incidence of costs and life-saving benefits) and issues of identifiability and attributability, may often dictate against decision making based solely on the efficiency criterion. To the extent that these factors—and others, such as political influence—result in a suboptimal level of life and health for any given level of resource commitment, they should be evaluated critically in terms of the expected number of quality-adjusted present-value life years foregone.

3. *Insurance premiums and court-decided compensation.* Insurance as a measure of value of life in a sense deals with a different matter; i.e., it does not reduce the probability of death, but compensates the survivors.

Court cases vary rather widely in their dollar awards for loss of life, and, although they may not be inconsistent with an enhanced human capital, they are not judged as definitive by economists.[17,20]

4. *The risk approach.* Thaler and Rosen[32] attempt to impute a set of implicit marginal prices for various levels of risk by observing the relationship between risky jobs and wage rates, obtaining a value of life in the neighborhood of $200,000.

Results of a UCLA Study

In addition to the very interesting work by Bergstrom,[19] the principal report emanating from the UCLA risk–benefit study in the general area of historical perspectives on risk is the work of Baldewicz et al.[33] In this report an empirical study of historical trends in the risks sustained by participating populations for various large-scale technological systems is presented. A new model for risk assessment is introduced which avoids the problems associated with assessing the value of human life in risk–benefit decision making; essentially, the model treats risk in terms of loss-of-life expectancy. For example, in the case of fatal insults sustained by a population at risk, the rate of loss-of-life expectancy is simply the lost years of life expectancy (the sum of the differences between the victims' ages and their expected "normal" life expectancy) divided by the total number of hours they have been exposed to the risk. For nonfatal insults (e.g., injury, illness, property damage), calculational procedures are suggested, and typical results are given in the case of property damage. In addition, a methodology is presented for dealing with deferred risk, and illustrative calculations are reported for coal workers' pneumoconiosis.

The average lost years of life expectancy per fatality are found to range from a low of 24 (rail passengers) to a high of 43.6 (lightning victims) for 10 risk systems studied and are found to be essentially invariant over the past two decades.

From the historical trends in the rate of loss-of-life expectancy for the risk systems studied, it is concluded that: (1) appreciable disparities exist in loss-of-life expectancy for occupational hazards, despite nearly similar benefits for the populations at risk; (2) federal legislation can have a significant impact on risk abatement, as has apparently been the case for coal mining; and (3) federal safety legislation efforts appear to be most responsive to highly publicized disastrous accidents rather than to chronic, low-level hazards (both accidents and disease), which actually contribute more significantly to loss-of-life expectancy.

The first conclusion is in conflict with the general findings of Thaler and Rosen.[32] Nevertheless, the results of Baldewicz et al.[33] are that coal miners have about 10 times the risk of steel workers with no increment in pay for that risk.

Apparently highly publicized disasters have led to more governmental action than have large numbers of small accidents, which may actually have greater effects. What is less clear is that what this represents is a consciously chosen quantitative risk aversion of society.

Results of a Psychometric Study

Starr's approach of revealed preferences has the advantage of dealing with public behavior rather than with attitudes. However, according to Fischhoff et al.,[34] it has a number of serious drawbacks:

> First, it assumes that past behavior is a valid indicator of present preferences. Second, it does not serve to distinguish what is "best" for society from what is "traditionally acceptable." What was accepted in the market place may not have accurately reflected the public's safety preferences. Consider the automobile, for example. Unless the public really knew what was possible from a design standpoint, and unless the automobile industry provided the public with a varied set of alternatives from which to choose, past market behavior may not have indicated what "the reflective individual would decide after thoughtful, intensive inquiry and good professional advice." A revealed preference approach assumes that people not only have full information, but also can use that information optimally, an assumption which seems quite doubtful in the light of much research[35] on the psychology of decision making.

Fischhoff et al.[34] employ the method of "expressed preferences," using questionnaires to attempt to measure the public's attitudes toward the risks and benefits associated with various activities. The participants in their study evaluated each of 30 different activities and technologies on the basis of (1) its perceived benefit to society, (2) its perceived risk, (3) the acceptability of its current level of risk, and (4) its position in each of nine dimensions of risk.

1. Voluntariness of risk.
2. Immediacy of effect.
3. Knowledge about risk (to the persons exposed).
4. Knowledge about risk (to science).
5. Control over risk (by the persons at risk).
6. Newness of risk.
7. Chronic vs. catastrophic risk.
8. Common risk vs. dread risk.
9. Severity of consequences.

The participants were members of the League of Women Voters of Eugene, Ore., and their spouses, a group not representative of Eugene or of the United States. However, they represented a group of private persons who were generally active in public policymaking matters.

The results of the study are of interest not only in the correlations found but also in the differences between "perceived risk" as indicated by the respondents and "actual risk" as represented by some body of technological study, albeit uncertain.

Fischhoff et al.[34] summarize their important findings as follows:

> 1. For many activities and technologies, current risk levels were viewed as unacceptably high. These differences between perceived and acceptable risk indicated that the participants in our study were not satisfied with the way that market and other regulatory mechanisms have balanced risks and benefits. Given this perspective, such people may also be unwilling to accept revealed preferences of the type uncovered by Starr as a guide for future action. In particular, the high correlations between perceived levels of existing risk and needed risk adjustment indicated that our participants wanted the risks from different activities to be considerably more equal than they are now. They wanted the most risky item on our list of 30 to be only 10 times as risky as the safest.
> 2. There appeared to be little systematic relationship between the perceived and existing risks and benefits of the 30 activities and technologies considered here. Nor are risks entered into voluntarily perceived as greater than involuntary risks at fixed levels of benefit. Such relationships appeared to emerge in Starr's revealed risk–benefit space.
> 3. However, there was a consistent, although not overwhelming, relationship between perceived benefit and acceptable level of risk. Despite

their desire for more equal risks from different activities, our respondents felt that society should accept somewhat higher levels of risk with more beneficial activities. They also felt that society should tolerate higher risk levels for voluntary, than for involuntary activities. Thus, they believed that Starr's hypothesized relationships should be obtained in a society in which risk levels are adequately regulated.

4. The nine characteristics hypothesized by various authors to influence judgments of perceived and acceptable risk were highly intercorrelated. They could be effectively reduced to two dimensions. One dimension apparently discriminated between high- and low-technology activities, with the high end being characterized by new, involuntary, poorly known activities, often with delayed consequences. The second dimension primarily reflected the certainty of death (often for large numbers of people) given that adversity occurs. Consideration of these two factors in addition to perceived benefit made acceptable risk judgments highly predictable. Conceivably, policy makers might use such relationships to predict public acceptance of the risk levels associated with proposed technologies.

Given the contrasts between our study and Starr's, the question arises, "who is right?" We believe that neither approach, in itself, is definitive. The particular relationships that Starr uncovered were based upon numerous ad hoc assumptions and applied to only a small set of possible technologies. Our own study used but one of the psychophysical measurement procedures possible, applied to a rather special participant population. Answering the question "How safe is safe enough?" is going to require a multimethod, multi-disciplinary approach, in which the present work and Starr's are but two components.

Balancing the results of these various approaches also depends upon one's conceptualization of the policy-making process. A definitive revealed-preference study would be an adequate guide to action only if one believed that rational decision making is best performed by experts formalizing past policies as prescriptions for future action. A definitive expressed-preference study would be an adequate guide only if one believed that people's present opinions should be society's final arbiter and that people act on their expressed preferences. The obvious reservation that many people would have about the former approach is that it is highly conservative, enshrining current economic and social relationships; an obvious problem with the latter approach is that it allows people to change planning guidelines at will, possibly resulting in social chaos.

Slovic, Fischhoff, and Lichtenstein[36] had previously reported a simple experiment that illustrated, by example, society's poor knowledge (or inaccurate perception) of risks for which good actuarial information exists. Specifically, they chose 41 causes of death, for which the average probability of death in the United States ranged from about 1×10^{-8} (botulism) to 8.5×10^{-3} (heart disease). They constructed 106 pairs of these events and asked a large sample of college students to indicate, for each pair, the more likely cause of death and the ratio of greater to the lesser frequency.

In that case Slovic, Fischhoff, and Lichtenstein[36] found that for actuarially known facts the subjective scale of the respondents often deviated markedly from the true scale, and they could consistently identify which of the paired events was the more frequent cause of death only when the true ratio of greater to lesser frequency was more than 2.1.

The very large difference between the judged ratio of emphysema to botulism and the true ratio was particularly illuminating. If public policy is being made in response to such public perception, even though such public perception is grossly incorrect, what are the implications?

Fischhoff et al.[34] note that their respondents assign a unique position to nuclear power, namely, great risk compared to two ostensibly similar technologies: X rays and nonnuclear power. The relative ratings for nuclear and nonnuclear electric power are shown in Fig. 8.

This comparison again provides a basis for contrasting the perceived risk with actual risk, albeit an uncertain one. Many published studies (see Refs. 6 and 37) yield a significantly higher expected mortality rate from coal-burning electricity-generating plants than from nuclear power plants. And, although Fig. 8 shows that the respondents perceive nonnuclear electric power production as not subject to catastrophic effects, in fact, many hydroelectric dams pose a potential hazard ranging from tens of thousands to a quarter of a million fatalities,[38] and the probability of gross sudden failure of a dam can be large compared to 10^{-6} or even 10^{-4} per year.[38,39]

Hence, perhaps the most important question raised by studies of the type reported in Ref. 34 is: How, in a democracy, are citizens to obtain more accurate information to serve as a partial basis for voting or other exercise of their right to influence public policy?

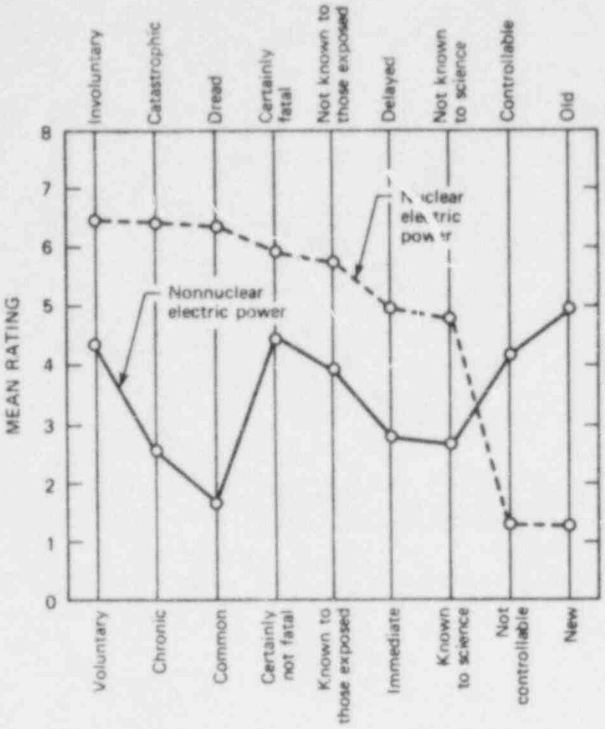


Fig. 8 Relative ratings of nuclear and nonnuclear electric power.

Unfortunately many, if not most, hazards and risks are not well studied, let alone known, even by experts. However, the difference between actual risk and hazard and risk as it is perceived by a well-educated group, such as the respondents in Ref. 34, poses a major unresolved problem for societal decision making.

SOCIETAL KNOWLEDGE OF HAZARDS AND RISKS

Except for those limited things covered by actuarial statistics, society is remarkably deficient in its knowledge of the hazards and risks to which it is exposed. For example, there are thousands of large dams in the United States, many with large populations residing in their inundation plain. But there is little information on the safety standards to which these dams were built. Also, there exists no report that deals quantitatively with the risk from these dams collectively, and for only very few individual dams is information available on the maximum hazard or on the estimated risk.

The same lack of quantitative information on safety standards, hazards, and risks is equally true with regard to the storage of large quantities of dangerous chemicals. The transportation of dangerous chemicals is only slightly better off with regard to the quantification of risk.

Other examples of unquantified hazards and risks abound; they include research with and application of recombinant deoxyribonucleic acid (DNA) techniques, the so-called "greenhouse effect" from the global buildup of carbon dioxide, and the health effects of pollutants, including industrial and agricultural wastes released into the environment. The recent general acceptance by the medical and public-health professions that 60 to 90% of all cancer is environmentally produced, rather than hereditary,[40] adds a sense of urgency to efforts to better understand the effects of chemicals in the environment, whether they be emissions from the combustion of fuels, additives in our food, or pollutants in our water.

Generally speaking, there exists almost no literature dealing quantitatively with low-probability accidents for which little or no data can be provided by actuarial statistics. In the practice of medicine itself, only recently has an effort begun to accumulate specific, detailed statistics that could, at least in principle, provide a basis for detailed risk quantification and risk–benefit analysis with regard to possible improvements.

It is reasonable to draw the conclusion that, in most aspects of society, a process of learning by experience still continues; that nuclear energy represents a complete break with past practice in its major efforts to quantify low-probability events; and that, to a limited extent, other technologies and societal situations are starting to undergo the quantitative scrutiny given to nuclear energy.

However, most societal decision making involving risk, whether by individuals, regulators, political representatives, or representatives of advocacy groups, is being made in the absence of knowledge by the decision makers of the actual hazards and risks; and the lack of knowledge is much more acute for society in general.

To provide some insight into the magnitude of several low-probability hazards, the degree to which a risk estimate may be subject to uncertainty, or the degree to which some hazards are even considered by the nominally responsible governmental bodies, the UCLA study group undertook several specific studies as part of the NSF grant, as well as under other auspices. Some of these studies are summarized as follows.

Seismic Effects

When seismic experts independently evaluate the likelihood of relatively severe earthquakes, whether it be for California, Mississippi, or Massachusetts, a difference of 10^4 in the estimated likelihood per year can occur as a direct result of our imperfect knowledge of earthquakes and their causes, and because historical records are too brief to provide a definitive empirical base.[41] Such a large uncertainty in the likelihood of severe earthquakes poses safety questions for essentially all our cities, for dams, for storage facilities for hazardous chemicals, for nuclear power plants, etc. Except for nuclear power plants, seismic design requirements are usually rather modest. Several cities, including Los Angeles, face the difficult problem of dealing with the existence of large numbers of heavily populated buildings that lack resistance to a strong earthquake. A limited case study has been prepared on how the city of Los Angeles has been struggling with the problem of deciding what to do about old buildings that do not meet current seismic design standards and may pose a substantial risk.[42]

What is poorly recognized is that essentially every city in the United States has a similar seismic safety question; the major difference for each city lies in the probability that a seismic event could occur which would lead to a large-scale loss of life and property.

Dams

Dam failures are not uncommon events. Thirty-three dams failed in the United States between 1918 and 1958; five of these were major disasters involving the loss of 1680 lives. Assuming that the average number of dams over the 40-year time interval was 1000, these data suggest a failure rate approximately 8×10^{-4} per dam-year and a major disaster rate of approximately 1.3×10^{-4} per dam-year. Between 1959 to 1965, nine major dams of the world failed in some manner. In 1962 there were about 7800 major dams (*Engineering News Record*, 1967), indicating a worldwide failure rate of about 2×10^{-4} per dam-year for that period. These estimates are in accord with that of Gast,[3] who estimated a failure rate of 10^{-4} per year based on historical records and design flood probability. In the first 9 months of 1976 there were six dam failures, four of which are considered major disasters, resulting in substantial property damage and more than 700 deaths. The causes of dam failures can generally be categorized as design, construction, or site inadequacies, or natural phenomena (primarily floods or earthquakes) in excess of design criteria.

In the study, made by the UCLA study groups,[38] of the probability of failure of 12 dams in California due to a severe earthquake, failure probabilities were estimated as ranging from 1 in 100 to 1 in 10,000 per year. Estimates of fatalities based on the assumption of total and instantaneous failure of dams filled to capacity ranged from 10,000 to 250,000.

The UCLA study is one of the few published reports giving estimates of the maximum hazard and a crude failure probability for specific dams. One additional piece of information comes from the federal hearings on Mar. 21, 1977, conducted by the Water Projects Review Committee, U. S. Department of the Interior. H. Cedergren[43] testified at these hearings that sudden failure of the proposed Auburn dam in California could kill up to three quarters of a million people. Hence, dams clearly pose great hazards.

What remains unavailable are the quantitative criteria for acceptable failure probabilities for dams that are inherent in the judgment made by responsible governmental authorities that a dam is "safe."

Hazardous Chemicals

This subject might be divided into transportation and storage. A previous study on the risks from the rail transportation of chlorine[44] provided an estimate of the upper-limit hazard (75,000 fatalities at a probability of 0.0003 per year if evacuation is completely ineffective for a densely populated area) and an estimate of the risk (about 13 mortalities per year). By contrast the actual experience had been only one directly attributable fatality in 40 years in the United States, which suggests that (1) evacuation is very important, (2) the analysis may be unduly pessimistic in other ways, and (3) the statistics are inadequate for lower probability events. In all likelihood a combination of all three factors contributes to the discrepancy between analysis and experience. There undoubtedly are other situations in which the reverse is true, namely, that what is nominally a low-probability high-consequence event (the equivalent of two airliners colliding on the ground) has occurred.

With regard to the storage of large quantities of hazardous chemicals close to towns or larger population centers, the direct way to approach the question would be to obtain specific information on locations where such chemicals are stored and on the safety standards used in building and maintaining the storage facilities. Given such information, fault-tree and other methodologies could be used to estimate the probabilities of release from man-made and natural causes, and the consequences of such releases on the public health and safety could be evaluated, considering meteorological factors and population distribution, as well as the potential for evacuation in case of an accident.

However, very few such evaluations have been published in the United States.* Those that exist apply primarily to proposed or recently built liquefied-natural-gas storage and receiving facilities.

A preliminary look at the regulation of hazards from the storage of chemicals was made by the UCLA group.[45] This included a limited poll of activities and cognizance by the states; a survey of the specific safety requirements imposed by the cities of Los Angeles and El Segundo, Calif., and a rough estimate of potential hazards and risks.

It was found that only a limited regulatory control is imposed by states and cities. No detailed hazard or risk evaluations appeared to have been made, and official knowledge of hazardous situations was less than complete. In fact, there are large quantities of potentially hazardous chemicals stored near population centers.

The probability of a chemical facility accident causing a hundred or more fatalities in a nearby population center is not insignificant. Considering all the chemical facilities located close to population centers, at least one hazardous event can be expected in the next several years. The policy implications are obvious: in the future siting of chemical facilities, the proximity to population centers should be taken into consideration as well as the adequacy of safety design criteria. Furthermore, evaluations should be made of existing facilities to see if they meet an "acceptable" level of risk.

RISK ACCEPTANCE CRITERIA: HOW SAFE IS SAFE ENOUGH?

Although a very considerable number of decisions are made every year involving an implicit acceptance of some risk level or a reduction in some risk, very little quantification of the criteria being used exists or has been made publicly available.

For example, in the State of California, the law now requires a finding by the State Division of Dam Safety that dams are "safe," but the state office does not define what level of risk is accepted when such a finding is made.

For a time the Atomic Energy Commission (and then the Nuclear Regulatory Commission) licensing staff adopted the quantitative objective that the probability of a serious reactor accident should not exceed one in a million per reactor-year. However, the Commissioners themselves have since stated that they have not adopted a quantitative risk–acceptance criterion.

One of the few proposals for a quantitative determination of acceptable levels of societal risk was given by Rowe[4] in 1975. His proposed methodology involves several sequential steps, as follows:

1. *Balancing costs and benefits.* The direct and indirect societal benefits of a proposed activity must be balanced against the total direct and indirect societal cost of the activity. Rowe[4] assigns a numerical factor P which depends on whether the balance is favorable or unfavorable.

2. *Achieving "as low as practicable" risk levels.* When the incremental cost per risk averted is equivalent to similar costs for similar risks in society, the system's risk will be as low as practicable, according to Rowe.[4] He also gives an alternative definition, namely, "when the incremental cost per risk averted is such that a very large expenditure must be made for a relatively small decrease in risk as compared to previous risk reduction steps."

3. *Reconciling identified risk inequities.* When risks are not uniformly distributed among the beneficiaries of the activity, the risk is compared to societal risk experience for similar activities and a factor A_i is assigned in terms of fatalities per year per individual.

4. *Degree of systemic control.* Rowe[4] defines levels of "controllability" of risk, and assigns a factor G.

Rowe then defines a risk acceptability factor, R_i, as

$$R_i = A_i \times P \times G$$

The actual level of risk of type i must not exceed R_i or at least must be in the same order of magnitude.

Assuming that nuclear reactors have a "favorable" cost–benefit balance and demonstrated controllability, Rowe found a rough equivalence between measured and acceptable risks for 100 reactors but not for 1000 reactors (except for property damage); he permitted insurance to make up this gap.

Rowe[4] also used liquefied natural gas (LNG) and liquefied propane gas (LPG) as examples and found

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*The Health and Safety Executive of Great Britain published a detailed study in June 1977 entitled *Canvey—An Investigation of Potential Hazards from Operations in the Canvey Island/Thurock Area.* The risk estimates are relatively high compared to those for a nuclear reactor.

that LNG has acceptable "measured" risks, whereas LPG does not.

Levine[46] has made several comments on the Rowe model, including the following:

1. The model, as presented, is simplistic and excludes many factors which are discussed in the report itself and which would be required to achieve an overall, complete benefit–risk assessment.

2. The model is risk dominated and includes essentially no provisions for consideration of benefits. In particular, Levine[46] says that requiring permissible risk levels for new activities to be below those for existing activities makes the implicit judgment that no new activity can have benefits that outweigh those of existing activities.

3. The evaluation of data relating to accident consequences does not appear to have a related statistical basis and is incomplete, leading to far lower risk factors than actually would apply with the proposed criteria.

Bowen[47] has argued for a basic criterion of 10^{-5} events per plant per year for off-site hazard (loss of life), with a requirement for increasingly high confidence levels (say, 99% or 99.9%) for a potential major disaster, rather than a much lower probability per year at unknown confidence level (or best-estimate value) to cover risk aversion to large events.*

He arrives at 10^{-5} per plant per year as reasonable on the basis of a cost–benefit balance for the United Kingdom in which he loosely equates the increase in life expectancy with the growth of national income. He also feels that at 10^{-4} per year the benefit–risk ratio is marginal and that the money would not be well spent to reduce the risk from 10^{-5} to 10^{-6} per year.

Bowen[47] argues strongly against a risk criterion proportional to the square (or some power significantly larger than 1) of the number of casualties, both on the basis of fairness to the sole individual who is exposed to larger risks and on the difficulty (or lack of measuring) of striving for very low probabilities, such as 10^{-10} per year.

He applies the risk criterion of 10^{-5} per plant per year equally for an individual, a family, or a community, not distinguishing between "individual" risk and "statistical" risk.

Specific to his entire approach is the fact that any individual is affected significantly by only a few plants.

In a report by Okrent and Whipple,[48] emanating from the UCLA study, societal activities are categorized as essential, beneficial, or peripheral. A decreasing level of acceptable risk to the most exposed individual is proposed (say, 2×10^{-4} per year for essential, 10^{-5} per year for beneficial, and 2×10^{-6} per year for peripheral activities). The risk would be assessed at a high confidence level (say, 90%), thereby providing an incentive to the search for better knowledge.

Each risk-producing major facility, technology, etc., would have to undergo assessment of risk both to the individual and to society. This applies to chronic and to accidental risks. The cost of all nondirectly attributable and insured risks would have to be internalized, probably via a tax paid to the federal government, which in turn would redistribute the benefit as national health insurance (to cover the statistical risks) or as reduced taxes to individuals.

It is proposed that some risk aversion to large (catastrophic) events be built into the assessment of a tax, and hence the internalization of costs. However, a risk-aversion factor much lower than that proportional to the cube or even the square of the number of casualties is suggested.

CONCLUDING REMARKS

It is impossible to summarize briefly so broad a topic as that encompassed by this project. Perhaps, the highlighting of some of the individual reports and a few general remarks will suffice.*

The work by Bergstrom appears to have provided considerable insight into how one should think about the "value of life," namely, in terms of the value to be attributed to small changes in the probability of death. The study on historical perspectives by W. Baldewicz et al.[33] specifically proposes the use of loss of life expectancy, rather than mortality, for evaluating risks and provides a formalism which permits the inclusion of associated factors such as pain or anguish. Fischoff et al.[34] provide a psychometric study *(How Safe Is Safe Enough?)* and some insight into the perception of risk. Okrent and Whipple[48] pose a trial quantitative approach to risk–acceptance criteria and risk management.

A group of papers on storage of chemicals, on the uncertainty in our knowledge of earthquakes, and on

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*In a personal communication, Bowen[47] has since indicated that a larger level of risk, more like 10^{-4} per plant per year, may be more practical for the person living near a large chemical facility.

*In this summary we have completely neglected the considerable contributions made to probabilistic methodology and nuclear reactor safety as part of the NSF-funded UCLA study.

seismic design criteria for Los Angeles illustrate both the very considerable gaps in society's knowledge of the hazards and risks with which it lives and the very considerable difficulties which face decision makers. The survey of expert seismic opinion provides a continuing challenge to those who are developing methods for decision making under uncertainty. Of course, the proceedings of the Asilomar workshop provide a second perspective on much of the preceding.

In conclusion, the following suggestions are made as to areas of risk–benefit assessment that appear to be among those which warrant particular emphasis in the future:

1. A better quantitative knowledge of all risks in society, which now are poorly known and are not accurately perceived.

2. A study of the risk–acceptance levels currently in use, overtly or de facto, and the reasons therefor.

3. More study of the expenditures which society can afford to further reduce risk and the benefit which should accompany such expenditures.

4. Increased effort on specific approaches to risk–acceptance criteria and to risk management in the face of large uncertainties and continuing disagreement among experts.

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A Cost-Benefit Comparison of Nuclear and Nonnuclear Health and Safety Protective Measures and Regulations

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[Editor's Note: This article was prepared for *Nuclear Safety* at the invitation of the editor. The article proposes a rationale for the implementation of safety measures and regulations based on a cost-benefit comparison derived from just principles of logic. However, the real world of nuclear power plant licensing makes little use of the principle of balancing monetary costs of safety features against the incremental improvements in safety. On the other hand, NEPA requires that there be a balancing of environmental costs vs. societal benefits. Although the Atomic Energy Act of 1954 requires a showing that the plant can be built without "undue risk" to the health and safety of the public, the term "undue risk" was not defined in such a way as to require balancing against cost. Even though the author faults the Nuclear Regulatory Commission for failing to apply cost-benefit balancing, in reality his complaints are more appropriately directed toward the Congress that passed the legislation.]

Abstract: *This article compares the costs and benefits of health and safety measures and regulations in the nuclear and nonnuclear fields. A cost-benefit methodology for nuclear safety concerns is presented and applied to existing nuclear plant engineered safety features. Comparisons in terms of investment costs to achieve reductions in mortality rates are then made between nuclear plant safety features and the protective measures and regulations associated with nonnuclear risks, particularly with coal-fired power plants. These comparisons reveal a marked inconsistency in the cost effectiveness of health and safety policy, in which nuclear regulatory policy requires much greater investments to reduce the risk of public mortality than is required in nonnuclear areas where reductions in mortality rates could be achieved at much lower cost. A specific example of regulatory disparity regarding gaseous effluent limits for nuclear and fossil-fuel power plants is presented. It is concluded that a consistent health and safety regulatory policy based on uniform risk and cost-benefit criteria should be adopted and that future proposed Nuclear Regulatory Commission regulatory requirements should be critically evaluated from a cost-benefit viewpoint.*

Protective measures and regulatory policy in the United States regarding health and safety are developed and implemented on a number of governmental levels (federal, state, and local) and at each level by a variety of agencies. In some instances the regulatory policy is focused on a particular type of hazard (e.g., radiation exposure), in others on an individual industry (e.g., automotive safety) or on a particular segment of the population or human activity (e.g., occupational or consumer product safety). The policy is carried out with varying degrees of government involvement and specification as to the precise measures required to provide protection. In some cases very detailed protective regulations are developed and enforced by governmental agencies, whereas in others the policy relies mainly on the self-interest of industry or the public to voluntarily reduce risk.

From its inception the nuclear power industry has been subject to a comprehensive regulatory policy at the highest governmental level, initially administered by the Atomic Energy Commission (AEC) and now by the Nuclear Regulatory Commission (NRC). Yet there are still concerns in some quarters that the existing nuclear regulatory policy is inadequate and that more stringent requirements must be imposed. Indeed, there are those who contend that no amount of regulation can achieve the desired result. Alternatively, there is strong sentiment, particularly within the regulated industry, that existing nuclear regulatory policy has already far surpassed the objective of adequate protection and that additional requirements merely add to the cost of the plants without yielding justifiable benefit.

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It is obvious that those holding these diverse opinions are basing their judgments on widely varying perceptions of (1) the residual risk associated with nuclear power, (2) the level at which such risk would become acceptable, or (3) the acceptable cost of achieving further reductions in risk. These perceptions are rarely expressed explicitly or in quantifiable values, but nonetheless they play an important role in shaping regulatory policy.

To provide some basis for judging the validity of these perceptions, it is instructive to review specific NRC licensing requirements against quantitative risk and cost–benefit criteria and to compare these results with similar values for protective measures associated with nonnuclear risks. Of particular interest are comparable regulations applicable to coal-fired power plants since coal is presently the primary alternative source of electric energy. This report summarizes several recent studies by the authors which address this subject.$^{1-3}$

EFFECT OF REGULATORY POLICY ON POWER PLANT COSTS

New regulatory requirements have produced a dramatic impact in recent years on the cost of new power plants, both nuclear and fossil fueled. Since 1969 the capital cost of a new nuclear plant has increased from $160/kW to $913/kW, while the comparable cost of a coal-fired plant has gone from $122/kW to $639/kW (Ref. 4). Figure 1 shows the elements of this increase. Although inflation contributes to a significant portion, the predominant impact has been attributed to new regulatory requirements, an important element of which has been the cost of licensing delays. These capital cost increases have contributed significantly to changes in the relative cost of producing power at the bus bar for nuclear and coal-fired power plants.

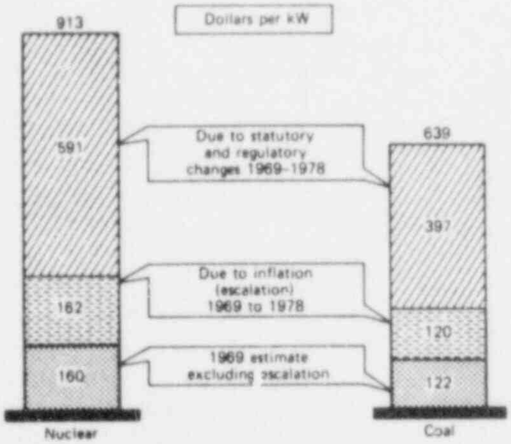

Fig. 1 Allocation of plant cost increases 1969 to 1978 (from Ref. 4).

As shown in Fig. 2, in 1969 nuclear enjoyed a 26% advantage over coal (7.9 vs. 10.7 mills/kWh), whereas in 1978 this gap narrowed considerably. This is due primarily to increases in the fixed charges, which are in turn mainly influenced by the changes in capital cost which, as noted, have been largely attributed to increased regulatory requirements.

It must be noted that these cost estimates are based on composite or average indices of equipment, labor, and fuel costs covering various areas of the United States and are therefore representative of a plant located in a hypothetical "Middletown, USA." Specific estimates of these factors for different areas of the country can and have produced^{5,6} different conclusions regarding the relative cost of nuclear and coal-fired plants for specific utility service areas. Nonetheless the results indicate that the future direction of regulatory policy can have a critical influence on future decisions to choose nuclear or coal and could result in reversal of decisions that would otherwise indicate the choice of one over the other based on regional economic factors. The relative cost–benefit effectiveness of regulatory policy regarding these

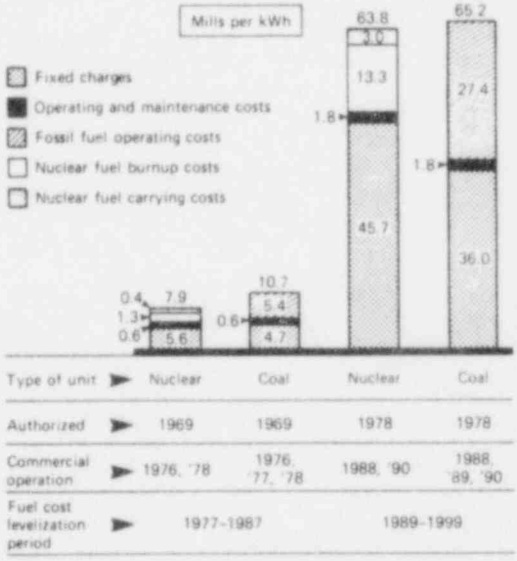

Fig. 2 Levelized bus bar power costs for first 10 years of plant operation (70% capacity factor) (from Ref. 4).

energy sources is therefore of more than academic interest.

COST–BENEFIT METHODOLOGY FOR NUCLEAR PLANT SAFETY FEATURES

A quantitative cost–benefit methodology has been used with respect to assessment of the radiological impact of normal plant operation on the environment and is, in fact, required by NRC regulations.[7] The methodology involves calculating the benefit of a particular design feature in terms of its ability to reduce annual population radiation exposures due to normal plant operation. This benefit (Δ man-rem/year) is then balanced against the annualized incremental cost of the design feature ($/year) to obtain the cost–benefit ratio ($/man-rem) of the feature. Should this ratio compare favorably with (i.e., be less than) the current acceptance criterion of $1000/man-rem, the feature should be incorporated in the plant design. A similar approach can be used to evaluate the cost effectiveness of safety features.

Since such environmental impact assessments are concerned with normal operation, there is no need to consider probabilistic uncertainties. However, when dealing with nuclear safety concerns involving accidents of low probability, the expected annual frequency of the events must be included. A generalized expression for the cost–benefit ratio, which takes into consideration both probability and consequences of events, is as follows:

$$\text{Cost/benefit ratio} = \frac{C}{\sum_{i=1}^{n} [P_i R_i] - \sum_{i=1}^{n} [P_i' R_i']}$$

where C = annualized cost of safety feature, $/year

P_i = probability of ith accident sequence of interest without safety feature installed, year^{-1}

R_i = radiological consequences of ith accident sequence of interest without safety feature installed, man-rem

P_i' = probability of ith accident sequence of interest with safety feature installed, year^{-1}

R_i' = radiological consequences of ith accident sequence of interest with safety feature installed, man-rem

n = number of accident sequences of interest (i.e., those upon which the proposed safety feature would have an effect in reducing probability and/or consequences).

In the following discussions this approach is used to evaluate the cost effectiveness of various engineered safety features (ESFs).

Cost–Benefit Analysis of Existing Engineered Safety Features

The design of current nuclear plant ESFs has been arrived at in a deterministic manner; that is, a set of rules and criteria has been established that specifies certain worst-case assumptions that must be used in determining ESF requirements. These rules are contained in the NRC's General Design Criteria,[8] siting regulations,[9] and in various regulatory guides. They are based, in large part, on a qualitative assessment of what is important to safety and on the concept of "defense in depth." As a result, all plants are now required to have an emergency core-cooling system (ECCS), a containment (including containment heat removal systems and fission product removal system), an on-site source of emergency electric power, and various other engineered safety features.

In applying cost–benefit methodology to such ESFs, the logical process to be followed would be to start with a hypothetical nuclear plant that does not contain these safety features, consisting primarily of design features and equipment necessary for normal operation and equipment protection. A risk assessment would then be performed, taking into account the various accident sequences and their consequences in the absence of ESFs. Then, in step sequence, each ESF would be added, the risk assessment re-performed with the feature added, and its cost–benefit ratio calculated until the established acceptance criterion is satisfied.

Since the *Reactor Safety Study*[10] (WASH-1400) represents a risk assessment of a typical nuclear plant, it can be applied to such an evaluation by modifying the calculated probabilities and consequences of relevant sequences to reflect the absence of various ESFs. In this way, equivalent event sequences that reflect the expected event probabilities and consequences without the ESF can be determined for each event. For example, in a plant without an ECCS or containment, it may be assumed that any loss-of-coolant accident (LOCA) could result in core melting and rapid atmospheric dispersion of the resulting fission products. Although the event of interest is simply any LOCA, the consequences of the event would be the same as for those WASH-1400 event sequences in which the ECCS and containment also fail. However, since the ECCS and containment are nonexistent, their failure probability is unity, and the probability of such severe consequences occurring is the same as the probability of the initiating LOCA, reflecting an increased risk. An example of the application of this approach is given in Table 1.

ESFs Evaluated

A cost–benefit evaluation using the foregoing methodology was made for the following key ESFs for a typical pressurized-water-reactor (PWR) plant as described in WASH-1400:

1. Emergency core-cooling system (ECCS)

Table 1 Example of ESF Cost–Benefit Analysis

ESF case	Accident event sequence*	Probability, year^{-1}	Equivalent WASH-1400 consequence sequence*	Release category	Radiological consequences, man-rem	Risk, man-rem/year
		P_i			R_i	P_iR_i
No ESFs	A	1×10^{-4}	AB − α	1	8.0×10^7	8.0×10^3
	S_1	3×10^{-4}	S_1 B − α	1	8.0×10^7	2.4×10^4
	S_2	1×10^{-3}	S_2 B − α	1	8.0×10^7	8.0×10^4
	TMLB	3×10^{-4}	TMLB − α	1	8.0×10^7	2.4×10^4
						$\Sigma P_iR_i = 1.4 \times 10^5$
		P_i'			R_i'	$P_i'R_i'$
ECCS only	A	1×10^{-4}	A − β	8	4.0×10^4	4.0×10^0
	S_1	3×10^{-4}	S_1 − β	8	4.0×10^4	1.2×10^1
	S_2	1×10^{-3}	S_2 − β	8	4.0×10^4	4.0×10^1
	AB	1×10^{-7}	AB − α	1	8.0×10^7	8.0×10^0
	AD	2×10^{-6}	ADC − α	1	8.0×10^7	1.6×10^2
	AH	1×10^{-6}	AH − α	3	4.4×10^7	4.4×10^1
	S_1 B	2×10^{-7}	S_1 B − α	1	8.0×10^7	1.6×10^1
	S_1 D	3×10^{-6}	S_1 DC − α	1	8.0×10^7	2.4×10^2
	S_1 H	3×10^{-6}	S_2 H − α	3	4.4×10^7	1.3×10^2
	S_2 B	8×10^{-7}	S_2 B − α	1	8.0×10^7	6.4×10^1
	S_2 D	9×10^{-6}	S_2 DC − α	1	8.0×10^7	7.2×10^2
	S_2 H	6×10^{-6}	S_2 H − α	3	4.4×10^7	2.6×10^2
	TMLB	3×10^{-4}	TMLB − α	1	8.0×10^7	2.4×10^4
						$\Sigma P_i'R_i' = 2.5 \times 10^4$

$$\text{ECCS cost–benefit ratio} = \frac{C}{\Sigma P_iR_i \text{ [illegible]}} \text{ [illegible] } \frac{\text{[illegible]}/\text{year}}{\text{[illegible]} - 2.5 \times 10^4} = \$14/\text{man-rem}$$

*Key to PWR accident sequence symbols [illegible] Report WASH-1400, Table 5-2):

A, Intermediate to large LOCA

B, Failure of electric power to ESFs.

B′, Failure to recover either on-site or off-site electric power within about 1 to 3 h following an initiating transient which is a loss of off-site a-c power.

C, Failure of the containment spray injection system.

D, Failure of the emergency core-cooling injection system.

F, Failure of the containment spray recirculation system.

G, Failure of the containment heat removal system.

H, Failure of the emergency core-cooling recirculation system.

K, Failure of the reactor protection system.

L, Failure of the secondary system steam relief valves and the auxiliary feedwater system.

M, Failure of the secondary system steam relief valves and the power conversion system.

Q, Failure of the primary system safety relief valves to reclose after opening.

R, Massive rupture of the reactor vessel.

S_1, A small LOCA with an equivalent diameter of about 2 to 6 in.

S_2, A small LOCA with an equivalent diameter of about $\frac{1}{2}$ to 2 in.

T, Transient event.

V, Low-pressure injection system (LPIS) check valve failure.

α, Containment rupture due to a reactor vessel steam explosion.

β, Containment failure resulting from inadequate isolation of containment openings and penetrations.

γ, Containment failure due to hydrogen burning.

δ, Containment failure due to overpressure.

ε, Containment vessel melt-through.

2. Containment (including associated heat and fission product removal systems)

3. Emergency on-site alternating-current (a-c) power system [diesel-generator (DG) sets]

These key ESFs were applied individually and in all possible combinations and sequences to a base case involving a PWR devoid of these safety features.

Report WASH-1400 was based on a PWR plant that went into operation in 1972 and, of course, included these basic ESFs. Since that time NRC regulations have required the incorporation of additional ESFs, which are not reflected in the WASH-1400 risk analysis. One such addition is the hydrogen recombiner system, the need for which is based on deterministic assumptions. For the contribution of a hydrogen recombiner system to the reduction of accident risk to be assessed, a cost–benefit evaluation was performed for such a system applied to the complement of ESFs analyzed in WASH-1400 for a typical PWR. In this analysis it was assumed that the hydrogen recombiner system would be capable of eliminating entirely the risk of those accident sequences in which the containment failed due to hydrogen-related overpressure (i.e., all $P_i' = 0$). Since no ESF is capable of reducing the probability of any accident sequence to zero, the actual benefit will be less. This procedure, therefore, provides a lower limit on the cost–benefit ratio for the hydrogen recombiner system.

Probability and Consequence Values

The probabilities (P_i) of the various accident sequences of interest were obtained from WASH-1400, using median estimates for accident sequence probabilities. The fractions of core fission products released for each accident were classified, in the manner of WASH-1400, into nine release categories ranging from Category 1, corresponding to a core melt condition with rapid, direct atmospheric dispersion (i.e., without effective ECCS or containment) to Category 9, corresponding to no core melt with effective containment (i.e., ECCS and containment function as designed).

The radiological consequences (R_i) of each accident sequence of interest were calculated in terms of total integrated whole-body dose to an exposed population (man-rem), assuming a uniform population density of 400 persons per square mile surrounding the site. This value is consistent with NRC guidelines[11] on site suitability with respect to population density and is typical, on a cumulative population basis, of many existing nuclear plant sites. The population dose for a Category 1 release was obtained from Fig. VI 13-18 in WASH-1400 (Ref. 10). Total doses for other release categories were obtained on the basis of the fractional quantities of the various nuclides included in each release category and their relative contributions to whole-body dose. Table 2 gives the radiological consequences (R_i) for each release category.

Table 2 Population Doses Resulting from Various Accident Release Categories

Release category	Whole-body dose, man-rem
1	8.0×10^7
2	7.2×10^7
3	[illegible]$.4 \times 10^7$
4	7.6×10^6
5	1.9×10^6
6	4.4×10^5
7	1.0×10^4
8	4.0×10^4
9	40

Cost Values

Annual costs for each ESF were based on estimates for typical PWR plants in 1978 dollars with 8% interest over 40 years. In each case the costs include only the *incremental* cost of providing the ESF function with respect to equipment or structures that would be expected to be provided for normal plant operation. The additional cost of a full-pressure-retaining containment structure and associated systems over the cost of a conventional-type power-plant structure housing the reactor coolant system was estimated for containment. For the ECCS, it was assumed that a residual heat removal system would be provided for normal plant shutdown. Thus the ECCS costs are those associated with the additional equipment (high-pressure safety injection system and accumulators) required to perform the ECCS function. Emergency diesel-generator system costs were based on replacing a small diesel generator used for plant equipment protection with two redundant full-capacity diesel generators capable of supplying ESF loads and housed in a separate seismic Category I building. Hydrogen recombiner system costs are based on actual costs for a typical PWR plant. (ESF cost values are summarized in Table 5.)

ESF Cost–Benefit Ratios

Table 3 gives the summation of $(P_i R_i)$ values for all accidents of interest for the base case (no ESF) and for the ECCS, containment, and DG sets applied individually and in combination. This summation represents the residual risk in man-rem/year for each case. The risk reduction for an ESF in any particular case is the difference between the residual risk for that case and the residual risk for the corresponding case without that ESF. It is this benefit value which must be compared to the annualized cost (C) of the ESF to determine its cost–benefit ratio. Table 4 presents the benefits and cost–benefit ratios for the ECCS, containment, and DG sets applied in various sequences.

Table 3 Nuclear Plant Accident Risks for Various ESFs and Combination of ESFs

Installed ESFs	Residual risk, man-rem/year	Risk reduction factor
Base (no ESFs)	1.4×10^5	
DGs only	1.1×10^5	1.2
ECCS only	2.5×10^4	5.4
Containment only	1.9×10^4	7.2
ECCS + containment	1.8×10^4	7.6
ECCS + DGs	1.8×10^3	76
Containment + DGs	840	160
ECCS + containment + DGs	360	378

An examination of the data given in Table 4 shows that the cost–benefit ratio for any particular ESF is highly dependent on the sequence in which it is applied in the risk assessment. When considered first, the cost–benefit ratio for each of the three ESFs is well below \$1000/man-rem, indicating that, individually, the cost of these features would be well justified in the absence of any other ESFs. However, using the traditional cost–benefit methodology of adding improvements in order of increasing cost–benefit ratio, ESF Sequence 3 would be chosen, which could lead to the faulty conclusion that the containment is not justified since its cost–benefit ratio is \$2083. While this methodology is suitable for determining optimum allocation of a fixed sum of money which is available for investment in safety, it does not necessarily guarantee satisfaction of a criterion which specifies

Table 4 Cost–Benefit Ratios for ESFs Applied in Various Sequences

ESF sequence	Sequence of ESF application 1	 2	 3
1	DG	ECCS	Containment
Risk reduction, Δ man-rem/year	2.4×10^4	1.1×10^5	1.4×10^3
Cost–benefit ratio, \$/man-rem	83	14	2083
2	DG	Containment	ECCS
Risk reduction, Δ man-rem/year	2.4×10^4	1.1×10^5	4.8×10^2
Cost–benefit ratio, \$/man-rem	83	27	3125
3	ECCS	DG	Containment
Risk reduction, Δ man-rem/year	1.1×10^5	2.4×10^4	1.4×10^3
Cost–benefit ratio, \$/man-rem	14	85	2083
4	ECCS	Containment	DG
Risk reduction, Δ man-rem/year	1.1×10^5	6.8×10^3	1.8×10^4
Cost–benefit ratio, \$/man-rem	14	441	111
5	Containment	DG	ECCS
Risk reduction, Δ man-rem/year	1.2×10^5	1.8×10^4	4.8×10^2
Cost–benefit ratio, \$/man-rem	25	111	3125
6	Containment	ECCS	DG
Risk reduction, Δ man-rem/year	1.2×10^5	4.0×10^2	1.8×10^4
Cost–benefit ratio, \$/man-rem	25	3750	111

that any and all safety improvements should be made which cost less than \$1000/man-rem. In this case, ESF Sequence 4 results in the optimum cost–benefit utilization of the three ESFs considered, with cost–benefit ratios of \$14, \$441, and \$111 per man-rem for the ECCS, containment, and DG sets, respectively.

The addition of the hydrogen recombiner system to the ECCS, containment, and the DG sets resulted in a minimal additional reduction in risk (less than 0.13 man-rem/year) because, according to WASH-1400, the probability of post-LOCA containment failure due to hydrogen explosions or combustion even without recombiners is extremely low. This estimated benefit value is so small that, even though the cost of the recombiner system is relatively small compared with the other ESFs, the cost–benefit ratio is quite high. The benefits, costs and cost–benefit ratios of hydrogen recombiners compared with the other ESFs are shown in Table 5 for the most cost–beneficial sequence of addition.

Table 5 Summary of Cost–Benefit Analysis for Engineered Safety Features

Engineered safety feature	Risk reduction, man-rem/year	Cost, \$/year	Cost–benefit ratio, \$/man-rem
ECCS	1.1×10^5	1.5×10^6	14
Containment	6.8×10^3	3.0×10^6	441
Emergency power system	1.8×10^4	2.0×10^6	111
Hydrogen recombiner system	<0.13	4.0×10^4	$>3 \times 10^5$

Consideration of the Risk to Individuals

The cost–benefit analysis thus far has been based on the risk to populations. Since the effects of radiation doses resulting from accidents generally decline with distance from a plant, the risk to individuals is clearly nonuniform over the entire population. An individual located immediately adjacent to the site boundary may therefore understandably question the validity of cost–benefit criteria that rely on benefit measurements based solely on the risk to populations.

An assessment of the maximum risk to an individual near a nuclear plant site was made to see whether or not such concerns are warranted. The nuclear accident risk to an individual located near the site is dominated by the probability of those accidents which could result in core melting and rapid release of resulting fission products to the atmosphere (i.e., WASH-1400 release categories 1 to 5). Such accidents could result in early fatality (death within a year) of any individual directly exposed to the accident plume within a few miles of the site. Other accidents involving release categories 6–9 involve delayed release of much smaller inventories of fission products to the atmosphere. Evacuation procedures and lower exposure dose rates would result in much lower risks, even though the probability of such accidents may be much higher.

The maximum fatality risk to an individual was calculated assuming that the individual is always located near the site and that, in the event of a serious accident, there is a 50% probability that the plume will traverse this location (i.e., the individual is downwind of the plant). It is further assumed that in such an event exposures will result in early fatality. These assumptions are clearly conservative since they do not account for time spent away from the site, narrowness of the plume, and the mitigating effect of intensive medical treatment, all of which would serve to reduce individual risk.

Figure 3 shows the maximum risk to an individual from nuclear plant accidents with respect to the cumulative cost of adding ESFs to reduce that risk. Also shown are the average background risks for an individual from nonnuclear accidents (falls, fires, etc.) and from disease. As indicated, even with no ESFs installed, the maximum risk to an individual is only slightly more than the nonnuclear accident risk and less than 10% of all nonnuclear risk. Adding an ECCS, a containment, and DG sets reduces the nuclear risk to less than 0.1% of the total nonnuclear risk. Conservatively assuming that all persons within 3 miles of the plant would be exposed to this maximum risk and again assuming a density of 400 persons per square mile, the installation of these ESFs would reflect an annual expenditure of over \$500 per person to achieve a reduction in nuclear risk from 10% to less than 0.1% of the total background nonnuclear risk.

This figure would seem to compare favorably with the amount individuals themselves are willing to voluntarily pay for nonnuclear risk reduction. For example, it is unlikely that many individuals would be willing to support such a cost–benefit ratio themselves if it were demonstrated to them (as it probably could be) that annual physical examinations costing \$500 could reduce by 10% the risk of death due to disease. Indeed, an opinion survey[12] showed that individuals are willing to spend, on the average, only \$56 to achieve a reduction in personal risk of five times greater than this. The question of individual risk and individual cost–benefit criteria, therefore, should not be an overriding issue with respect to risk and cost–benefit criteria applied on a population basis.

Discussion

The foregoing analysis demonstrates the usefulness of quantitative cost–benefit analysis as applied to ESFs and nuclear safety concerns. However, the results should not be taken as a definitive cost–benefit analysis on an absolute scale. There are large uncertainties in the probabilities and consequences presented in WASH-1400. Further, the idealized nature of the assumed population distribution could result in significant variations from actual site conditions. In addition there may be other monetary costs or benefits, such as risk of property damage or plant outage, which have not been included here.

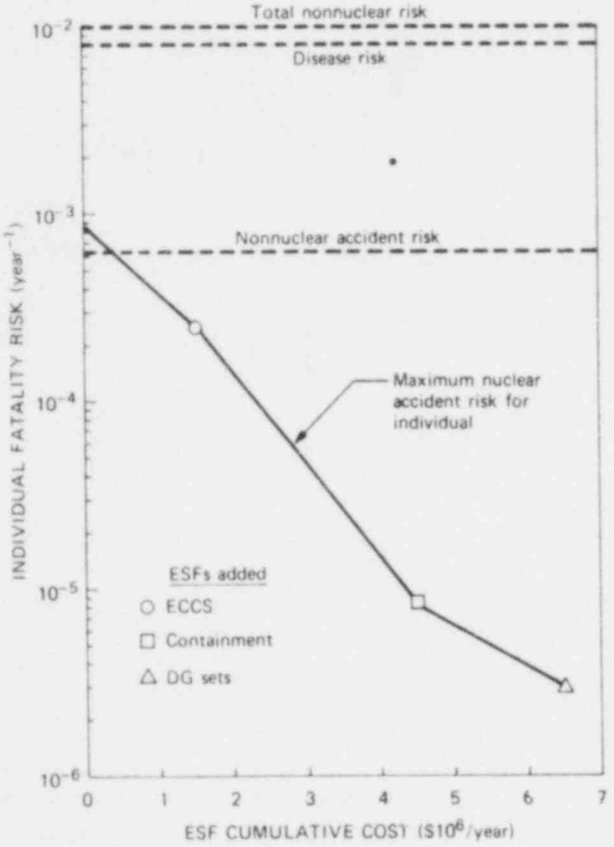

Fig. 3 Maximum risk to an individual from nuclear plant accidents with respect to the cumulative cost of adding engineered safety features (ESFs) to reduce that risk. Also shown are the average background risks for an individual from nonnuclear accidents (falls, fires, etc.) and from disease.

The methodology does provide insight into the relative cost effectiveness of existing ESFs and the manner in which they contribute to reducing accident risk. The results show that the major contributors to risk are the small LOCAs and transient events involving loss of electric power. As might be expected, the DGs by themselves provide a small fractional risk reduction factor (see Table 3). The ECCS or containment each reduces risk by a factor of 5 to 7. With diesel generators installed, the effectiveness of the ECCS or the containment is increased by at least an order of magnitude and, with all three, the overall risk is reduced by almost a factor of 400. This interdependence supports the defense-in-depth concept wherein the effectiveness of each ESF is amplified greatly in combination with other ESFs.

It would also appear that the regulatory policy regarding the need for ECCS, containment, and emergency power systems is supported on a quantitative cost–benefit basis at least with respect to the \$1000/man-rem criterion. However, the cost–benefit evaluation for hydrogen recombiners shows that they are orders of magnitude less cost effective relative to the three other basic safety features evaluated. Moreover, even considering large uncertainties in the WASH-1400 risk values, they probably could not be justified with respect to a \$1000/man-rem acceptance criterion, which is generally recognized to be a conservatively high value.

This conclusion may seem unwarranted in view of the apparently prominent role played by hydrogen recombiners in the recent Three Mile Island accident. However, a number of factors would seem to indicate that the actual risk of serious population exposures due to hydrogen-related containment failure in that event would not have been great even if recombiners had not been installed prior to the accident.

From preliminary data on the event, it appears that the hydrogen level in the containment quickly rose to about 2.5% within about 4 days after the onset of the event and remained at about that level even though the recombiners were not brought into operation until an additional 2 days had elapsed. This indicates that there probably would have been considerable additional time available before hydrogen levels would have reached even the lower flammability limit of 4%. It then would have permitted consideration of such alternative actions as bringing a portable recombiner unit from offsite for emergency operation or reliance on controlled purging to limit hydrogen levels in the absence of permanently installed recombiners. Ultimately, evacuation of the surrounding population, already partially achieved, could have been (and presumably would have been) extended out to several miles or more if recombiners had not been available and containment hydrogen levels approached dangerous levels. While certainly not a public relations coup, this would have drastically reduced population exposures in the event of additional releases of contained fission products due to controlled purging or even hydrogen-related containment failure. Furthermore, it is not at all clear whether the containment would have failed catastrophically in the event of hydrogen burning or explosion.

Of course, given a set of preexisting events involving release of fission products and hydrogen to the containment, such as occurred at Three Mile Island, hydrogen recombiners could most probably be shown to be cost effective on a *conditional* basis. This may support the concept of sharing a portable recombiner among a number of plants with provisions for its installation and operation in any unit. However, it does not necessarily follow that the inclusion of redundant recombiners as permanently installed engineered safety features in all plants is cost-effective as a predetermined design decision, particularly when considered relative to alternative engineered safety features. The very same post-Three Mile Island knowledge which appears to support the wisdom of having recombiners installed also clearly demonstrates the greater relative importance of the emergency feedwater system, ECCS, and the containment and indicates that other design measures (such as positive indication of pressurizer relief valve position, which could have averted the accident) may have been, in retrospect, far more cost-effective.

COMPARISON WITH COAL-FIRED POWER PLANTS AND OTHER NONNUCLEAR RISKS

For an even broader perspective to be achieved on the effectiveness of the guidelin , under which the nuclear power industry is regulated, it is meaningful to compare the risk and cost–benefit values for nuclear regulatory policies with those for the protective measures associated with nonnuclear risks, particularly with regulations for coal-fired power plants.

For such comparisons to be made, a common standard of measuring cost–benefit effectiveness must be used. A commonly used index relates investment costs to expected reduction in health effects in terms of the reduced excess mortality rates achieved. This should not be taken as a precise or complete measure of effectiveness since there may be additional health and safety benefits (i.e., reduction in illnesses or injuries) or additional cost impacts or benefits (e.g., reduced risk of property damage) associated with regulations or protective measures. However, it does provide a useful measure for making order-of-magnitude comparisons of cost effectiveness since it relates costs and benefits in consistent units for both nuclear and nonnuclear risks.

Proposed EPA Regulations for SO_2 Removal

There is considerable uncertainty in estimating the health effects associated with coal-fired power plants. However, it is generally agreed that increased sulfur dioxide (SO_2) emissions are highly correlated with observed increases in morbidity and mortality. If a linear relationship is assumed for SO_2-related mortality,[13] these effects could be reduced linearly by reducing the amount of SO_2 discharged to the atmosphere. This could be accomplished either by burning low-sulfur coal or by removing the SO_2 deposited in the plant's vent stack (scrubbing) after combustion.

The Environmental Protection Agency (EPA) has proposed regulations[14] that would limit the permissible concentrations of various pollutants in the emissions from fossil-fuel plants and would, in particular, require full scrubbing (at least 85% removal) of sulfur dioxide regardless of the sulfur content of the fuel. Within the power industry there are serious questions as to the technical feasibility of meeting these proposed regulations, and a "sliding scale" for SO_2 removal, ranging from 40 to 85% depending on the sulfur content of the coal, has been suggested as an alternative.

Because of the large uncertainty in regard to the health effects of SO_2 and uncertainties in the installation and operating cost of SO_2 removal equipment, it is difficult to assign a single cost–benefit value for scrubbers. Hamilton and Manne[15] have estimated a range of values for SO_2-related mortality for situations involving the use of high- and low-sulfur coal with and without scrubbers. The Hamilton and Manne (Ref. 15) SO_2–mortality estimates provide a basis for comparison with the nuclear plant cost–benefit ratios since they are based on an equivalent unit size [1000

MW(e)] and population distribution (400 persons per square mile).

These values, adjusted for 85% removal, were used in conjunction with high and low estimates of the costs of scrubbers to provide maximum and minimum cost–benefit ratios.

Nuclear and Nonnuclear Cost–Benefit Ratios

Table 6 presents a comparison of cost–benefit values in terms of investment costs necessary to achieve a reduction in mortality risk for NRC-mandated nuclear plant design features, EPA-proposed coal-plant design features, and other nonnuclear health and safety protective measures. For the nuclear plant radwaste systems and engineered safety features, these values are based on a linear dose–mortality relationship of 1.0×10^{-4} excess deaths per man-rem exposure,[16] using the \$1000/man-rem criterion for radwaste systems and the \$/man-rem cost–benefit ratios developed previously for the ESFs. The range of values for SO_2 scrubbers was established as described above. Cost–benefit ratios for other protective measures were obtained from Refs. 12, 17, and 18 through 22.

Table 6 Cost–Benefit Ratios for Various Health and Safety Protective Measures

	Cost–benefit ratio, \$1 million/life saved
Nuclear power-plant design features	
Radwaste effluent treatment systems	10
ECCS	0.1
Containment	4
DG sets	1
Hydrogen recombiners	>3000
Coal-fired power plant design features	
High-sulfur coal with SO_2 scrubbers, 85% removal	0.1–1.4
Low-sulfur coal with SO_2 scrubbers, 85% removal	0.7–10
Occupational health and safety	
OSHA* coke fume regulations	4.5
OSHA benzene regulations	300
Environmental protection	
EPA† vinyl chloride regulations	4
Proposed EPA drinking water regulations	2.5
Fire protection	
Proposed CPSC‡ upholstered furniture flammability standards	0.5
Smoke detectors	0.05–0.08
Automotive and highway safety	
Highway safety programs	0.14
Auto safety improvements, 1966–1970	0.13
Air bags	0.32
Seat belts	0.08
Medical and health programs	
Kidney dialysis treatment units	0.2
Mobile cardiac emergency treatment units	0.03
Cancer screening programs	0.01–0.08

*OSHA, Occupational Safety and Health Administration.
†EPA, Environmental Protection Agency.
‡CPSC, Consumer Product Safety Commission.

Table 6 shows that, in general, nuclear plant regulatory policy results in a considerably higher investment to achieve reductions in public mortality risk than for other activities. With the exception of the ECCS, all other nuclear plant design features have cost–benefit ratios of \$1 million or more per life saved, with the hydrogen recombiners having a ratio in excess of \$3 billion per life saved.

With respect to coal-fired plants, it would appear that requirements for full scrubbing where low-sulfur coal is used could yield cost–benefit values comparable to those associated with nuclear plant design features. However, even with the use of scrubbers and low-sulfur coal, the residual mortality risk for a coal plant remains significantly higher than for a nuclear plant (0.4 to 7 vs. 0.04 excess deaths per year), though well below that associated with other commonly accepted risks.

Of greater significance, Table 6 demonstrates a complete lack of consistency in health and safety policy on any uniform cost–benefit basis among agencies or even within agencies. With respect to occupational hazards, it has been estimated that the Occupational Safety and Health Administration's (OSHA) near-zero limit on benzene in the work place will prevent two cancer deaths every 6 years at a cost of \$300 million each. These regulations have been challenged and struck down in court because OSHA has not shown that the benefits of its requirements justify the cost. However, OSHA has maintained that it is not required to make cost–benefit judgments, and has taken the case before the Supreme Court which should rule on this important matter soon. By contrast, OSHA's regulations for limiting coke fumes in the steel industry have been estimated at \$4.5 million per worker life saved.[12]

The EPA regulations for controlling vinyl chloride emissions have been estimated to cost at least \$4 million per life saved,[19] and drinking water regulations proposed by EPA imply a cost of \$2.5 million[17] per reduced fatality in the exposed population.

In the area of consumer product safety, the National Bureau of Standards has proposed a comprehensive analytical approach to determining cost effectiveness of regulations.[20] A preliminary application of this methodology[21] to standards being considered by the Consumer Product Safety Commission (CPSC) to reduce the fire hazards of upholstered furniture shows that several hundred lives could be saved each year at a cost of about $500,000 per reduced fatality. However, it appears that the standards may not be adopted owing to the perceived inflationary and economic impact on the furniture industry.

A value of $140,000 per life has been used explicitly in decision making regarding highway safety programs,[17] and many highway improvements (such as guardrail installation, better surfaces for skid resistance, and improved warning signals) that could save many lives could be made at costs between $20,000 and $100,000 per life saved.

In automotive safety, improvements made between 1966 and 1970 have been estimated to have reduced traffic fatalities by 28,200 during this period at a cost of $130,000 per life saved. Among these, seat belts save 5,000 lives per year at a cost of $80,000 per life. Installation of airbags in new cars, a safety measure that has been delayed because of concern for the cost (about $200 per car), could save additional lives at a cost of about $320,000 per life.[22]

One of the best life-saving bargains available appears to be the smoke detector. It has been estimated that placing smoke detectors in all residences in the United States could result in several thousand fewer deaths annually at a cost of between $50,000 and $80,000 per life saved.[18] However, no comprehensive regulatory policy yet exists to require their use.

In the area of medical treatment, it has been estimated that kidney dialysis treatment units and mobile emergency cardiac units save lives at an investment cost of $200,000 and $30,000 per life, respectively.[22] The federal government has established a program for subsidizing the cost of dialysis treatment, which undoubtedly has saved numerous lives, but has left the determination of need and funding for emergency cardiac units largely up to local political jurisdictions, with predictably uneven results in degree of protection provided. Various cancer screening programs, which are largely voluntary, have been demonstrated to prevent cancer deaths at costs between $10,000 and $80,000 per life saved.[27]

All these cost–benefit ratios imply a monetary value for a statistical life.* Although this is a highly subjective and controversial matter, there have been estimates made on the basis of implied and explicit values which society has associated with the actual or potential loss of human life. Table 7 lists some of these values.

Table 7 Costs Placed on a Statistical Life

	Cost, dollars per life
Average loss of income due to death (6000 lost working days at $50/day)*	300,000
Jury awards in loss-of-life lawsuit†	50,000–500,000
Hazardous duty pay for pilots, taking into account the probability of death†	135,000–980,000
Dollar value of property loss in cases where people near an accident primarily remembered the property loss rather than the loss of life†	200,000

*Ref. 23.
†Ref. 24.

The cost–benefit ratios for nuclear plant-design features compare favorably with the statistical life values given in Table 7; i.e., the amount being spent to reduce mortality risk is well in excess of the amount that has been associated with the statistical value of human life. Many of the cost–benefit values for nonnuclear risks are well below these values, indicating that the public should be willing to support greater investments in protective measures to reduce these risks further. This suggests that the regulatory emphasis on further reducing nuclear plant risks may not be [illegible]ied in view of the availability of more cost-effective means of reducing risks that are not being fully pursued. Indeed, it would appear that the $4 million annual cost involved in equipping 100 nuclear plants with hydrogen recombiners could more effectively be invested in emergency cardiac treatment units or cancer screening programs, which at the cost–benefit values cited for them, could result in several hundred additional lives saved per year.

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*It is important to distinguish between a statistical (or unidentified, theoretically calculated) loss of life and an actual (or identified) loss of life.

COMPARISON OF GASEOUS EFFLUENT STANDARDS FOR NUCLEAR AND FOSSIL-FUEL POWER PLANTS

The analysis presented above indicates a marked inconsistency between the cost–benefit effectiveness of public health and safety policy regarding nuclear and nonnuclear risks. A specific example of this disparity can be seen in a direct comparison of regulatory standards for gaseous effluents from nuclear and fossil-fuel power plants. Lave and Freeburg[13] addressed this subject in 1973; however, the regulatory limits have since been drastically changed as a result of Appendix I to Title 10, *Code of Federal Regulations*, Part 50 (10 CFR 50) and the 1977 amendment to the Clean Air Act. The regulations considered appropriate for performing a comparison of limitations imposed on gaseous effluents from nuclear fossil-fuel power plants are Appendix I to 10 CFR 50, Section II for nuclear plants and Section 163(b)(2) of the Clean Air Act (as amended) for fossil-fuel plants.

Gaseous Effluents Limitations for Nuclear Power Plants

Appendix I to 10 CFR 50, Section II requires that the design of a nuclear power facility must provide assurance that (1) the calculated annual total quantity of all radioactive material above background to be released to the atmosphere from each light-water-cooled nuclear power reactor will not result in an estimated annual dose of 5 mrems to the whole body of any individual in an unrestricted area, and (2) the calculated annual total quantity of all radioactive iodine and radioactive material in particulate form to be released to the atmosphere in effluents from each light-water-cooled nuclear power reactor will not result in an estimated annual dose or dose commitment to any individual in an unrestricted area from all pathways of exposure in excess of 15 mrems to any organ. These regulations establish the design basis of the building ventilation and gaseous radwaste systems of nuclear power facilities.

Gaseous Effluent Limitations for Fossil-Fuel Power Plants

With the issuance of the August 1977 amendment to the Clean Air Act and the anticipated regulatory modifications associated therewith, it is difficult to select a gaseous effluent limitation for fossil-fuel plants that can be appropriately compared to the nuclear plant limits. However, considering the new source performance standards, the existing primary and secondary national ambient air quality standards, and the prevention of significant deterioration (PSD) limits for Classes I, II, and III as described in Section 163 of the Clean Air Act as amended in August 1977, the Class II concentration limits are considered the most appropriate for comparison to the nuclear effluent guidelines. This section of the act sets a limit on the maximum allowable increase in concentrations of sulfur dioxide and particulate matter over the existing baseline concentration.

Comparison of Risks to Individuals

The gaseous effluent regulations cited establish radionuclide and air pollution limits to which an individual may be exposed. Since these peak average annual concentrations would only occur at specific "maximum" locations off-site, the number of people exposed to these limited concentrations would be limited. The general population would be exposed to levels well below these limits.

Table 8 presents the maximum risks associated with exposure to the regulatory limits for gaseous effluents from nuclear and fossil-fuel plants. These results reveal that the potential adverse health implications of the effluent limits for gaseous effluents for nuclear plants are about 400-fold less than those for coal-fired power plants. When we consider that adverse human health effects associated with ambient SO_2 concentrations which are close to the PSD Class II regulatory limits[25] have been observed, but no adverse effects have been observed from radiological exposures which are well above the Appendix I regulatory limits,[26,27] the disparity in actual risks may be much greater than indicated.

To put these risks into perspective, the public thinks an individual risk is high if it is greater than 10^{-4}/year and low if it is less than 10^{-4}/year (Ref. 28). Clearly, by this criterion the nuclear risks (5.8×10^{-8} per year) should be acceptable and the fossil-fuel risks (2.4×10^{-4} per year) should be border[illegible].

Comparing these risks with the risks to individuals in the general population from various types of accidents[10] reveals that (1) the maximum calculated individual risk from exposure to nuclear plant effluents at their regulatory limits is comparable to the actual risk of being struck by lightning (8×10^{-7} year^{-1}) and (2) the calculated individual risk from exposures to the gaseous effluent from a coal plant operating at the PSD Class II regulatory limits is comparable to the risk

Table 8 Individual Mortality Risks Associated with Gaseous Effluent Standards for Nuclear and Fossil-Fuel Plants

NUCLEAR PLANT STANDARDS

Risk contributor	10 CFR 50 App. I regulatory limit, rem/year	Risk* coefficient, deaths/rem	Mortality risk per year
Whole-body dose	0.005	1.0×10^{-4}	5.0×10^{-7}
Thyroid dose	0.015	5.0×10^{-6}	7.5×10^{-8}
		Total individual risk per year =	5.8×10^{-7}

FOSSIL-FUEL PLANT STANDARDS

Risk contributor	PSD Class II regulatory limit, $\mu g/m^3$	Risk† coefficient, deaths/(year)($\mu g/m^3$)	Mortality risk per year
Sulfur dioxide	20	3.9×10^{-6}	7.8×10^{-5}
Particulates	19	8.5×10^{-6}	1.6×10^{-4}
		Total individual risk per year =	2.4×10^{-4}

*From Ref. 16. †From Ref. 13.

of death by a motor vehicle accident (2.8×10^{-4} year^{-1}).

On the basis of the preceding comparisons of individual risk of death, it seems the regulations, limiting gaseous effluent emission from fossil-fuel plants are less restrictive than the regulations that set radiological limits for nuclear plants by at least two orders of magnitude.

At each step in the foregoing analysis there are numerous assumptions that could be modified to give different results. However, each assumption was selected so that the measure of risk for each pollutant has the same degree of inherent conservatism. Accordingly, the values of 5.8×10^{-7}/year for radiological risks and 2.4×10^{-4}/year for fossil-fuel risks should be viewed as an index of risk rather than an accurate expression of absolute risk.

Comparison of the Risks to Populations

If a power plant is discharging gaseous effluents at its regulatory limits, the average member of a population in the vicinity of the plant would be exposed to concentrations of airborne pollutants, both radiological and nonradiological, which are well below the regulatory limits. This is a result of atmospheric dispersion, in-transit depletion, and, for radioactive effluents, radiological decay. Assuming that a nuclear power plant is operating at its regulatory limit, the average individual within 50 miles of the plant would receive an exposure of less than 0.1 mrem/year to the whole body and the thyroid gland. At a comparable coal-plant site, the average individual would be exposed to less than 0.1 $\mu g/m^3$ of SO_2 and particulates. This is based on an assumed 100-fold difference between the peak annual and average annual concentration within a 50-mile radius of the plant.

Accordingly, the nuclear regulatory limits are also at least 100-fold more restrictive than fossil-fuel effluent limits when assessed in terms of health impact on the population in general. It could be argued that the difference is even greater since SO_2 is transformed to sulfates during transport and the concentration of sulfates relative to SO_2 increases as a function of distance from the source of release. Since sulfates are believed to be more toxic than SO_2 [EPA-450/2-75-007 (Ref. 25)], the risk as a function of distance from the point of release may not decline as rapidly as it does for radiological effluents. In addition, the population density in the vicinity of a fossil-fuel plant is usually greater than that in the vicinity of a nuclear power plant, causing relatively greater cumulative impacts on the population.

Cost Implications of Regulatory Disparities

The apparent two-orders-of-magnitude disparity between the health effects of effluent limits for nuclear and fossil-fuel power plants has cost implications. For example, the present generation of nuclear power plants is provided with extensive effluent processing capabilities to meet the stringent requirements of Appendix I to 10 CFR 50. For the individual dose limits of Appendix I to be met, many gaseous-waste processing systems are required to provide holdup and filtration of radioactive effluents. When the costs of these additions are amortized over the life of the plant and operating and maintenance costs are included, the total annual cost for the additions required to meet Appendix I is approximately $0.5 million per plant. Since none of these additions to the radwaste system would be required if the effluent guidelines were 100-fold less restrictive (i.e., comparable to the fossil-fuel plant limits), it is clear that the disparity between the gaseous effluent limits for fossil-fuel and nuclear power plants has adverse economic implications for nuclear plants. Alternatively, if fossil-fuel plants were required to effect an additional 100-fold reduction in effluent releases to attain a health impact comparable to that of nuclear plants, it would in all probability render construction of such plants economically and technically unfeasible.

The preceding discussion is not intended to imply that the power industry is not spending large sums of money to meet the existing regulations for fossil-fuel plants. In fact, the costs of meeting the new Clean Air Act guidelines for a coal plant is well in excess of $0.5 million per year. The point is that the industry would be spending about $0.5 million per year less for each nuclear plant if the NRC's effluent guidelines for nuclear plants were comparable to those for fossil-fuel plants in terms of ill health.

CONCLUSION

The foregoing analyses indicate a marked lack of uniformity in the level of public health and safety protection on a comparative risk or cost–benefit basis. This raises the fundamental questions of whether such disparities as these should be allowed to continue and, if not, how they may be resolved.

The fact that these inconsistencies exist is the result of (1) having the public health and safety protection administered by a host of agencies, each independently focusing on specific industries or hazards, and (2) a philosophy whereby regulations are set as far below the hazardous level as the market can bear. Regulating a particular industry in this manner can have the effect of subsidizing an otherwise noncompetitive alternative at the cost of the health and well-being of the general public. These disparities could be resolved by a unified regulatory philosophy founded on uniform cost–benefit and risk standards. This approach would ensure that the cost savings of a safe technology could be passed on to the public or applied in a more cost-effective manner to reduce other hazards rather than spent on design augmentation that is not cost effective.

For example, it is conceivable that a broad set of regulatory limits could be established which (1) define an upper level of risk to which no individual should be exposed and, after meeting this individual risk criterion, (2) define cost–benefit criteria for additional reductions in the cumulative allowable risk to the exposed population. The former would protect the individual, and the latter would ensure that incremental investments in health and safety protection are made in a manner which provides optimum benefit to society.

It is recognized that this type of regulatory structure would require much more definitive data on the nature and levels of many hazards than presently exist and would involve complex analyses and collective agreement on many basic societal value judgments. Furthermore, additional work is required to develop much more comprehensive methodology for balancing costs and benefits, including consideration of nonquantifiable parameters. Therefore, although it is desirable, such a development is unlikely within the near future. However, the policies of individual regulatory agencies can be effectively viewed even now in this broad perspective.

The analysis indicates that NRC policy regarding changes to plant designs to achieve improvements in safety should be critically evaluated on a relative cost–benefit basis to ensure that additional investments in safety provide maximum benefit in terms of reduced risk. With regard to comparisons between the use of nuclear fuel or coal for the production of electricity, nuclear appears to cause lower adverse health impacts than does coal, although both compare favorably with other accepted risks. It would be highly ironic, therefore, if the pursuit of greater protection of the public health and safety through increased regulation of nuclear plants were to result in the choice of coal over nuclear as a result of higher nuclear plant costs.

This effect of such a regulatory policy would be a net decrease in public health and safety protection. Thus the NRC has an obligation to ensure that additional costs imposed in the name of public health and safety are justified on a cost–benefit basis and result in maximum net benefit to society.

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Control of Spending on Nuclear Safety

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Abstract: *Nuclear safety is reviewed in relation to safety in the community as a whole. A method is proposed which points to an optimum expenditure on nuclear safety measures as opposed to the present open-ended situation. At this optimum point the cost of saving extra lives in the nuclear field is equal to the cost of saving extra lives in other activities in the community. The method requires that the present level of safety be estimated, and this is done by relating the work of Rasmussen, Farmer and Beattie, and the recent German study to the actual record of accidents. The analysis indicates that present expenditures on reactor safety are far in excess of the optimum. An even more striking conclusion is reached when the possible effect of the wealth generated by the nuclear industry on the general safety of the community is considered. The application of the theme to the Pickering Nuclear Generating Station is developed.*

In the OECD (Organization for Economic Cooperation and Development) nuclear countries, with a population of nearly 650 million, the nuclear industry is a major potential source of the low-cost energy needed to improve or even maintain our way of life. It has already generated a product worth about *$60 billion (1979 U. S. dollars) since 1944. In that same area and period, roughly 35 million people have died prematurely; roughly 56 000 have died in disasters considered worthy of listing in a popular book of reference;[1] roughly 1 death among members of the public can be attributed to nuclear accidents. Despite this record, the pressure on the industry, ostensibly for reasons of public safety, has now become a serious impediment to development and a major source of added cost.

This strange state of affairs is mainly traceable to widespread emotional concern about nuclear risk coupled with a remarkable failure to develop the study of safety in general as a scientific or technological discipline. The controlling element which has been absent is any authoritative attempt to relate the standard of safety which has been achieved to a rational absolute standard.

This article, which addresses this problem, is modified and condensed from Refs. 2 and 3. Many numerical and other changes have been made in the light of subsequent comment, discussion, and additional information, but the underlying disparity which is revealed is so striking that these changes make no difference to the conclusions.

To facilitate the subsequent discussion, the following definitions of key terms will be used:

Premature death: Death from any cause before age 65; delayed deaths and deaths in future generations are always included.

Safety: The saving of life; the reduction of risk; the prevention or avoidance of premature or statistical death.

CSX: The cost of preventing or avoiding an extra premature death; the cost of saving an extra statistical life.

Ratchetting: The proliferation of reactor safety requirements and practices since 1968.

**$:* Constant-value dollars; 1979 U. S. dollars unless otherwise stated.

THE COST OF SAVING LIVES (CSX)

A number of authors have drawn attention, directly or indirectly, to the great disparity between the magnitude of various risks in our societies and the apparent concern, or lack of it, about such risks; Refs. 4 and 5 discuss this subject very fully. A few authors have analyzed what has been spent to save a life in various fields of human activity and have considered economic optimization of safety spending in various aspects; Ref. 6 is an early and thoughtful example and Ref. 7 is recent and authoritative. It appears, however, to have escaped general notice until recently (Refs. 2, 3, 8, and 9) that this latter line of enquiry leads directly to a principle which is valid in

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humanitarian as well as economic terms and which forms a basis for the management of spending on safety. This principle is as follows. The components of any safety activity should be carried out in order of diminishing cost effectiveness; the activity should be terminated when a further amount of money spent on it will not save as many lives as it would have done if spent in some other way.

It will be noticed that this principle is "mechanistic" in nature and does not involve value judgment, at least in its application in a particular society at a particular time.

The implications of applying this principle in a society as a whole are developed in Ref. 3. For this article, it is sufficient to say that, in our present OECD societies, it appears that large numbers of statistical lives could be saved at a cost (CSX) less than *$300 000 per life (Refs. 3, 7, and 10). It follows that spending on any nuclear safety measure should be considered for elimination if the CSX associated with that spending exceeds this figure.

Planning and control of safety activities must necessarily relate to the future and therefore to estimates of future risk; observations and study of past failures, accidents, and mortality are the means to that end. An important consequence of the approach now being considered is that the overall safety of a society is likely to be degraded if risks are either underestimated or overestimated; in the latter case, planning would be based on a risk assumed to be higher than it actually proves to be. This means that money (or other resources) would be diverted to safety activities in those fields considered to pose high risks rather than being spent on some other safety activity which would save more lives. An estimate of a risk cannot therefore be "conservative." Only the correct estimate leads to optimum safety.

Another consequence of this theme is that, if the highest degree of public safety is to be achieved for a given total cost, all sources of money or other resources available for the improvement of safety should be pooled. It is the breach of this principle which mostly accounts for the almost incredible differences that exist at present between the CSX in different safety activities. Safety activities in industries associated with large production of revenue, such as nuclear power and air transport, are greatly oversupported. Other safety activities in the society, such as medical research, are undersupported, regardless of their effectiveness, simply because they are not associated with a large cash flow which can be unobtrusively tapped.

Another important point is that the CSX associated with a particular element of safety spending depends not only on the nature of the equipment or technology involved but also on the magnitude of the risk against which it is intended to guard; if this risk is very small, few statistical lives can be saved, and the CSX must necessarily be high, no matter how technically effective the safety measure appears to be.

THE COST OF SAVING LIVES IN THE NUCLEAR FIELD

Estimating the CSX of a particular item or category of safety expenditure requires, in principle, the determination of the reduction of mortality which that expenditure would bring about. This is an unfamiliar and difficult task, but it is essential if rational control is to be exercised. The steps which follow enable some bounds to be set on the CSX associated with the proliferation of overall nuclear safety requirements and costs from about 1968 to the present.

The first large reactors started up in the United States in 1944, and in the OECD nuclear countries a total of about 2000 reactor-years have accumulated with large reactors [say, greater than 10 MW(t)]. (See Table 1.) During that time, approximately one statisti-

Table 1 The Experience of Nuclear Reactor Operation—Mid-1979 (Includes All OECD Nuclear Countries)

Reactors	Reactor-years
"Early" reactors—in service 1968 or earlier, or not subject to a public regulatory process	
Plutonium producers (guess)	350
Various experimental and test reactors >10 MW(t) (guess)	200
British electricity producers*	440
French electricity producers*	78
German electricity producers*	40
Japanese electricity producers*	10
Canadian electricity producers*	26
U. S. electricity producers	141
	1285
Subtotal	~1300
"Late" reactors	
Outside United States (estimated from Ref.11)	351
United States (estimated from Ref. 1, p. 92)	324
	675
Subtotal	~700
Total	2000

*Estimated from Ref. 11.

cal public fatality has, in effect, occurred as a result of a reactor accident (see Table 2). This can be asserted with confidence even though some of the experience was with military reactors; it would have been impossible to keep any serious accident secret for more than a short time. The accidents at Windscale and SL-1 bear this out directly; the accident at NRX was also promptly publicized despite a considerable element of military secrecy about its operation at that time.

For the purpose of this study, the experience is divided into approximately 1300 reactor-years with "early" reactors, which entered service in 1968 or earlier or which are not subject to a public regulatory agency, and 700 reactor-years with "late" reactors, which started up in 1969 or later (Table 1). Both groups are varied in type and size, the early ones much more than the late ones. The early group includes some of quite primitive type. Many are quite small, but for this very broad brush study, it seems reasonable to assume that they all posed a similar risk of releasing fission products as a result of reactor accidents, the various factors tending to counter each other. The group also includes well-developed examples such as Dresden 1, San Onofre 1, Douglas Point, and the Magnox reactors. The new group had an average date of entering service of mid-1974.

In considering the risk to the public from nuclear accidents, it is necessary to consider a "spectrum" of possible accidents resulting from the combination by chance of a great variety of possible failures and possible adverse circumstances. The more severe accidents are more actively guarded against in the tech-

Table 2 Reactor Accidents in OECD Countries, 1942–1979*†

Date	Reactor	Group	Country	Public mortality‡	News medium sensation §	Remarks
1952	NRX	Early	Canada	0	Moderate	Mainly one fuel channel, but reactor core damaged
1957	Windscale	Early	Great Britain	0.1	Great	Military reactor; core badly damaged
1958	NRU	Early	Canada	0	Small	One fuel channel; reactor core not damaged
1961	SL-1	Early	United States	0	Moderate	Military reactor; three staff members killed
1966	Enrico Fermi	Early	United States	0	Moderate	Two fuel channels; core not damaged
1969	Lucens	Early	Switzerland	0	Small	Core damaged
1975	Brown's Ferry	Late	United States	0	Moderate	Two reactors involved; both remained intact and undamaged
1979	Three Mile Island	Late	United States	0.7	Very great	Reactor core damaged; 3300 man-rems population exposure
				0.8		

*There have been a few other cases of trouble with single fuel channels and numerous cases of local fuel sheath failure; also a number of leaks and spills, mostly inside containment buildings. The EBR-1 and Yugoslav accidents are omitted as being "laboratory-type" accidents. Their inclusion would not alter the public mortality total.

†This table shows those reactor accidents of importance in the OECD countries from 1942 onward. From the safety viewpoint, they constitute a virtually perfect record. The degree of "news medium sensation," entirely a subjective judgment on the author's part, is important with respect to safety because of the extent to which it distorts the judgment of decision makers in ways which are shown in this paper to be adverse to real safety. By contrast, Ref. 1 lists 280 disasters in the OECD countries from 1943 onward. In 33 of these, the death toll was 300 or more, the overall total being about 56 000.

As shown earlier in this section, the record summarized in this table, giving a gross figure of about 1 public fatality in 2000 reactor-years or 5×10^{-4} fatality per reactor-year, is in fact consistent with an estimate of 0.08 fatality per reactor-year when considered in relation to a spectrum of possible accidents in a population density of 150 per square mile. It is interesting to compare both of these figures with the target of 0.17 fatality per reactor-year suggested by the author in 1957 (Ref. 12) for a very safe industry.

‡Typically delayed 10 to 100 years. In the first three cases the estimates are very crude. Greater precision seems pointless; the first four cases did not have "containment" and were not typical in several other respects.

§Author's impression.

nology than the less severe accidents and usually require more adverse factors to combine to produce them; they therefore tend to be less probable (i.e., to occur less frequently in a hypothetically infinite period of operation) than the less severe accidents.

This spectrum of possible accidents has been studied with varying degrees of generality and scale of effort by Rasmussen,[13] Farmer and Beattie,[14] and in the recent German report (Birkhofer).[15] These studies are logically complete and coherent, and the first two have been exposed to scrutiny and discussion for a number of years. All these studies contain some element of normalization to the observed record of failures and abnormal conditions and to that extent can be expected to be realistic and to agree broadly with each other.

The risk to the public is estimated as follows. The published curves of probability vs. severity for the three studies are adjusted along the severity axis to correct roughly for the different effective population densities. This is done in Table 3 and Fig. 1. The total public mortality cannot necessarily be deduced from these curves. For the Rasmussen study,[13] it can be calculated from Tables 5-7 and 5-8 to be approximately 0.02 fatality per reactor-year (early and delayed cancer and genetic damage). It has not been possible to deduce a corresponding figure from the Birkhofer report,[15] but it can be calculated from Fig. 10 of the report that, after adjustment for the North American population pattern, the corresponding figure is about a factor of 8 higher. A total of 0.08 fatality per reactor-year is used as the basis for Table 4. This tabulation specifies severity categories, and the calculation of mortality as shown is therefore rigorous.

Table 4 and the composite curve shown in Fig. 1 are suggested as a working hypothesis for the rational management of all aspects of safety in the nuclear industry. This hypothesis is presented in much greater detail than is warranted by the basic information, but it can easily be simplified if necessary. The probable errors are no doubt large, but no reason, including the critique of the Rasmussen report by Lewis et al.,[16] can be found for raising or lowering the curve. This hypothesis fits the best information to date and can be compared with actual experience in the future.

As noted in the following section, the total cost of ratchetting from 1968 to 1978 is taken as *$30 million per reactor-year in the United States and *$8 million per reactor-year in Canada. Since the late reactors came into service at various times over this period, a composite North American figure of *$9 million per reactor-year is taken.

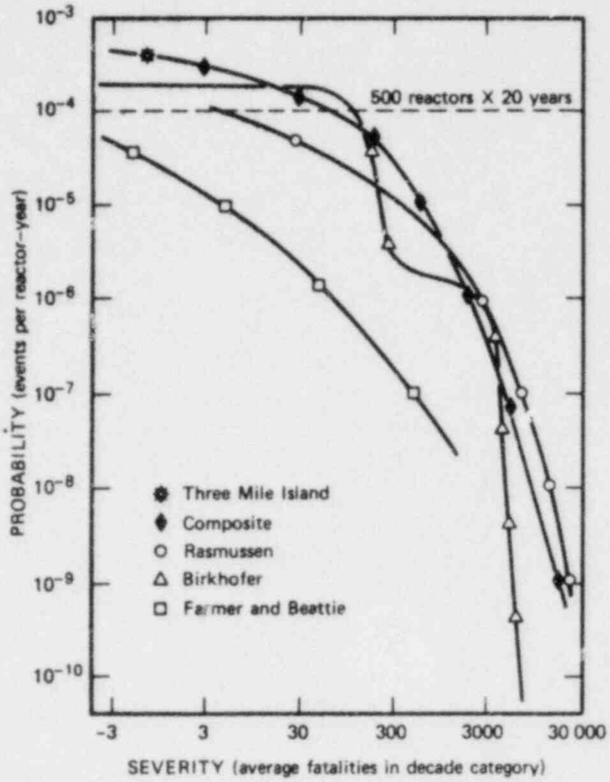

Fig. 1 **Adjusted accident spectra.**

The ratchetting may, at one extreme, have resulted in all the late reactors being perfectly safe, the whole risk then arising from the early reactors. In that case, since the exposures are 1300 and 700 reactor-years, respectively, for the early and late types, the mortality for the early reactors would be

$$0.08 \times \frac{2000}{1300} = 0.124 \text{ per reactor-year}$$

Thus the added cost of *$9 million per reactor-year would have saved 0.124 life per reactor-year, giving a CSX of

$$\frac{9 \times 10^6}{0.124} = \text{*\$73 million}$$

More plausibly, it is suggested that the ratchetting might have reduced the risk by a factor of 2 from the early to the late designs. In that case, the figures are: 0.096 (early) and 0.048 (late). The saving of life is 0.048 per reactor-year, giving a CSX of

$$\frac{\text{*\$9 million}}{0.048} = \text{*\$188 million}$$

Table 3 Accident Spectra

Study	Population density,* people per square mile	Severity, SF† per event	Adjusted severity,‡ SF† per event	Probability, events per year	Mortality contribution,§ SF† per reactor-year	Total mortality from study, SF† per reactor-year
Rasmussen[13] (United States)	300	90		5×10^{-5}	0.004 5	
		8 850		1×10^{-6}	0.008 9	
		23 020		1×10^{-7}	0.002 2	
		43 200		1×10^{-8}	0.000 4	
		73 800		1×10^{-9}	0.000 1	
Farmer and Beattie[14] (Great Britain)	300	3	1.5	4×10^{-5}	0.000 06	
		30	15	1×10^{-5}	0.000 15	
		300	150	1.5×10^{-6}	0.000 23	
		3 000	1 500	1×10^{-7}	0.000 15	
					0.000 59	
Birkhofer[15] (Federal Republic of Germany)	650	2 700	623	4×10^{-5}	0.024 9	~0.16 (after adjustment for population density)‡
		3 900	900	4×10^{-6}	0.003 6	
		54 000	12 461	4×10^{-7}	0.005 0	
		65 000	15 000	4×10^{-8}	0.000 6	
		72 000	16 615	4×10^{-9}	0.000 1	
		83 000	19 154	4×10^{-10}		
		94 000	21 692	4×10^{-11}		

*Roughly estimated for area mainly at risk.

†SF = statistical fatalities; considered to be incurred at the time of the accident but mostly (cancer and genetic damage) delayed 10 to 150 years.

‡Adjusted to a population density of 300 per square mile.

§Calculated to show the relative importance of accidents of various severities; not vigorous for Rasmussen and Birkhofer because severity interval not defined.

Table 4 Global Accident Spectrum—Preliminary Working Hypothesis (Population Density: 150 per Square Mile)

Accident category			
Severity range, SF* per event	Mean severity, SF* per event	Probability, events per year	Mortality contribution,† SF* per reactor-year
0.3–3	1	5×10^{-4}	0.0005
3–30	10	3×10^{-4}	0.0030
30–300	100	1.5×10^{-4}	0.0150
300–1 000	600	5×10^{-5}	0.0300
1 000–3 000	2 000	1×10^{-5}	0.0200
3 000–10 000	6 000	1.3×10^{-6}	0.0078
10 000–30 000	20 000	7×10^{-8}	0.0014
30 000–100 000	60 000	1×10^{-9}	0.0000
			0.0777

*SF = statistical fatalities.

†The use of defined categories makes these calculations, and the summation, mathematically correct. The numbers are chosen so that the mortality agrees broadly in magnitude and distribution with the Rasmussen and Birkhofer[15] studies.

THE COST OF RATCHETTING

In the case of the United States, which represents a major part of the OECD nuclear industry in all senses, Bennett and Kettler[17] deduce a total increase in cost resulting from statutory and regulatory changes between 1969 and 1978 of $591 (1978) per kilowatt. This becomes roughly *$638 per kilowatt, or *$638 million for a nominal 100-MW(e) reactor. At a nominal 10% per year service of capital, this is roughly *$64 million per reactor-year.

Sagan[18] postulates that the total cost to the nation of compliance with government regulatory agencies tends to be 40 times the budget of the agency. The Nuclear Regulatory Commission (NRC) budget was $206 million in 1976. Taking the 1979 budget to be 8% per year more, the total cost of compliance becomes *$10.4 billion per year. Dividing this over, say, 150 reactors operating or under construction gives an average of $69.3 million per reactor-year.

In the case of Canada, the Pickering Nuclear Generating Station provides an example of particular relevance to this article. The four A units came into production about 1972 and cost $345 per kilowatt (electrical). At an assumed general inflation rate of 8% per year, this becomes *$592 per kilowatt (electrical). The four B units are scheduled to come into production about 1982 and are estimated to cost $1138 per kilowatt (electrical). With the same inflation rate, this becomes *$903 per kilowatt (electrical). The rate of increase is thus *$311 per kilowatt (electrical) per year. Taking the annual cost to be 10% of the capital cost and a reactor size of 550 MW(e), this gives *$15.5 million per reactor-year for the 10-year period from Pickering A to Pickering B.

The reasons why nuclear power plants have increased in cost in the last decade at a rate far greater than can be accounted for by general inflation—despite the gain in experience in every phase of the activity—are no doubt many and varied. However, in every country there has been a rapid escalation of every aspect of regulatory intervention, and the associated procedures have become more detailed, more inflexible, and more time-consuming, even in cases where no change of principle was thought to be involved. These changes have worked in diametric opposition to almost all the factors which lead to efficiency and low cost in all phases of the industry.

Even if the estimates for the United States are too high by a factor of 2 and if only 50% of the Pickering increase is attributable to ratchetting, the figures still come to *$30 million per reactor-year in the United States and *$8 million per reactor-year in Canada.

THE RELATION BETWEEN SAFETY AND MATERIAL STANDARD OF LIVING

The fact that almost every category of mortality tends to diminish as the average material standard of living increases among the different countries of the world is well known (Ref. 19 is a recent illustration). The abundant availability of electrical energy at a low price is an obvious component and contributor to a high material standard of living. The immense nuclear fission resources (^{235}U, ^{238}U, and thorium) are likely to constitute a considerable fraction of the world's usable low-cost sources of energy. The way in which the safety of the community is affected by the nuclear industry through its effect on standard of living is therefore likely to be important.

Table 5 shows how a number of indicators of safety and factors which might reasonably be expected to affect safety vary with average income and electricity production in three selected population groups. It is based mostly on Refs. 1, 20, and 21.

Group P is a composite of four very poor countries (Afghanistan, Ethiopia, N. Yemen, and S. Yemen) for which most of the desired information could be obtained. Great Britain is chosen because the information is available to show subdivisions into six subgroups (Refs. 20 and 21). Group R is a composite of three countries (Canada, Sweden, and Switzerland), which are among the richest in the world. The use of composite groups reduces the influence of local geographical factors and brings the total populations into a reasonably narrow range. Most of the information applies to 1970 through 1972 or 1973, but population figures apply to 1976; these were the latest figures readily available at the time of this writing.

Table 5 is discussed in some detail in Ref. 2 and will not be further justified here. However, the shift of large populations to the right side of Table 5 represents the avoidance of premature deaths in very large numbers. The cost of saving an extra life (CSX) by deliberate action to produce this "right shift" in a community can therefore be considered. Taking all the OECD countries as one unit, for example, they have broadly progressed from the state of group P to their present state close to that of group R over the last 300 years or so. The unit was not owed any money overall at the beginning of this period and owes little or nothing at the end. Thus the entire cost of the shift must have been earned within the unit. The net cost,

Table 5 Variation of Indicators of Safety and Factors Affecting Safety Vs. Average Income and Electricity Production in Three Population Groups*

		Great Britain (social group)							
	P	5	4	3N	Average	3M	2	1	R
Population in 1976, millions	57.4				55.9				37.6
Income per head in 1973, 1973 U. S. dollars per year	91				3 684				6 549
Cost of living in principal city, % of New York	90				83				103
Corrected income per head (item 2 ÷ item 3), dollars per year	101				4 438				6 358
Subgroup income in 1970–1972, pounds per week		22.1	22.5	24.1	24.7	27.1	34.0	44.1	
Electrical energy per head, kWh/yr	19				4 955				10 972
Hospital beds per 100 000 of population	33				943				971
Physicians per 100 000 of population	3.7				132				166
Teachers per 1000 pupils	3.3				42				48
Expectation of life at birth in 1973, years	39.9				70.8				73.2
Expectation of life at age 15 plus 15 (1970–1972), years†		68.5	70.1	71.0	70.6	70.7	72.0	72.2	
Adult male premature death rate for all causes, per 100 000 per year‡		863	692	590	597	630	469	474	
Adult male premature death rate for circulatory disease, per 100 000 per year‡		338	310	278		295	241	243	
Adult male premature death rate for cancer, per 100 000 per year‡		227	190	147		180	123	126	
Adult male premature death rate for respiratory disease, per 100 000 per year‡ §		123	75	47		62	27	28	
Childhood death rate, per 100 000 per year		73.3	53.4	43.0	45.9	43.8	37.3	36.9	(1973)
Infant mortality, per 1000 live births¶	128	31.0	19.5	14.5	17.5	17.0	13.5	12.0	13.4

*Notes: M = skilled manual workers; N = skilled nonmanual workers; P = a composite of four very poor countries (Afghanistan, Ethiopia, N. Yemen, and S. Yemen); R = a composite of three rich countries (Canada, Sweden, and Switzerland). Because of the particular forms of presentation in Ref. 21, it was not possible to derive age-corrected death rates for women. The gradient appears to be in the same direction as men but less in magnitude.

†Table 8A, Ref. 21.

‡Calculated from Table 4.7 of Ref. 21. Age corrected by an approximate method.

§Table 7.8, Ref. 21. Average of rates for six age and sex groups.

¶Sec. 7.2.1, Ref. 21. Average of male and female. Also Ref. 1.

looking at the unit from the outside, was zero. The situation is complicated by the fact that cause and effect are separated by time delays and by complex political and economic factors; nevertheless, the saving of enormous numbers of lives at a cost which is apparently around zero implies a CSX of zero. This indicates the possibility that the greatest effect an industry might have on the safety of a society might be through advancing the general material standard of living.

INDIVIDUAL RISK

Even if the effects of an activity on the overall safety of the community are correctly managed in other respects, it would obviously be wrong if the risks were so concentrated on an individual or a small group as to greatly increase their individual risk. This factor was considered in the basic Canadian regulations, but the limit was then set so low that it amounts to a requirement that no one should be appreciably injured even in a major disaster. This arbitrary factor often becomes the limiting factor in siting and reactor design and would threaten to negate the approach developed in this article.

It does not appear to be possible to find a mechanistic basis for a limit, but consideration of the nature of individual risk helps to put the matter in perspective. The "background" risk of premature death is about 2.6×10^{-3} per year (Canada, 1973, Ref. 20).

Table 6 Premature Mortality Among Groups of Various Sizes During Their Time Living or Working near a Reactor

Size of group	Average premature deaths in 10 years	Standard deviation
10	0.26	0.5
30	0.78	0.9
100	2.6	1.6
300	7.8	2.8
1000	26	5.1
3000	78	8.8

The mortality which this represents is by its nature random in time and in respect to whom it affects and is, of course, quantized into integers whatever the group size. Assuming that people living or working near a reactor do so for an average of 10 years of their lifetime per person, Table 6 shows the background premature mortality among groups of various sizes during their time near the reactor. The actual numbers would form Poisson distributions, tending toward Gaussian distributions for the higher numbers. The standard deviations of these distributions, equal to the square roots of their averages, are shown.

It is now proposed that the added inferred risk to any group resulting from their proximity to the reactor should be permitted to equal one standard deviation of the average background mortality in that group. The added individual risk would then be insignificant statistically for any group size.

THE SAFETY OF A CANADIAN "NUCLEAR COMMUNITY"

As a contribution to perspective and to illustrate the practical implication of the theme of this article, it is convenient to study the real safety of a community whose electricity is supplied entirely from a nuclear station located in the community. In effect, such a community already exists around the Pickering Nuclear Generating Station in Ontario, Canada. This station actually consists of four units (A) already in operation which may be roughly considered as "early" units and four units (B) under construction which are "late" units. The complete station will represent about 20% of Ontario's electrical generation capacity, and the community to be considered is therefore chosen to be 20% of Ontario's population. This is enclosed by a circle of 24-mile radius around the station.

The risk pattern is shown in Table 7. From the calculations in the section on The Cost of Saving Lives in the Nuclear Field, it is assumed that the basic accident mortality is 0.096 and 0.048 per reactor-year for the early and late units, respectively. The mortalities shown from nuclear accidents assume that all the deaths occur within the 24-mile radius. In fact, the mortality would be spread over a large area. This treatment allows roughly for the risks from other more distant reactors if the whole population were made up of similar communities. The mortality from routine operation is roughly derived from estimates of the actual and expected total man-rem exposure per year. All the other mortality figures are derived from Ref. 20, being 20% of the 1973 figures for Ontario.

It will be seen that if the four B (late) units were replaced by four more units built to A (early) standards, the public accident mortality would increase from 0.58 per year to 0.77 per year, an increase of 0.19 per year. At the CSX of *$300 000 in this community, it would cost *$57 000 per year to augment some other lifesaving activity to exactly nullify this increase. However, at the estimated Canadian ratchetting cost of *$8 million per reactor-year

Table 7 The Safety of a Canadian Nuclear Community: Approximate Average Annual Mortality in a Population of 1 600 000 People Within a 24-Mile Radius of the Pickering Nuclear Generating Station

Cause	Premature mortality (age less than 65)	Other mortality (age 65 or more)
Heart disease, strokes, arterial disease, etc.	1401	4747
Cancer (includes 0.04 total from radioactive releases)	1015	1397
Respiratory disease	207	573
Congenital anomalies (includes 0.04 total from radioactive releases)	99	2
Other disease and illness	784	683
Road vehicle accidents	266	32
Pedestrians killed	53	15
Suicide	175	22
Falls	39	91
Fire	32	11
Accidental poisoning	40	3
Collision with train	13	1
Other accidents	259	9
	4383	7586
Standard deviation of annual figures	66	87

(see the section on The Cost of Ratchetting), the cost saving would be *$32 million per year.

The Bruce site in Ontario, 140 miles northwest of Toronto, is much further from the load center and has a much lower population density near the site. This means that the mortality at the Bruce site would be less than that shown for Pickering. However, the extra transmission costs which would have been involved if the 4000 MW of generating capacity needed for the Pickering community had been located at Bruce would have been about *$30 million per year. Even if the Pickering mortality with eight A units were entirely eliminated by relocation at Bruce, only 0.77 + 0.04 + 0.04 = 0.85 lives per year would be saved. At the CSX of *$300 000, it would cost only *$255 000 per year to save this number of lives in some other way.

IMPLEMENTATION OF THE CSX CONCEPT

The importance of knowing the cost of saving lives (CSX) in all activities in the society which are meant to save lives can now be appreciated. However, the concept is sufficiently novel that much work needs to be done if the benefits of better safety planning are to be realized. It will be clear from what has been published recently (Refs. 5, 7, 8, and 10, for example) that many activities where large numbers of lives can potentially be saved at low CSX are associated with health care and medical research, whereas other activities where, conversely, few lives are being saved at high CSX are related to excessive regulation.

It appears to be desirable and necessary that some agency should be set up to monitor and coordinate safety activities, thus giving an industry such as the nuclear industry the policy guidance, mainly in the form of a CSX level, to which it should work.

DISCUSSION AND CONCLUSION

As shown in the section on The Cost of Saving Lives in the Nuclear Field, the evidence indicates that the ratchetting (proliferation of safety costs) from 1968 onward may in effect have saved a few statistical lives at a global cost per life (CSX) of about *$188 million. In contrast, there are indications that many statistical lives were and are available to be saved at a cost of less than *$300 000 each.

It can thus be seen that, in the short term, the thoughtful transfer of a small fraction of the dollar saving which would have resulted if the ratchetting had not taken place could have saved more lives. It appears that the ratchetting was wrong, both on humanitarian and on economic grounds, when viewed in the true perspective of the whole society.

In the longer term, there is the further possibility that the production of wealth resulting from the nuclear industry may be a major factor in increasing the safety of our societies; thus the removal of obstacles to the expansion of the industry may emerge as an important safety measure.

Most of the raw and derived data used in this article can and should be improved; it will nevertheless be noted that the conclusions are more than usually insensitive to the accuracy of the data.

If the theme of this article survives discussion and criticism, it will be apparent that the present concepts and practices relating to nuclear safety should receive fundamental reassessment.

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D. NUCLEAR FUEL CYCLE RISKS VERSUS OTHER RISKS

Significance of Contributions of Atomic Energy to Public Health Hazards

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Those of us engaged in the development and use of atomic energy have a duty to keep the public informed about the advantages to be gained, the penalties to be paid, and the risks to be taken. This responsibility has been recognized from the very beginning of the development of atomic energy. It is perhaps fair to say that more effort has been expended on informing the public about atomic energy than on any other new field. The task is a particularly difficult one, partly because of the way atomic energy was first introduced, but mainly because of the radical new concepts involved which are difficult to comprehend and accept by the layman and the technical man as well. As a result, there has been criticism of the atomic energy industry for not making information available and, from some sources, for minimizing the hazardous aspects of the atomic energy applications. Such criticism is unfair and wrong, as could be easily demonstrated by piling up the immense amount of material that has been written and published in this attempt.

At present there appears to be a rising tide of criticism of the use of atomic energy for the generation of power, particularly when it would be close to concentrations of population. There is no evidence that this protest represents a majority opinion. In fact, the evidence seems to be that it is a very small minority, but certainly a noisy one. The motivation of the protesters is mixed and various aspects are emphasized, depending on the interests affected and the power plant location. In all these protests, however, there is, as part of the reason, the charge that the nuclear power plant poses too great a safety threat. It is with this aspect of the protests that I would like to deal briefly.

As one of the participants in the effort to make sure that the application of atomic energy to peaceful purposes, especially the building of reactors and their use for the production of electrical energy, will not threaten the health and safety of the employees and the public, I could assume an air of injured virtue, since there has been a very studied and elaborate effort to make sure that there was adequate, yes, even more than adequate, protection. I can say with conviction that there has been much more effort spent on safety in the atomic energy field than on safety in any other field. This has been so from the very beginning of the exploration of atomic energy. I am afraid, however, that these persons raising this safety question would not be impressed by any such attitude. I also become indignant at the half-truths, distortions, and actual falsehoods which frequently creep into the statements and testimony of these protesters. In response to this the only practical course I see is to continue with a studied, deliberate, and vigorous effort to acquaint the public with the truth and to welcome investigation and inquiry. Another part of this problem arises from the difficulty that people have in really understanding atomic energy concepts, and therefore the dangers and risks, in their proper perspective. This is the issue which I am attempting to develop, suggesting, I hope, ways in which the public's understanding can be improved so that the advantages and risks of atomic energy can be understood in their proper context within the complex pattern of life as it is lived today.

Health Effects of Radiation

Let me state at the beginning of this discussion that too much radiation is harmful. As will be brought out later, it is not the only source of harm. The question is how harmful. Because of the very large amount of effort spent on understanding the effects of radiation, partly as basic scientific research and partly as a means of avoiding damage to people, we know more about the effects of radiation than any other substance. We know that certain radiation damage is repairable, a certain amount is not and shows up as delayed effects, and there is a genetic effect. The Federal Radiation

Council (FRC) accepts the philosophy that there is a linear relation between dose and damage, even down to very low doses.[21] Accordingly, the benefit must be balanced against the biological risk, and doses should be kept as low as practical.

As the result of careful study and discussion on the part of the well-qualified scientists on the International Commission on Radiation Protection (ICRP) and the National Committee on Radiation Protection (NCRP), radiation protection guides have been set[22,23] and are implemented by the regulations of the Atomic Energy Commission.[24] The limits set by these regulations imply that below these limits there is a minimal or negligible amount of harm. It is worth examining some of the specific numbers relating to dose and effect. Whole-body gamma exposures will be used as a convenient comparison. It is estimated that the average life span is shortened by seven to four days for each rem of whole-body radiation exposure.[25] On this basis, natural background accounts for life shortening of 49 to 28 days. If a large number of persons were exposed continuously to whole-body radiation at the maximum allowable doses[24] for the general population, the average calculated life shortening for a 70-year lifetime would be 245 days (0.7 year) to 140 days (0.4 year). The best estimates that can be made of radiation levels in the vicinity of actually operating large atomic power plants result in average doses of 0.0005 rem[26] per year or less. Again, performing the arithmetic, this calculates to an average life shortening in 70 years of less than 0.25 day. Persons farther away receive doses that rapidly diminish with distance. These are *estimated* doses, since there is no practical way of measuring doses as low as this. It should be emphasized that life expectancy itself has meaning in terms of a population. The numbers cannot be applied as predicting a change of life expectancy for individuals or even small groups of people.

Health Effects of Other Factors

If one believes that figures such as I have given above have any real significance even for large numbers of people, then it is worthwhile to examine the other factors that influence the health and longevity of populations. Table I-2 gives these values together with those for radiation exposures mentioned above. Note that all other factors listed give greater negative effects than those for radiation workers, except being a man instead of a woman. No cases exist where either radiation workers or persons in the environment are exposed to anything like maximum permissible doses continuously. Actual exposures are small enough to give calculated life shortening of a small fraction of a day. Obviously, any such quantity as one thousandth of a year is the result of an exercise in arithmetic with no real meaning. The effects of other factors are only crudely known. Comparisons are valid only in the range of more than several years.

It would be interesting to compare the effects of air pollution, but unfortunately the data are not expressed in terms of life shortening. However, records do show that in London, in 1962, 340 people died as a result of smog which persisted only a few days and, in 1952, a "pea

Table I-2 LOSS OF AVERAGE LIFE-SPAN (MINUS) AND GAIN OF AVERAGE[27] LIFE-SPAN (PLUS) AS A RESULT OF VARIOUS FACTORS

	Loss or gain of average life-span, years
Nonradiation factors	
Country vs. city dwelling	+5.0
Married status vs. single, widowed, or divorced persons	+5.0
Smoking	
1 pack of cigarettes per day	−7.0
2 packs of cigarettes per day	−10.0
Overweight by 25%	−3.6
Female vs. male sex	+3.0
Both father and mother lived to age 80	+3.7
Rheumatic heart disease	
Heart murmur	−11.0
Heart murmur plus strep infection	−13.0
Natural background radiation	
Calculated life shortening due to natural background radiation, 7 rem in 70 years	−0.1
Man-made radiation	
Radiation worker, 30 years' continuous exposure to maximum permissible dose of 5 rem/year	−2.9
Individual, general population, 70 years' continuous exposure to maximum permissible dose of 0.5 rem/year	−0.7
Person in immediate vicinity of nuclear power station, estimate of actual condition	−0.0007

soup" fog for five days resulted in 4000 more than usual deaths during the week starting the first day of the fog.[28] In the United States, studies of urban areas with populations from 10,000 to 3,000,000 show excellent correlation between mortality rates and the amount of benzene-soluble organics in suspended particles. The variation of the pollution and the mortality rate per 100,000 due to respiratory-system cancers is about a factor of 2, being greater for the larger populations.[28] It is likewise disturbing to find that from 1950 to 1959 the death rate per 100,000 for males due to pulmonary emphysema increased from 1.5 to 8.0, or over five times.[28] On the basis of this evidence, it would appear more useful to the world to find ways to reduce the damage from air pollution, disease, and other harmful factors than to attempt to cut radiation doses below levels now being experienced from atomic energy plants.

Mutagenic Agents

As a result of this extensive research in the field, radiation has been found to be a mutating agent. It is generally agreed, however, that of the naturally occurring mutations, a relatively small fraction, perhaps 5 to 10%, is due to radiation. The other causative factors are not defined, but higher temperatures and some chemical compounds are known to be mutagenic. I have been unable to find any data on the mutagenic effects of air pollutants, but it seems quite probable that some of these may have significant mutagenic effects. (A list of some known chemical mutagens was included in the first article of this series.[29])

Accident Statistics

One of the big worries about nuclear plants, including nuclear power plants, is the possibility of accident. This worry has been given attention from the beginning and has been the major effort on the part of the Advisory Committee on Reactor Safeguards. Since the very word "accident" prevents forecast and there is insufficient statistical data, the probability and consequences of an accident are solely a matter of judgment. The system of review that has been set up for nuclear reactors is unusually thorough and painstaking. It is far above any other review system for industrial plants. For example, not only is it demanded that a pressure vessel and piping system be supplied which are in accord with the accepted standards, but there must be emergency shutdown and emergency cooling systems of high reliability. Finally (at least in most cases), there must be another containment of high integrity surrounding at least the primary system.

Although not sufficient for statistical purposes, there is a considerable accumulated history of nuclear reactor operation with an outstanding safety record. Hanford reactors have been operating since 1944; naval reactors started in 1954, and there are now more than 35 nuclear-powered ships; Shippingport has operated for over six years; Dresden for over four years; and Yankee for over three years. There are many other smaller reactors. In no case has a reactor accident in the United States released significant amounts of radiation to the public. There is no evidence of any damage to the public from any nuclear accident in the United States. In all AEC nuclear installations, 226 fatal injuries to employees from all causes occurred from 1943 to 1961. Of these, only six were due to radiation.[29] It is useful to compare the accidental death rate in AEC installations with all industries. Over a period of 17 years, 1943 to 1959, inclusive, the accidental death rate in all U. S. industries was 26.9 per 100,000 workers, whereas in AEC installations it was one-half of this, or 13.4, from all causes, and 0.19 from radiation.[30] Table I-3 compares the death rates in the United States from all causes.[31] From this table, if one uses death rate as a yardstick, the emphasis on the cure of disease is of far more importance than reducing the accident rate. It is interesting to note that the respiratory-disease death rate totals 44.6, very comparable to the rate for accidents from all causes. The rate for all industry of 26.9 is one that has been reached because of a consistent safety effort. The value of 13.4 for the atomic energy industry shows the greater emphasis that has been placed on safety in this industry. The rate of fatal injuries due to radiation is vanishingly small, representing only three cases in 17 years. Including the three unfortunate deaths in 1961 raises the rate

Table I-3 DEATH RATES IN THE UNITED STATES—1961 PER 100,000

All causes	930.3
Diseases of the cardiovascular system	507.6
Malignant neoplasms	147.5
Influenza and pneumonia (except pneumonia of the newborn)	29.8
Asthma	2.7
Bronchitis	2.4
Other bronchopulmonic disease	9.7
Accidents	
All categories	50.7
Motor vehicle	20.5
All other	30.2
In all industries*	26.9
Accidents in AEC installations*	
All causes	13.4
From radiation	0.19

*Average 1943 to 1959, inclusive.

to only about 0.4. In making comparisons, readers should note that the accident data for industries relates to workers and not the general public. So far as radiation is concerned, there are no fatalities other than workers.

A study was made in 1957 of the possible consequences of a hypothetical nuclear accident.[32] In this report three cases were considered. Case I assumed all the engineered safeguards failed except the final containment. In this case there were no lethal exposures. Cases II and III assumed failure of all the engineered safeguards including the containment and a variety of conditions relating to the dispersal of the fission products. The calculated lethal exposures ranged from 2 to a maximum of 3400 people. Since this report was written, there has been considerable progress in the design of nuclear power plants and understanding of dispersion conditions. The designs being proposed today are superior to those considered in this report, and it is highly desirable that a study be made to update this report in light of present conditions and knowledge.

It is worthwhile to look at the record of disasters that have occurred over the years to give perspective. In 1961, 24,700 people were killed in automobiles and taxis.[33] This is really a disaster but in a different context than is being considered here. A study of the more serious marine disasters, worldwide, since 1860, excepting military action, shows the single worst accident caused a loss of 1517 lives (sinking of the *Titanic*, 1912).[33] Railroad wrecks in the United States have resulted in as many as 101 deaths in the worst case.[33] In the United States there have been fires that killed 119 (Winecoff Hotel, 1946), 168 (Ringling Circus, 1944), and 491 (Cocoanut Grove, 1942);[33] there have been explosions[33] that killed 10 (chemical plant, 1960), 13 (dynamite truck, 1959), 22 (rail tank cars, 1959), 17 (gas pipeline, 1957), 561 (ship and pier, Texas City, 1947), and 8 mine disasters, mostly coal mines, over the past 16 years resulting in a total of 352 deaths, with 119 in one disaster alone.[33] These unpleasant numbers are given to show that in the world in which we live we do experience disasters. We have not yet learned how to eliminate them. However, I can state that in all cases of the disasters quoted above there has not been anything approaching the rigorous specifications and searching review which is given nuclear reactor plants.

This discussion would be more complete if it included data on injuries from various kinds of accidents, including radiation, which did not result in deaths. This more complicated and lengthy subject is not covered here. It is worthy of a considerable amount of discussion so that the public may have a clear understanding of the character of radiation injury as compared to the other kinds with which it is more familiar. Briefly, there have been several cases where persons have been exposed to doses of radiation of 100 to about 400 rem and have subsequently borne normal children and continued to work and live a normal life. This can be compared to the situation of persons who recover after an accident involving fire, explosion, a fall, or poisoning.

Conclusions

The effects of radiation are well understood, better than the effects of many materials. There is a considerable and increasing history of successful and phenomenally safe operation of nuclear installations. The amounts of radiation to which workers and the public may be exposed will result in effects which can be expected to be much less than those from ordinary hazards of life, including the rapidly growing air pollution. There have been no disasters in the nuclear industry, and in my opinion disasters are most unlikely—I can almost say impossible.

Those of us in the atomic industry are biased. For my part I believe that atomic energy has tremendous possibilities for the benefit of the world in the future. In the case of nuclear power plants, we have the possibility of the generation of electric power *without* air pollution at locations and in such sizes as the public requires. We have tried and are trying to build these plants so that they are economic and safe, safer than any other kind of plant. The record shows that we have succeeded so far. Let us increase our efforts to help the public understand the advantages of nuclear power. Let us try to help channel protest effort toward the alleviation of the dangers that are more serious than radiation. The facts are available. The people can read and study for themselves. They should look to the benefits that nuclear power can bring in improving the urban and suburban environment rather than being misled into believing that fossil-fuel plants and their increasing pollution of the atmosphere are a satisfactory solution to our growing power needs.

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Radiation in Perspective—The Role of Nuclear Energy in the Control of Air Pollution

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Abstract: *Nuclear energy can play a critically important role in combating the growing assault on the purity of our atmosphere by supplanting fossil-fuel energy for most of the power plants to be built late in the century. Even then the same tight control that is currently exercised over the nuclear industry must come into being for other industries that are actual and/or potential polluters of the atmosphere. Several air-pollution disasters of the past emphasize the potential for future disasters.*

Man is a consumer of energy and of space–time. The mere fact of his occupation of space and time is a problem of increasing concern to the population dynamicists and to the other social scientists. At the same time the so-called "population explosion" creates problems for the technologists who are concerned with providing the energy necessary to sustain each man during his existence.

With our present knowledge, there is little we can do to remedy the problems of man's occupation of space–time except to prevent them, as is being attempted through various birth-control efforts or, failing that, eventually through the brutality of war. However, since man's use of energy can be accomplished in a variety of modes, it continues to be our fond hope to find new ways or to change the old ones so as continually to better our position as consumers.

Nuclear energy offers a basis for hope in this regard through its promise as an essentially clean source of power. A review of the reported experiences of operating nuclear facilities in the United States, although brief and incomplete, indicates that the routine operation of nuclear electric plants does not lead to significant release of pollution to the atmosphere. Because of its potential for the release of vast amounts of radioactivity to the environment, however, the nuclear energy industry has grown to the threshold of maturity with a unique burden of strict review and control at every step. Nevertheless, this feature which has appeared to be a handicap may well become the industry's greatest asset at a time when effective control of atmospheric pollution is rapidly becoming an absolute imperative. It is suggested that all levels of government interested in pollution control should examine the impressive achievement records of the various review boards and control agencies within the U. S. Atomic Energy Commission and consider adoption of comparable methods for controlling other actual and potential polluters.

Basic to our utilization of energy are our requirements for the intake of food, water, and air. In order to survive, some animals must take in food practically continuously. Others must live in the water to maintain a constant liquid intake. Of these three components, however, the only item of continuous obligatory consumption for man, even when asleep, is air.

Amount of Air Required

First, it may be instructive to review briefly some measurements made by Silverman and his associates[1] on the intake of air by average, healthy, adult males while exercising at known work rates. Table 1 represents a selection of work rates taken from a much larger table of data in Ref. 1. Column headings have been modified to translate the original work rates in kilograms per meter per minute to approximate easily recognized levels of effort.

Such measurements form the basis of the air-intake values assumed by the International Commission on Radiological Protection (ICRP) Committee II on Internal Radiation and are used in the computation of maximum permissible concentrations of radionuclides in the air.[2-4] Thus the ICRP calculations are based on

At work: 10^7 cm^3 in 8 working hours = 20.8 liters/min

Away from work: 10^7 cm^3 in 16 rest hours = 10.4 liters/min

With very little juggling of numbers, it is seen that a normal, healthy adult male easily can take in an average of nearly 54 lb of air per day (assuming complete rest 2 days in 7). This represents about an order of magnitude greater intake of air by weight than the combined intake of food and water.

One further comparison may serve to emphasize the relative position of air in the hierarchy of intake

Table 1 Mean Respiratory Air-Flow Measurements: Healthy Young Men*

	Work rate, kg/(m)(min^{-1})				
	~0 (rest, watching TV)	>0 (light work, slow walk)	208 (average work)	622 (heavy work, slow run)	1660 (maximum effort)
Respirations per minute	14.6	19.6	21.2	23.0	47.6
Minute volume, liters	10.3	14.2	20.8	37.3	113.8
Tidal volume, ml/breath	705	725	981	1620	2390

*Adapted from Silverman et al.[1]

requirements. Consider the expected survival time of man if completely deprived of all intake. Man can live on the order of 5 weeks without intake of food and perhaps 5 days without water, but, if his air intake is restricted for 5 min, he is in serious trouble.

Deposition of Pollutants in the Respiratory System

We might look upon the lung as a processing plant, small by industry standards, but specialized and performing an indispensable service. The lung processes just under 10 tons of raw air per year for a total of about 620 tons per lifetime (women average perhaps 80% of these amounts). As in any well-designed system required to process raw materials of variable quality, there are features of the respiratory system which serve to prevent or reduce the intake and retention of many of the noxious substances that might be admixed with the air we breathe. An excellent introduction to the subject of inhalation of particulate aerosols is given in a book by Hatch and Gross.[5]

In 1964, ICRP Committee II created a special Task Group on lung dynamics (P. E. Morrow, Chairman) to review the so-called ICRP-lung model[2] and to suggest changes where appropriate. The Task Group report[6] includes much detail on the estimation of particle deposition and clearance in the respiratory tract. One of the significant features of the report is that, within fairly narrow limits, it is only necessary to know the mass median aerodynamic diameter* (MMAD) of a particle size distribution in order to estimate the fraction of the inhaled mass deposited in the three major divisions of the respiratory system—the nasal–pharyngeal region (N–P), the tracheobronchial region (T–B), and the pulmonary region (P). Estimates of particle deposition given in Table 2 are based on a gross interpolation of data given in the Task Group report[6] and should be considered of qualitative significance only. Although the tabulated values refer to the mass fraction deposited and the mass median size, the words *count* (particle number), *area* (surface), or *radioactivity* may be substituted for *mass* in the table.

Table 2 Estimates of Particle Deposition and Clearance in the Respiratory System

Mass median aerodynamic diameter, μ	Mass fraction deposited			
	N–P	T–B	P	Exhaled*
0.01	0.01	0.18	0.70	0.05
0.1	0.02	0.08	0.55	0.35
1	0.25	0.05	0.25	0.45
10	0.85	0.05	0.09	0.01
100	0.95	0	0	0.05
Clearance rate	Minutes	Minutes to hours	Days to years	

*Includes particles too large to be inhaled efficiently.

It should not be supposed that the lung model for particle inhalation is a closed question. There are numerous features of the lung model that require clarification. Nevertheless, there is a serviceable model that yields predictions not grossly at variance with experimental data. Unfortunately, there is no comparable model that may be used to predict the site of deposition for partially soluble or reactive gases and vapors in the lungs.

Effects of Air Pollution on People

The undesirable direct effects of air pollution on man may be classified according to the mode or site of

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*As defined in the Task Group report: "Diameter of a unit density sphere with the same settling velocity as the particle in question."

attack on the sensitive tissue of primary concern. Thus specific pollutants may attack the surface of the body, e.g., acrolein or sulfuric acid mist in the eyes or large-particle fallout from nuclear weapons tests falling onto unprotected skin.

Respirable pollutants, including all gases and vapors, as well as particles of less than 300- to 400-μ aerodynamic diameter, may affect various regions of the body. In the first place, for a very soluble particle or vapor, whose effect is not local, it matters little at what site it is deposited; the important factor is the total quantity absorbed into the bloodstream. This is true of systemic poisons, such as arsine or carbon monoxide, and materials that concentrate in a specific organ, as ^{131}I in the thyroid. On the other hand, local irritants, as represented by sulfur dioxide, or short half-lived radionuclides such as radon and its radioactive daughters, may be expected to produce the greatest damage at the intake site where the tissue sustains the greatest exposure (= concentration × time). Obviously, the significance of local exposure cannot be independent of tissue sensitivity and of the importance of the tissue to the well-being of the individual. This may be illustrated qualitatively by referring to sulfur dioxide, which is moderately soluble in lung fluids. Inhalation of a few parts per million of SO_2 can produce local irritation in the nose and throat because of the corrosive action on tissues exposed to the sulfuric acid formed at the sorption site. Continued exposure to somewhat elevated concentrations or short-term exposure to very high levels can result in the extension of the damaged region further into the lungs and possibly alter the caliber of the airways through a bronchoconstrictive reaction. If the high concentration of SO_2 is carried far enough into the lungs to involve the functional gas-exchange tissues of the pulmonary region, the otherwise irritant reaction may become a fatal reaction as the body loses vitally needed respiratory tissues. In the widely reported[7] air-pollution disasters of the Meuse Valley in Belgium (1930), of Donora, Pa. (1948), and of London (1952), there are indications that the pollution levels did not vastly exceed previously experienced levels; however, there are suggestions of a possible synergism between particles, possibly fog droplets and SO_2, whereby a portion of the gas, which normally would become an irritant in the nose, throat, or tracheobronchial region, may have been delivered to the vital pulmonary tissues via sorption on particles penetrating through the airways.

It is possible to undergo exposure to the gastrointestinal (GI) tract by inhalation. Referring to the report[6] of the ICRP Committee II Task Group on Lung Dynamics (or taking roughly the numbers given in Table 2), we can see that essentially all particles having an aerodynamic diameter exceeding 10 μ will be deposited in the nasal pharyngeal or the tracheobronchial regions. From these regions undissolved particles are cleared rather quickly to the esophagus and thus directly to the GI tract. It should be kept in mind that a single 100-μ-diameter particle contains the same mass as a million 1-μ particles of the same density; hence an inhaled, soluble systemic poison may enter the body in larger quantities through the GI tract than through the lungs. Furthermore, if the action of the strong acids in the stomach is such as to increase the solubility or the toxicity of an inhaled pollutant, the significance of the GI tract as an entry portal may become equal to or greater than that of the lungs.

Air-Pollution Disasters

Usually one thinks of a disaster as something that occurs suddenly, perhaps explosively, such as an earthquake, a tornado, or a fire. The classic air-pollution disasters are of an entirely different character. Except for such sudden releases as that which occurred in Poza Rica, Mexico, in 1950, the quantities of the pollutants released to the atmosphere during the most significant episodes were not unusual.[7] Thus no breakdown in equipment or normal operating procedure nor a process accident could be blamed. Rather, the pollutants were routinely being released in disaster quantities; it was only necessary to wait until weather conditions prevented the adequate dispersion and dilution of the noxious effluents.

Meuse Valley, Belgium, 1930 (modified from Ref. 7). On Monday, Dec. 1, 1930, the narrow valley of the Meuse River in Belgium experienced an unusual and widespread weather condition that persisted the remainder of the week. In this river valley, 15 miles long with hills about 300 ft high on either side, a thermal inversion confined emitted pollutants to the limited air volume contained in the valley. There were many industries in the valley, including coke ovens, blast furnaces, steel mills, glass factories, a zinc smelter, and sulfuric acid plants. On the third day many people became ill with respiratory-tract complaints, and, before the week was over, 60 had died. In addition, there were deaths in cattle. Older persons with previously known diseases of the heart and lungs had the greatest mortality; however, illness affected persons of all ages and was best described as an irritation of all exposed membranes of the body, especially those of the respiratory tract. Chest pain, cough, shortness of breath, and eye and nasal irritation were the most common symptoms. Fatalities occurred on both December 4 and December 5, although frequency of symptoms decreased strikingly on December 5. Autopsy examinations showed only congestion and irritation of the tracheal mucosa and large bronchi. However, there was some black particulate matter in the lungs, mostly within the phagocytes.

The chemical substances responsible for the illness and fatalities have been disputed. In the original report on the episode, it was estimated (since no measurements had been made during the event) that the sulfur dioxide content of the atmosphere was from 9.6 to 38.4 ppm. Assuming complete oxidation of the sulfur dioxide, even though unlikely, sulfuric acid mist concentrations of 38 to 152 mg/m^3 might theoretically have resulted. It is generally thought that a combination of several pollutants may have been associated with this, as well as with other community disasters. Certainly, strong suspicion attaches to sulfur dioxide, but it is more likely that this substance, when dissolved or otherwise combined with water droplets, and in the presence of other pollutants, oxidizes to sulfuric acid mist with a particle size sufficiently small to penetrate deeply into the lungs.

Donora, Pa., 1948 (modified from Ref. 7). The impact of the Donora disaster has been eloquently described by Roueche.[8] "The fog closed over Donora on the morning of Tuesday, October 26th. The weather was raw, cloudy, and dead calm, and it stayed that way as the fog piled up all that day and the next. By Thursday, it had stiffened adhesively into a motionless clot of smoke. That afternoon it was just possible to see across the street, and except for the stacks, the mills had vanished. The air began to have a sickening smell, almost a taste. It was the bittersweet reek of sulfur dioxide. Everyone who was out that day remarked on it, but no one was much concerned. The smell of sulfur dioxide, a scratchy gas given off by burning coal and melting ore, is a normal concomitant of any durable fog in Donora. This time it merely seemed more penetrating than usual." During this period, temperature inversion and foggy weather affected a wide area. Donora is located on the inside of a horseshoe-shaped valley of the Monongahela River about 30 miles from Pittsburgh. The city contains a large steel mill, a sulfuric acid plant, and a large zinc production plant, among other industries. The hills on either side of the valley are steep, rising to several hundred feet. At the time there were about 14 thousand people living in the valley. A meticulous health survey of the population was made within a few months of the episode.[9] The investigation was directed at the health effects that occurred among people and animals, the nature of the contaminants, and the meteorological conditions. Interviews were obtained with persons who were ill and from physicians in the community. Roentgenograms and blood tests were taken; and teeth, bone, and urine samples were studied to determine whether fluorides might have been involved. These studies indicated that 43% of the population was made ill during the episode. Curiously, a large number of the persons who were not ill were unaware of the extent of ill health. Cough was the most prominent symptom, but all of the respiratory tract and the eyes, nose, and throat were irritated. Many complained of chest constriction, headache, vomiting, and nausea. There was a relation observed between the frequency and severity of illness and the age of the population. Most of those who became ill did so on the second day of the episode; of the 20 deaths, most occurred on the third day. Among the fatalities, preexisting cardiac or respiratory-system disease was common. From examinations made for fluorides, it was felt that fluorine was probably not involved. Retrospective examination of mortality indicated that a similar event might have occurred in April 1945. Autopsy examinations from the 1948 fatalities were nonspecific, but there was abundant evidence of respiratory-tract irritation. Environmental measurements had not been made during the episode, but it was inferred that sulfur dioxide had ranged between 0.5 and 2.0 ppm. Particulate matter was undoubtedly present. The calls for medical assistance in Donora ceased rather abruptly on Saturday evening despite the fact that the fog remained quite dense. This suggests that some change in the physical nature of the fog droplets may have occurred; for example, the particles may have increased sufficiently in size so that they were deposited in the upper airway instead of penetrating deeply into the lung.

London, England, 1952 (modified from Ref. 7). From Dec. 5 through Dec. 9, 1952, most of the British Isles were covered by a fog and a temperature inversion. One of the areas most severely affected was London, which is located in the broad valley of the Thames. During this period an unusually large number of deaths occurred, and many more persons were ill. The illnesses were usually sudden in onset and tended to occur on the third and fourth days of the episode.[10] Shortness of breath, cyanosis, some fever, and rales were observed. Most of those seriously ill were in the older age groups. Admissions to hospitals for the treatment of respiratory diseases increased markedly, but so did admissions for heart disease. An increase in mortality among all ages was observed. However, the very old, those in the seventh and eighth decades, had the highest increment. The most frequent causes to which deaths were ascribed were chronic bronchitis, bronchopneumonia, and heart disease. Of particular interest was the fact that mortality remained elevated for several weeks after the weather had improved. The total excess was between 3500 and 4000 deaths. Measurements were available for the amount of suspended smoke and sulfur dioxide. The highest values reported were 4.46 mg/m^3 of smoke and 1.34 ppm of sulfur dioxide. Autopsy examination did not reveal any characteristic mode of death other than evidence of respiratory-tract irritation. Search of the past records of meteorology and mortality indicated that periods of excessive mortality had occurred previously. Three hundred excess deaths occurred in the winter of 1948; detectable increases in mortality associated with fog were found in December 1873, January 1880, February 1882, December 1891, and December 1892. A subsequent episode occurred[11] in 1959. None of the other episodes, however, was quite as severe as the one in 1952.

Poza Rica, Mexico, 1950 (modified from Ref. 7). Another type of community disaster resulting from the sudden discharge of a toxic gas from a single source occurred in the small town of Poza Rica, Mexico.[12] Here a new plant for the recovery of sulfur from natural gas put a portion of its equipment into operation on the night of Nov. 21, 1950. One of the steps in the process was the removal of hydrogen sulfide from natural gas. In order to do this, the hydrogen sulfide was concentrated in a system in which it was intended to be burned. During the night of November 23 and 24, the flow of gas into and through the plant was increased. The weather was foggy, with weak winds and a low inversion layer, and, between 4:45 a.m. and 5:10 a.m. of November 24, hydrogen sulfide was released inadvertently and spread into the adjacent portion of the town. Most of the nearby residents were either in bed or had just arisen; many were afflicted promptly with respiratory and central nervous system symptoms. Three hundred and twenty were hospitalized, and 22 died. The characteristic manner in which the hydrogen sulfide affected these individuals was to produce loss of sense of smell and severe respiratory-tract irritation. Most of the deaths occurred in persons who had such central nervous system attack symptoms as unconsciousness and vertigo. A number of the affected individuals also had pulmonary edema. Persons of all ages were affected, and preexisting disease did not seem to have much influence on which persons were afflicted.

Future Air-Pollution Disasters

The title of this section may appear to be gloomy indeed. To some extent it does presume that the reckless dumping of gaseous and particulate wastes to our atmosphere will continue to be dominated by a philosophy better suited to the frontier days than to our increasingly urbanized world. Until quite recently, and still very much in evidence, the prevailing attitude toward water pollution, for example, has been for the user to treat it at the point of use *if it needs treatment.* The air-pollution equivalent is the suggestion that we should build domed cities and clean the air at the city intakes.[13,14] This clearly presumes two things: (1) the priority of man as a polluter over man as a breather with respect to their rights to use the atmosphere; (2) it assumes that we are willing to give up the vegetative cover of the space between domed cities.

A more optimistic approach to predicting the future emissions of SO_2 was made by Rohrman, Steigerwald, and Ludwig.[15] Figure 1 was taken from their paper and represents their best estimates of SO_2 control and emission per year in the United States. In preparing this figure the authors assumed "that no new fossil-fuel power plants will be built after 1995, and that in the year 2000 approximately half of all electricity will be generated by nuclear power." Thus going ***all nuclear*** late in this century will not of itself prevent a threefold increase in SO_2 emissions. Clearly the alternative to going nuclear, without severely restricting the fossil-fuel-plant effluents, would be an increase over present levels of about an order of magnitude.

The authors described the assumptions used in obtaining the prediction curves labeled Case 1 and Case 2 as follows:

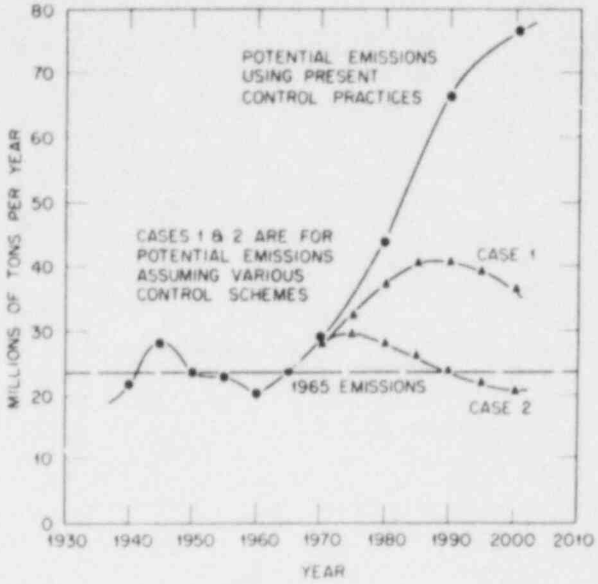

Fig. 1. Potential SO_2 emissions in the United States. (From Ref. 15.)

Case 1

The control assumptions for Case 1 are severe but realistic. They do not assume early development and universal use of highly effective SO_2 gas cleaning methods for power plants nor the rapid application of available methods of fuel desulfurization.

1. Beginning in 1970, 1-percent control [i.e., reduction] is applied to existing power plants, increasing 1-percent each year; and 5 percent control yearly to new power plants, starting in 1975, to a maximum of 80 percent control for new plants put on stream in 1990. After the initial year, control of these new plants increases 1-percent per year, the same as existing plants. This assumes some increased use of fuel desulfurization, selection of fuels with lower sulfur content, miscellaneous uses of fuel additives, improved design of plants, and eventually perfection of processes to remove SO_2 from power-plant stacks [effluents].

2. One-percent control of all non-power-plant emissions in 1965, increasing 1-percent each year.

Case 2

The control assumptions for Case 2 are very severe and probably represent the maximum that can be achieved technically. They will require an immediate and vigorous program of research and pilot plant efforts on power-plant gas cleaning methods, fuel desulfurization, and forced application of control methods as they become available.

1. Seventy-five percent control of SO_2 emission from new power plants put into operation in 1975, including replacements or expansion of existing plants. This 75 percent control in 1975 is increased 1-percent each year after 1975 to a maximum of 90 percent in 1990. Since there is a minimum of 5 years lag time between initial design of power plants and the time the unit is put on stream, the initiation of control by 1975 requires that proven designs must be available in 1970. Achieving this

goal will require extensive development in the next 5 years, since most of the methods for control of SO_2 in power plants are only in the bench-test stage and effective coal desulfurization methods are not now available for 75 percent removal. The increase of average removal efficiency by 1-percent per year to 90 percent maximum is in keeping with expected improvements in technology.

2. Two-percent control of SO_2 from all coal and oil combustion beginning in 1970, increasing by 2 percent per year to a maximum of 50 percent control in 1994 (excluding new power plants after 1975, which are covered in the preceding paragraph). This assumption requires increased use of available techniques for fuel desulfurization, selection of fuels with lower sulfur content, and miscellaneous schemes for control of SO_2, such as use of fuel additives.

3. One-percent control for all noncombustion sources in 1965, increasing by 1-percent each year to 35 percent in the year 2000.

The Roles of Nuclear Energy

First the role of nuclear energy as a source of air pollution should be considered. This requires that a clear distinction be made between potential releases of pollution under accident conditions, such as at Poza Rica, Mexico, and the continuous real release of pollutants to the atmosphere.

With respect to accidents, most of us will agree with Sporn's[16] comment in his presentation to the National Conference on Air Pollution ". . . on the basis of safety all fuels—and this includes nuclear power—represent potential hazards." He also expressed the opinion that ". . . nuclear power continues to make progress and will substitute for an increasing share of the new power generation plants to be built. Undoubtedly its rate of substitution is being moderated by the cost burden of responsible conservatism in design and construction to assure safety and surely it must continue to be, for a long time, part of AEC, and in this case, national policy, to promote by every practical means absolute assurance of the safety of our nuclear power installations." Although many of us will agree with continuing and strengthening this responsible conservatism in design and construction, a growing number of people are beginning to wonder if a comparable quality might not be desirable in the design, site selection, construction, and operation of other types of facilities. This might prevent, or at least reduce, the occurrence of incidents such as the hydrogen sulfide release (and the 22 deaths) at Poza Rica, gas pipeline explosions, tank-car accidents releasing poisonous gases and vapors, pier explosions (e.g., the Texas City disaster of 1947), and numerous other potentially hazardous operations that are currently subject to the loosest review, if any at all, by responsible public officials.

Apart from potential accidents, the central problem of this section is the role of nuclear energy in air pollution. A synopsis of the views of the AEC was given by Chairman Glenn T. Seaborg[17] to the National Conference on Air Pollution:

> With reference to the primary focus of this conference—air pollution—nuclear power plants offer decided advantages over fossil fueled plants. The main advantage stems from their control of waste. In a nuclear reactor the split atoms, "fission products" as they are called, remain essentially within the fuel cladding until such time as the reactor is refueled. Then the used fuel elements are removed, stored under water for a cooling off period, after which they are safely shipped to a reprocessing plant where unused fuel and valuable radioisotopes are extracted for future use. The remaining waste products are then safely disposed of in storage tanks at underground burial sites. The extremely minute amount of radioactivity produced auxiliary to the operations can be held and released in such tiny amounts, and under such favorable atmospheric conditions, that it poses no health hazard whatsoever. Or it can be packaged for safe disposal in other ways. In fact, a nuclear plant can be built without any stack at all, and such a plant is under construction today in the Rochester, N. Y., area.

Similar comments were made by Grob[18] in his paper given at the 1967 Annual Meeting of the Air Pollution Control Association:

> It should be noted, however, that continuous release is not required in nuclear plant operation. The radioactive noble gases produced during reactor operations may be stored and released during favorable meteorological periods.
>
> Radioactivity released to the atmosphere by nuclear power plant operations is no greater than radioactivity released to the environment by conventional power plant operations. Both of these sources of radioactivity are insignificant compared to natural radioactivity, natural radiation fields, and man's non-nuclear and non-power generation activities. Discharges from our Company's (Consolidated Edison Company of New York) nuclear plant, Indian Point Unit No. 1, have been less than 0.01% of what the plant's license permits. The limits imposed by the license are such that they prevent achieving the legal limits set forth in 10CFR20 by orders of magnitude. The legal limits of 10CFR20 themselves have safety factors, which amount to orders of magnitude.

In his recent book on the technology of nuclear power facilities, Wills[19] includes a tabulation of typical radioactive wastes and disposal methods (his Table 29). Table 3 includes the airborne wastes mentioned by Wills.

Table 3 Typical Airborne Radioactive Wastes Related to Nuclear Power*

Type of waste radioactivity	Source of waste	Form of waste	Typical isotopes	Type of radiation	Disposal methods
Natural activity	Mining of uranium ores	Gases, dusts	^{222}Rn	α	Ventilate mine
	Fuel-fabrication plants	Dusts	^{238}U ^{235}U	α,γ	Ventilate, filter, and disperse to air
Fission-product activity	Fuel irradiation and processing	Gases	^{131}I	β,γ	React with chemicals to bind in solid, e.g., silver iodide
			^{85}Kr	β,γ	Disperse to air
Activation-product activity	Reactor materials unavoidably irradiated during operation	Gases	^{16}N	β,γ	Hold for decay (very short life); then disperse to air

*Modified from Table 29, Ref. 19.

Wills also commented on the relative amounts of radioactivity released from nuclear energy plants and from coal-burning plants, although he did not cite the source of his numbers nor did he identify the specific radionuclides which are, in fact, dispersed from a coal-fired plant:

> Gaseous Wastes—The gaseous effluent from a nuclear plant, which may occur from dissociation of the coolant, is removed to holdup tanks to permit decay of short-lived isotopes. The remaining gases are monitored and diluted with air and discharged through a tall stack when meteorological conditions are suitable for dispersion high into the atmosphere. This discharge is controlled in compliance with AEC regulations (activity limited to 10^{-9} $\mu c/cm^3$ of air), which are based on the annual radiation exposure that might be received by persons living at the plant exclusion-area boundary.
>
> Actually, a pressurized-water-moderated nuclear plant with a 150 MWe rating will in a year's operation disperse 2 mc of noble gases (Kr and I [*sic*]) into the atmosphere, whereas a coal-burning plant of equal capacity will disperse 20,000 mc of mixed nuclides into the atmosphere with other pollutants.
>
> Radiation levels inside and outside the plant exclusion area are constantly monitored to ensure that proper environmental conditions are maintained. Recently, a spokesman of the AEC's Division of Compliance summarized experience in the United States in years 1960 through 1963 as follows: "There has been no detectable increase in the amount of radioactivity, which could be attributed to the existence of the nuclear installation, in the environment of any reactor plant. This conclusion is based on the results of pre- and post-operation environmental surveys, which include sampling of the air, soil, water, vegetation, aquatic life, and milk in the vicinity of the reactor site."

The most thorough comparison of the environmental pollution levels from nuclear and conventional power plants was given recently by Terrill, Harward, and Leggett.[20] They point out the inherent difficulties in making such a comparison. One basic problem is the lack of accepted standards for permissible concentrations of nonradioactive pollutants in the environment in contrast to the well-established standards for radioactivity. A number of interesting points are given in the original paper, but only two will be treated here. First, the authors' discussion of the release of radioactivity from fossil-fueled plants and from nuclear energy facilities:

> Due to the presence of trace quantities of two naturally occurring radioactive materials in coal (1.1 ppm of ^{238}U and 2.0 ppm of ^{232}Th), the released fly ash would contain 10.8 mCi of ^{228}Ra and 17.2 mCi of ^{226}Ra per year, which are daughter products of ^{232}Th and ^{238}U. Thus, the question is raised: Do fossil fuel plants discharge significant quantities of radioactivity and how do they compare with releases of radioactivity from nuclear plants?
>
> On the basis of the AEC's regulations covering exposure to airborne radioactive materials, Eisenbud[21] states that this total of 28 mCi per year of mixed radium isotopes is approximately equivalent to 10^4 Ci of ^{85}Kr or 10 Ci of ^{131}I. Krypton-85 and ^{131}I were chosen for comparison, since they represent two of the principal gaseous radionuclides of concern in reactor stack effluents. Associated with the particulate emission from oil-fired plants will be approximately 0.5 mCi of radium per year (^{226}Ra and ^{228}Ra), which is roughly equivalent to 200 Ci of ^{85}Kr or 200 mCi of ^{131}I.
>
> A recent joint study[22] of natural gas from northwestern New Mexico and southwestern Colorado by the U. S. Public Health Service and the El Paso Natural Gas

> Company shows that ^{222}Rn, a daughter of ^{226}Ra, is present in natural gas at concentrations ranging from 0.2 pCi/liter to 158.8 pCi/liter. There is a lack of data concerning concentration of ^{222}Rn in the stack effluent of natural gas power plants, but it can be assumed minimal due to the 3.8 day half-life of ^{222}Rn and the transit and/or storage times from well to plant which are involved. There will be some activity from the longer-lived daughter products of radon, but since these are particulates and therefore subject to many removal forces about which there is a lack of data, it is difficult to determine the amount of activity emitted.
>
> Operating data is presently lacking for large nuclear power plants in the range of 500 to 1,100 MWe, because they are still in the construction or planning stage. However, published data are available from several smaller plants. For example, the Shippingport Atomic Power Station, located in Shippingport, Pennsylvania, and operated for the AEC by Duquesne Light Co., has been operating since 1957. This is a 100 MWe pressurized water reactor, and has generated a total of nearly 2,400,000 MWh as of May 1966.[23] During the five-year period, 1961–1965, this plant's annual average releases were 0.217 Ci of liquid radioactive waste (excluding tritium), 4.5 Ci of tritium in the liquid waste, and 0.57 Ci of noble gases (primarily ^{133}Xe).[24] These actual releases have been a small fraction of design discharge quantities and all releases have been well within the limits specified for the plant by the AEC and the liquid waste discharge permit issued by the State of Pennsylvania.
>
> Another pressurized water plant, the Yankee Nuclear Power Station, near Rowe, Massachusetts, has been operating since 1960 and its present power level is 185 MWe. As of May 1, 1966, it has generated over 5,500,000 MWh.[23] During the calendar year of 1965, this plant released 0.067 Ci of liquid waste (exclusive of tritium—published tritium data not available at time of this writing) and 1.66 Ci of gaseous waste to the environment.[25] All releases were within limits established by the AEC regulations as contained in 10CFR20.

The authors chose plausible values for the permissible concentrations of SO_2 and NO_2 from the literature and compared the various types of plants on the basis of the amount of air per year required to dilute the emitted pollutants to stated standard concentrations. Table 4 appeared as Table V in the article cited in Ref. 20.

In all these comparisons nuclear energy comes out well ahead of fossil-fueled plants in terms of its minimal direct contribution to noxious airborne pollution. Furthermore, to whatever extent carbon dioxide (CO_2) may be detrimental in connection with the heat balance of the atmosphere, as has been suggested,[26] nuclear power again has the advantage in that it does not result in CO_2 production. However, normal operation presupposes that the fission products remain essentially within the fuel cladding. The critical point is reached when the cladding is breached in the fuel-reprocessing operation. According to Mawson[27] the "gases evolved from fuel-reprocessing plants are usually heavily contaminated with such chemicals as nitric acid and organic solvents, as well as with fission products, but the chemical contaminants can be removed by conventional scrubbing systems." Obviously, the chemical composition of the airborne effluents from a fuel-reprocessing facility depends upon the particular process employed.[28] Perhaps the only general comment warranted is that, in the absence of established standards for nonradioactive air pollutants, reactor fuel-reprocessing plants are not likely to institute significantly stricter control than is the practice of similar, nonradioactive, chemical-processing facilities. Nevertheless, fuel reprocessors operate under the control of their licensing provisions for the limitation of radioactivity release, and, in treating effluent gases to remove minute quantities of radioactive materials, they must remove many of the nonradioactive components as well. An order-of-magnitude comparison might be gained by considering the relative "acceptable" levels of SO_2 and radioactive ^{131}I. At a level of 0.3 ppm SO_2, as assumed by Terrill, Harward, and Leggett[20] (see Table 4), 1 μg of SO_2 would be dispersed in each liter of air, whereas 1 μg of ^{131}I would have to be dispersed in approximately 0.1 cu mile of air to equal the maximum permissible concentration in air for the general population.[23] Thus it would seem difficult indeed to remove the micrograms of radioactivity without, at the same time, significantly reducing the pounds of vapors and acid mists.

Unfortunately, the foregoing references do not tell the complete story in that they all pertain only to pressurized-water reactors (PWR's). The boiling-water reactors (BWR's) also represent a major type of power reactor which must be considered. In two recent reviews, one by Blomeke and Harrington[29] and one by Goldman,[30] the BWR's have been shown to release a very much larger fraction of the radioactivity produced in the fission process than is released in the operation of the PWR's. Release rates that may be compared with those given in Table 4 can be derived from data summarized by Goldman.[30] Thus the Dresden BWR (Commonwealth Edison Company) released about 4.3×10^9 μc/Mw(e)-hr (noble gas) during the period 1963–1967, averaging about 2.4% of the limit imposed in the license; the Big Rock Point BWR (Consumers Power Company) released 23.8×10^9 μc/Mw(e)-year (> 99% noble gas) from May 1965 through April 1968, averaging 1.7% of the license limit, and the Humboldt Bay BWR (Pacific Gas & Electric Company) released

Table 4 Dilution Air Required To Meet Concentration Standards for Various Power-Plant Pollutants*

Type of plant	Critical pollutant	Exposure vector	Concentration standards†	Discharge quantities per Mw(e)-year	Yearly volume of air required for dilution, m^3/Mw(e)
Coal	SO_2	Air–SO_3–lungs Air–lungs	0.3 ppm	306×10^3 lb	1.77×10^{11}
	Fly ash				
	^{226}Ra	Air–lungs	1.0×10^{-13} $\mu c/cm^3$	17.2 μc	1.72×10^8
	^{228}Ra	Air–lungs	3.0×10^{-13} $\mu c/cm^3$	10.8 μc	3.6×10^7
Oil	SO_2	Air–lungs	0.3 ppm	116×10^3 lb	6.75×10^{10}
	NO_2	Air–lungs	2 ppm	47×10^3 lb	5.77×10^9
		Air–O_3–smog irritants of lungs and eyes	Unknown		
	Fly ash				
	^{226}Ra	Air–lungs	1.0×10^{-13} $\mu c/cm^3$	0.15 μc	1.5×10^6
	^{228}Ra	Air–lungs	3.0×10^{-13} $\mu c/cm^3$	0.35 μc	1.2×10^6
Gas	SO_2	Air–lungs	0.3 ppm	0.027×10^3 lb	1.5×10^7
	NO_2	Air–lungs	2 ppm	26.6×10^3 lb	3.22×10^9
	Particulates—radon daughters	Air–lungs	Unknown	Unknown	
Nuclear	Radioactive noble gases ^{85}Kr + ^{133}Xe	External	1×10^{-7} $\mu c/cm^3$	5.7×10^3 μc	5.7×10^4 (Shippingport 5-year average)
				9.5×10^3 μc	9.5×10^4 (Yankee 1965)
	^{131}I	Air–lungs–thyroid	1×10^{-10} $\mu c/cm^3$	No detectable levels reported in available literature	No detectable levels reported in available literature
		Air–grass–milk–thyroid	1.6×10^{-13} $\mu c/cm^3$		

*Table V of Ref. 20.

†In the case of radioactive materials, they are based on AEC regulatory concentration standards (10CFR20), and in the case of chemical pollutants from combustion of fossil fuel, they are based on recommended permissible concentrations in the available literature.

22.5×10^9 μc/Mw(e)-year (noble and activation gases) from February 1963 through February 1968, which, however, averaged about 23% of the limit (the Humboldt Bay limit is a factor of 20 lower than the limit for Big Rock Point).

To bring the values given in Table 4 further up to date, one would have to modify the limit assumed for SO_2. More recent air-quality criteria for SO_2 suggest 0.015 ppm instead of 0.3 as estimated by Terrill.[20] Applying this factor of 20 to the yearly dilution volume indicated for SO_2 in Table 4, we see that on the order of 3.5×10^{12} m^3 of air are needed to dilute the flue gas produced in generating each megawatt of electricity in a coal-fired plant. The average discharge rate of radioactive noble gases from the three BWR's discussed by Goldman[30] was 10^{10} μc/Mw-year which would require dilution by 10^{11} m^3 of air per megawatt, a factor of 35 less.

The high release rates from the BWR's occurred during periods of operation with defective stainless-steel-clad fuel elements in the cores.[29] For example, the release rate per megawatt for the Humboldt Bay reactor was a factor of 340 less during the 18-month period February 1963 through August 1964 than it was from February 1965 through February 1968. The replacement of defective elements may be expected to reduce the average release rate by at least an order of magnitude. In any case, present experience indicates that continuous release of gaseous wastes from either the PWR's or the BWR's presents a lower order of hazard than that of coal-fired plants.

Nuclear Energy To Control Air Pollution

In addition to its role as an essentially clean source of power, nuclear energy has contributed heavily to society through the way it has fired the imagination of creative technologists in many fields. The field of air pollution control is not lacking in this respect.

The massive technological effort of the national laboratory approach has impressed many scientists and engineers with its records of accomplishment. A number of comments were recorded in the biweekly newsletter *Environmental Technology and Economics*[31] for Apr. 13, 1967:

> Dr. Rene Dubos (Rockefeller Un.) said that what this country needs is a "Brookhaven applied to biology." He further said air pollution could be conquered if the country devoted the effort to it that it has given to probing the atom. Benn Jesser (M. W. Kellogg), speaking at the AIChE Workshop in NYC, suggested that process engineering concerns be given responsibility for running the pollution control R&D program just as the AEC gave responsibility for running its facilities to a number of concerns (UCC, duPont, Dow, Monsanto, GE, etc.). R. N. Rickles (Celanese), speaking at Rice Un., seconded Mr. Jesser's idea and further suggested the establishment of an ESC (Environmental Science Comm.) on the model of the AEC, to handle the development of new waste management techniques.

Use of nuclear energy to produce substitute fuels was discussed recently by Green.[32] He mentions the possible use of nuclear power to produce cheap ammonia for use as a fuel for internal combustion engines, and he points out the possibility of using nuclear energy as a clean source of process heat to convert coal and shale into gas to supplement our dwindling supplies of natural gas.

The use of chemonuclear reactors for the production of ozone to be used in odor control has been proposed by Steinberg.[33] Ozone could be produced for $47.00 per ton in a single-purpose, 600 ton/day plant costing $38 million. Such systems also could produce ozone for water treatment.

Beyond whatever secondary spinoff that may have come from nuclear energy programs, there have been extensive contributions in fields basic to air-pollution control. Fundamental and practical work in meteorology, air-cleaning technology, aerosol physics, inhalation physiology, process dynamics, ecology, and numerous other important areas have been supported by the AEC since its inception. It is impossible to look far in the literature of these fields without encountering many important contributions initiated by the nuclear program. In return, support of research in these areas has made it possible to provide the competent experts, hardware, and sound technological base which have enabled the nuclear industry to apply its "responsible conservatism in design and construction."

Summary and Conclusions

Nuclear energy has a critically important role in combating the growing assault on our atmosphere. Still, even with nuclear energy completely supplanting fossil fuels for new plants built late in this century, much more must be done. What then can the nuclear energy industry do to aid our fight for clean air? The answer is implicit in the very advantages claimed by nuclear power. Unquestionably, the potential for massive pollution exists in the fission products produced by a nuclear reactor; in the absence of effective control to restrict the emission of radioactivity, the nuclear program could have become a leading contributor to atmospheric pollution. The key word is control. Essentially every phase of design, site selection, construction, and operation of a nuclear power plant is under the strict surveillance and control of responsible and technically competent review boards. The same tight control is overdue for other actual and potential polluters and must surely come into being, hopefully soon.

What then are the technological problems for continued control of nuclear air pollution and for mounting a successful attack on nonradioactive pollution? There are at least two major stumbling blocks. First, providing the technically qualified people to man the review boards for the nuclear program alone is difficult at present and may eventually become the major bottleneck to the orderly advance of nuclear energy. Without question, if responsible review is to become a factor in the fight against conventional air pollution, the availability of technically competent hazards analysts is a basic prerequisite in this field. Thus those persons on local, state, and federal levels who are serious in their desire to combat air pollution had better begin now the structure of the necessary review boards by supporting graduate education in environmental hazards analysis. On the other hand, technically competent reviewers would wield an empty control if air-cleaning and fuel-treatment methods are not available to implement the control requirements. Thus a continuing pressure must be maintained on the problems of gaseous waste disposal from conventional power and other processing operations.

In view of our mounting needs for energy, it is not in the best interest of our society to proscribe the use of any important source of energy, such as the fossil fuels. Nevertheless, without the rapid institution of responsible control, we may well face a curtailment in the use of energy as our society reaches and fails to penetrate the coming air barrier to our continued existence. It is the clear duty of both government and private enterprise to look closely at the record of the nuclear energy program and to adopt those features of control which have worked so effectively. Two questions remain—will we do it, and is there time?

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Radiation in Perspective: Some Comparisons of the Environmental Risks from Nuclear- and Fossil-Fueled Power Plants

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Nucl. Safety, 12(3): 185-196 (May-June 1971)

Abstract: *Fossil- and nuclear-fueled steam plants seem the practical means for meeting immediate power needs. The use of nuclear-fueled plants is being restricted in several instances because reactor-related hazards have been exaggerated. Ninety power reactors, in the United States and abroad, have generated* 2.5×10^{11} *kWh over 650 reactor-years without serious incidents. Comparison of routine discharges of hazardous agents from different types of steam power plants shows that nuclear-fueled plants produce the lowest concentrations of such agents relative to protection standards. Radioactive releases associated with the Brookhaven Graphite Research Reactor are comparable to the upper amounts anticipated from 1000-MW(e) reactors, and the measured Brookhaven external radiation levels, deposition, and aquatic concentrations suggest that the radiation level in the vicinity of large power reactors should be insignificant. The calculated risk* ($\sim 10^{-7}$/year) *of fatal injury from the anticipated maximum exposures of a few millirems per year above natural background is small compared with that of other accepted hazards of everyday living.*

The safety of nuclear power reactors and the routine release of radioactivity from these plants has become a matter of widespread public concern. Much of this concern stems from conjecture and speculation that is due in part to the technical nature of the data and the nontechnical nature of the public.

Brookhaven National Laboratory (BNL) was established on Long Island 20 years ago, and the air-cooled Brookhaven Graphite Research Reactor (BGRR) was operated as one of its major research facilities from 1951 to 1968. The establishment of BNL preceded the adoption of uniform national radiation protection standards by the AEC, and at that time less was known about environmental radioactivity than is the case today. Conservative practices were adopted with regard to release of reactor air and liquid from the BGRR to the environment, and the releases turned out to be similar to those anticipated from the large nuclear power plants now under construction at many locations in the United States.

As part of its mission to obtain scientific information, BNL has maintained a more extensive environmental monitoring program than that which would be required in the vicinity of a nuclear power reactor to establish compliance with radiation protection standards. The experience to date with nuclear reactors, in addition to the data developed at Brookhaven, led to the conclusion that nuclear reactors possess a high degree of safety and that the environmental radiation risk associated with the operation of nuclear power reactors should be small compared with that from conventional fossil-fueled plants.

ASSUMPTIONS

The potential risks of nuclear power plants can be considered sensibly only in the context of the alternate choices. Three underlying assumptions are basic to this discussion.

1. Electricity is a basic necessity to a technological civilization. A review of recent electrical power statistics and a projection of future requirements to the year 2000 are presented in Table 1, which was adapted from information on the environmental effects of producing power and recently published for use of the Joint Committee on Atomic Energy.[1] Apparently the nation's generating capacity will have to be doubled about every decade to meet the anticipated demand, and, even with the anticipated introduction of nuclear power, a substantial increase in conventional fossil-fueled generating capacity will also be required to meet the total projected needs for electric power.

2. All human interventions related to the extraction and consumption of energy have the potential for both cost and benefit. Some concrete instances are suggested in Table 2 with regard to the present alternatives for electric-power generation.

3. For most areas of the United States, fossil- or nuclear-fueled power plants offer the only practicable

Table 1 Use and Projected Demand for Electric Power in the United States*

	Year			
	1950	1968	1980	2000
U. S. population, millions	152	202	235	320
Electricity generating capacity, 10^3 MW				
Total	85	290	600	1352
Conventional (hydroelectric, fossil)	85	287	450	411
Nuclear	0	3	150	941

*Based on data from Ref. 1.

Table 2 Risks and Benefits from the Generation and Distribution of Electricity

Type of plant	Risks	Benefits
Hydroelectric	Alteration of stream flow; destruction of habitats and scenery, such as by reservoirs and long transmission lines	Energy; employment; flood control; recreation
Gas-fired	Destruction of scenery, such as by pipelines and plant stacks; air pollution with many substances; alteration of local ecology by thermal waste	Energy; employment; by-products
Oil-fired	Destruction of scenery, such as by pipelines, storage tanks, plant stacks, and ash-disposal areas; water pollution, air pollution with many substances; alteration of local ecology by thermal waste	Energy; employment; by-products
Coal-fired	Destruction of scenery, such as by strip mining, transport and storage facilities, plants, stacks, and ash-disposal areas; stream pollution (from mining refuse); air pollution with many substances; alteration of local ecology by thermal waste	Energy; employment; by-products
Nuclear	Destruction of scenery, such as by mining and processing facilities, plants, and stacks; minimal routine air and water pollution with radioactive ash; possible leakage during the long-term confinement of high-level radioactive wastes from fuel-reprocessing facilities; possible accidental release of significant quantities of radioactivity due to a reactor malfunction; alteration of local ecology by thermal waste	Energy; employment; by-products (i.e., isotopes useful in medicine, industry, research, etc.)

means of meeting the near-future electric-energy demand. Various other methods for producing electricity, such as the magnetic-hydrodynamic topping cycle, the fuel cell, and the fusion reactor, are under development. However, none is sufficiently advanced to be applied "off the shelf" in meeting immediate needs for power.

It follows from these assumptions that the real issue before the public is which technology, fossil or nuclear, will yield the greatest overall benefit-to-risk ratio. In contrast to most technological innovations (including that of the use of fossil fuels), this sort of consideration has been uppermost from the outset in the development and employment of nuclear power reactors. In his annual report for 1969 to the United Nations, Dr. Sigvard Eklund, Director General at the International Atomic Energy Agency (IAEA), stated, in part, "From the start the utmost care has been exercised to control the release of artificial radioactivity into the environment, indeed far more care has been taken with, and far more rigid legislation and standards are applied to nuclear energy than to any other potential source of environmental contamination. Far from being a major contributor to the pollution of the environment, nuclear energy can be a factor which will diminish pollution if it is used as a substitute for other sources of electric power such as coal and oil."[2]

MALFUNCTIONS AND CATASTROPHES

Although a balanced assessment of the adverse effects of power-plant effluents on the environment should be devoted primarily to those released during routine operations, some considerations of the probability of catastrophic accidents seem appropriate in the present context. Even with conventional technologies, the dramatic nature of catastrophes is such that they are often given far more attention than routine mishaps, even though it may be shown that the latter are, in the aggregate, far more costly per capita. This is, for example, evident in the relative amounts of attention given and resources devoted respectively to air and to highway safety.

With regard to catastrophes, the *public safety first* approach of the atomic industry has included an assessment of the potential consequences of catastrophic events in what is known as a "safety analysis." In this analysis it must be convincingly established that, for the most serious plausible simultaneous occurrence of malfunctions and failures, the so-called DBA (design basis accident), the release of radioactivity would be sufficiently limited so that no person in the environs would be seriously affected now or in the future. Some unwarranted apprehension about the inherent safety of reactors has been created by a favored device of some reactor critics; they quote from the consequences portions of the safety analyses, out of context, with little or no indication of the exceeding improbability of the postulated events.

To inject a consideration of probability into this presentation, note that over 300 civilian and military nuclear reactors are now operating or have been operated in the United States.[3] A few have been functioning for as long as two decades, and a total of well over 2000 reactor-years of experience has been accumulated. A malfunction leading to the release of a significant, let alone a catastrophic, amount of radioactivity to the environment has yet to occur in this nation in connection with reactor operation. Perhaps more pertinent, it was recently indicated at an IAEA symposium on nuclear power-reactor components that the 90 power reactors now in operation throughout the world have generated 250 billion kWh of electricity and have accumulated 650 years of experience, all without serious incidents.[4]

A study of the possibilities and consequences of some hypothetical, but highly improbable, catastrophic reactor accidents was made at BNL almost 15 years ago, when the Price–Anderson Act (AEC indemnity legislation) was first proposed. This report[5], generally referred to as WASH-740, has frequently been cited in the continuing debate about reactor safety. Starr[6] has since calculated that the probability of the incident the authors envisioned is about comparable to that of a jet transport crashing into an occupied sports stadium, that is, about 1 : 300,000,000. Starr commented that no one has suggested, on the basis of this probability, that we should abandon either spectator sports or airline service. In reaffirming the applicability of the Brookhaven study, when the extension of Price–Anderson was under consideration in 1965, AEC Chairman Seaborg indicated that, although the consequences of a major accident could be greater, the likelihood of a major accident was still more remote than originally suggested.[7]

Perhaps because we are accustomed to them, we are sometimes forgetful of the catastrophes and near-catastrophes that are at least in part attributable to the uses of fossil fuels, such as mine explosions,[8] floods related to strip mining,[9] oil leakage from tanker wrecks,[10] and urban air-pollution incidents[11] in which excess mortality over normal rates has been documented.

The favorable safety record of nuclear reactors is a result of the conscious provision of several successive layers of protection in their design and operation. These include:

1. *Careful training and practices.* Operators are trained for licensing as though the entire safety of the reactor depended solely on their actions.
2. *Electronic safety monitors.* These automatic backup devices continuously sense the condition of the reactor and associated equipment. They react much faster than a human operator could to shut down a reactor in the event that any significant indication exceeds preset operating limits.
3. *Self-limiting behavior.* The arrangement of the fuel and the inherent characteristics of a nuclear reactor are such that most imaginable accidents would tend to be self-limiting if the many control devices ever failed to operate.
4. *Fuel cladding.* The fissionable material is "canned" to minimize the possible escape of fission products from the fuel.
5. *Primary-system enclosure.* The entire nuclear "furnace," or reactor, including the canned fuel, is located inside a pressure vessel to minimize release of fission products that might escape from the fuel.
6. *Building containment and engineered safety features.* These are provided to further minimize the release of fission products to the environment if they should escape from the primary system that is within the containment building.

It seems appropriate in concluding this consideration of catastrophes to suggest that the public welfare would be much enhanced if the degree of attention to safety and the employment of many backup devices comparable to those now routinely provided for nuclear reactors were applied to other large-scale technologies with a view to promoting the same kind of conservative design and review prior to their application or extension.

ROUTINE EFFLUENT RELEASES

When the situation with regard to the effluents produced by the routine operation of power facilities is examined, it appears that in principle the hazardous agents from both fossil- and nuclear-fueled plants are controllable at almost any level which those responsible deem advisable or which the public insists upon. However, the closer to zero this level is set, the greater is the economic cost ultimately passed on to the consumer. In practice, effluent control seems largely governed by the state of the available technology and the economic cost of its application. From both standpoints, nuclear plants appear to have an advantage; that is, the technology for the control of radioactive emission is more developed and, as suggested by Lane,[12] will probably be less costly than that for the comparable control of the several conventional pollutants emitted from fossil-fueled plants, particularly for advanced types of reactors.

What this means is suggested by the comparison of the respective fuel requirements and of the principal types and amounts of atmospheric pollutants released from various 1000-MW(e) plants using coal, oil, gas, or nuclear fuel, as shown in Table 3. The data for fossil-fueled plants are calculated from those published by Terrill, Harward, and Leggett[13] and, for nuclear plants, from those reported for 1969 by the Division of Compliance of the AEC.[14] The data for radioactive noble gases are from Ref. 15. As originally suggested by Eisenbud and Petrow, on the basis of the much greater health significance of radium nuclides, the amounts of radioactivity released from conventional plants are biologically comparable to those released from nuclear plants.[16] It is apparent from Table 3 that to meet projected power needs with fossil-fueled plants would require releasing millions of pounds of obnoxious agents, including some radioactivity, to the environment for years to come during the operational lifetime of these plants.

Table 3 Effluents from 1000-MW(e) Electric-Power Stations

	Type of Fuel			
	Coal	Oil	Gas	Nuclear
Annual fuel consumption	2.3×10^6 tons	460×10^6 barrels	6800×10^6 ft^3	2500 lb*
Annual release of pollutants,† millions of pounds				
Oxides of sulfur	306	116	0.03	0
Oxides of nitrogen	46	48	27	0
Carbon monoxide	1.15	0.02		0
Hydrocarbons	0.46	1.47		0
Aldehydes	0.12	0.26	0.07	0
Fly ash (97.5% removed)	9.9	1.6	1.0	0
Annual release of nuclides, Ci				
1620-year ^{226}Ra	0.0172	0.00015		0
5.7-year ^{228}Ra	0.0108	0.00035		0
10.8-year ^{85}Kr + 5.3-day ^{133}Xe	0	0	0	
Radioactive noble gases‡				
PWR §				600
BWR §				1.11×10^6
^{131}I	0	0	0	
PWR §				0
BWR §				0.85

* From a fuel reserve of approximately 27,500 tons.

† From Ref. 13.

‡ For a PWR with greater than 1 month gas holdup, these gases would be 10.8-year ^{85}Kr and 5.3-day ^{133}Xe. The typical 30-min-holdup and diffusion mixture from a BWR is composed primarily of 1.3-hr ^{87}Kr, 2.8-hr ^{88}Kr, 9.2-hr ^{175}Xe, and 17-min ^{178}Xe (from Ref. 15).

§ Calculated from average of releases during 1969 as reported in Ref. 14; yearly totals estimated for those plants with less than 9 months of full-power availability.

The clean-air advantages of nuclear plants are clearly shown in Table 4, which is also partly from Ref. 13 and partly from Ref. 14. Table 4 shows the volume of air required to dilute the yearly amount of released air effluents to suggested conventional-pollutant concentration standards or to established radiation protection standards.

It should be noted that a plant stack release limit for radioactive noble gases is based on ground-level dose and not the concentration per se. However, the Table 3 comparison remains valid insofar as the dose is closely related to the ambient radioactive gas concentration at and beyond most plant-site boundaries. One way of interpreting the generally smaller dilution volume of nuclear reactor plants is to say that, on the average, they release lower average concentrations of deleterious agents relative to accepted protection standards than do fossil-fueled plants.

The air pollutants from fossil-fueled plants are perhaps reason for greater concern when seen in the

Table 4 Volume of Air Required To Meet Concentration Standards for Yearly Emission from a 1000-MW(e) Plant

Type of plant	Pollutant	Standard*	Discharge quantity*	Dilution volume required to meet standard, 10^9 m^3
Coal†	Sulfur dioxide	0.1 ppM‡ 0.025 ppM§	306×10^6 lb	531,000 2,120,000
	Fly ash (97.5% removal)			
	^{226}Ra	0.1 pCi/m^3	0.0172 Ci	172
	^{228}Ra	0.3 pCi/m^3	0.0108 Ci	36
Oil†	Sulfur dioxide	0.1 ppM‡ 0.025 ppM§	116×10^6 lb	202,000 810,000
	Nitrogen dioxide	2 ppM	48×10^6 lb	5,770
	Fly ash (97.5% removal)			
	^{226}Ra	0.1 pCi/m^3	0.0015 Ci	1.5
	^{228}Ra	0.3 pCi/m^3	0.0035 Ci	1.2
Gas†	Sulfur dioxide	0.1 ppM‡ 0.025 ppM§	0.03×10^6 lb	45 180
	Nitrogen dioxide	2 ppM	27×10^6 lb	3,220
Nuclear¶	^{85}Kr + ^{133}Xe	300,000 pCi/m^3	PWR, 600 Ci	2.0
	Short-lived noble gases + ^{85}Kr + ^{133}Xe	330,000 pCi/m^3	BWR, 1,110,000 Ci	3,360
	^{131}I	100 pCi/m^3 for inhalation	PWR, 0 BWR, 0.85 Ci	0 8.5
		0.2 pCi/m^3 for air, grass, and milk	PWR, 0 BWR, 0.85 Ci	0 4,250

*1 ppM = 1 part per million = 1/1,000,000.
1 pCi = 2.2 radioactive events per minute.
1 Ci = 2,200,000,000,000 radioactive events per minute.

†Calculations based on Ref. 13.

‡1-hr exposure.

§Long-term average exposure.

¶Calculated from average of releases during 1969 as reported in Ref. 14; yearly totals estimated for those plants with less than 9 months of full-power availability.

context of the total emission from all conventional air-pollution sources, as tabulated below:[13]

Total	~125 × 10^6 tons
Source or pollutant	
Carbon monoxide	65 × 10^6 tons
Sulfur oxides	23 × 10^6 tons
Hydrocarbons	15 × 10^6 tons
Nitrogen oxides	8 × 10^6 tons
Particulates	1.2 × 10^6 tons
Electricity generation	12.5% of total, including most of the sulfur oxide emission

A National Research Council committee on pollution has calculated that the total cost attributable to these air pollutants is $13,000,000,000, or $65 per capita.[17] Starr has calculated that these air pollutants result in about 20,000 deaths per year.[6]

As shown in Tables 3 and 4, the principal air effluents from nuclear reactors, in particular the boiling-water (BWR) type, are the fission-product noble gases, xenon and krypton. Although they are not retained in the body, the short-lived nuclides of these gases are of concern insofar as they may contribute to a noncumulative increase in the external radiation background in the local vicinity while a reactor emitting them is in operation. The increases in background attributable to these gases in the vicinity of power reactors have been in general too small to be measurable. Although the increases in external radiation levels in the vicinity of BNL during the years in which the air-cooled Brookhaven Graphite Research Reactor (BGRR) was in operation were well within radiation standards, they were large enough to have been measurable and are therefore useful as a basis from which to estimate the upper limits that may be anticipated from operation of the large nuclear power reactors now coming on line. Since the air used to cool the BGRR was briefly subjected to the neutron flux in the reactor, some of its constituent elements were activated, with the principal product being ^{41}Ar (which has a half-life of 110 min). Its yearly emission rate[18] was about 4,350,000 Ci. This rate was comparable to the release of about twice as many curies of fission-product noble gases since the latter have a lower effective radioactive energy (about one-half that of ^{41}Ar).

To date the radioactive gaseous releases from power reactors have been much smaller than those from the BGRR. In 1969 the largest reported release was 800,000 Ci (4,000 Ci/MW) from the Dresden Nuclear Power Station.[14] This was comparable on an energy basis to about one-tenth of the annual release rate of ^{41}Ar from the BGRR. Other reported releases from BWRs during 1969 were Humboldt Bay Power Plant, 490,000 Ci (7,150 Ci/MW); Big Rock Point Nuclear Plant, 200,000 Ci (2,850 Ci/MW); Oyster Creek Nuclear Power Plant, 7000 Ci (130 Ci/MW*); La Crosse Boiling Water Reactor, 480 Ci (9.6 Ci/MW); and Nine Mile Point Nuclear Station, 55 Ci (4.6 Ci/MW*). The release rates from BWRs with a brief history are much less than those from older plants such as Humboldt Bay and Big Rock Point. The releases from the latter were indicated by Blomeke and Harrington[19] to have been abnormally high owing to the presence of defective stainless-steel-clad fuel elements in their cores. During 1969 the average gaseous radioactive release from pressurized-water reactors (PWRs) was 175 Ci (0.6 Ci/MW).

The increases in ambient gamma radiation when the BGRR was operated at 20 MW are shown in Fig. 1.

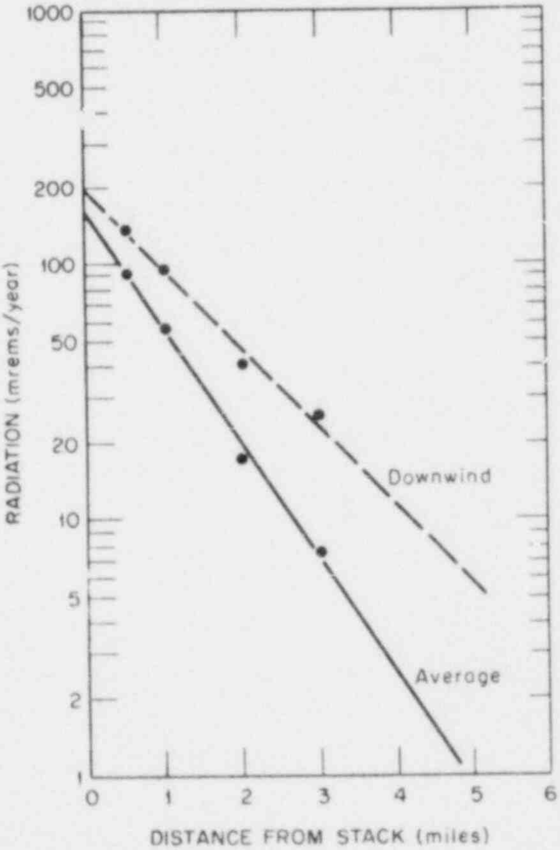

Fig. 1 Downwind and average gamma radiation in the vicinity of the BGRR when operated at 20 MW.

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*Estimated from release data for a partial year of operation.

At the distance to the BNL perimeter, about 1 mile, the average level was 0.055 rem/year. This was equal to about 50% of the measured natural background and was one-tenth of the applicable AEC radiation protection standard for individuals in the general population. At a distance of 2 miles the increase averaged 0.018 rem/year; at 3 miles, 0.007 rem/year.

If the average 1969 release rate of noble gases from BWRs is accepted as typical, an estimated yearly release of 1,110,000 Ci of fission gases would be contained in the air effluent from a 1000-MW(e) BWR. If we assume that conditions of stack height, prevailing winds, and terrain are similar to those which prevailed at the well-ventilated BGRR site, increases in background about one-seventh of those observed at BNL would be anticipated in the vicinity of this plant.

The 2.5 Ci/year of ^{131}I released from the stack during operation of the BGRR may be compared with an estimated 0.85 Ci/year from a 1000-MW(e) plant. The latter was calculated from the average of reported releases for 1969 adjusted for power level.[14] The average ground-level concentration of iodine 1 mile from the BGRR stack was about 0.005 pCi/m^3, or 1/20,000 of the applicable radiation protection standard. Comparable or lower concentrations may be anticipated in the vicinity of power reactors. At no time has ^{131}I or any of the particulate radionuclides released from the BGRR stack in somewhat smaller concentrations been present in detectable concentrations in vegetation or milk collected from nearby dairy farms (between 3 and 5 miles from the stack). There has also been no measurable long-term increase in external background radiation levels over those measured prior to the startup at the BGRR, which suggests that the accumulated deposition of long-lived stack effluent nuclides has been negligible. As also indicated by a recent U. S. Public Health Service survey around the Dresden plant,[20] no measurable deposition of long-lived nuclides would be anticipated in the vicinity of power reactors.

Principally in connection with releases from fuel-reprocessing facilities, concern has been expressed about the worldwide buildup of ^{85}Kr (which has a half-life of 10.4 years) and of tritium (which has a half-life of 12.3 years). Projections made by Cowser, Boegley, and Jacobs[21] of the worldwide accumulations of these nuclides through the year 2000 and of the accompanying increases in dose rates are shown in Table 5. The data for ^{85}Kr were derived from its radiation protection standard and were based on a calculated external dose of 500 mrems/year to the skin of an individual submerged in a semi-infinite cloud of this gas. Dunster recently pointed out that this standard is overly conservative since the accompanying genetic dose for a given concentration of ^{85}Kr would be only 1% of the external skin dose.[22]

Conventional power plants apparently have not contributed materially to the pollution of many of the rivers and lakes in the United States. There is no reason to suppose that nuclear plants will differ in this regard. The amounts of activity release that may be anticipated from a 1000-MW(e) PWR and from a BWR of similar capacity are shown in Table 6. These values are based on the average of the amounts of radioactive mixed fission and corrosion products and of tritium reported to have been released to liquid wastes from power reactors during 1969 (Ref. 14). In general, the amounts of tritium released from PWRs exceed those released from BWRs. The amounts of water required to dilute this released radioactivity to radiation protection standards appear to be small, when compared with the flow of a major river (such as the Hudson, 2.92 × 10^{12} gal/year) or to the volume of the large bodies of water (such as Long Island Sound, 16 × 10^{12} gal inventory and 5.5 × 10^{12} gal yearly inflow) that are suitable for power-reactor siting. The calculations for Long Island

Table 5 Calculated ^{85}Kr and Tritium Production and Dose Rates*

Year	Accumulated ^{85}Kr, 10^6 Ci	Sea-level body-surface dose rate, mrem/year	Accumulated tritium, 10^6 Ci	Body-tissue dose rate, mrem/year
1970	13	0.008	0.32	0.000008
1980	210	0.13	6.3	0.00015
1990	1100	0.65	32	0.00071
2000	3150	1.8	96	0.0021

*From Ref. 21.

Table 6 Calculated Radioactivity in Liquid Effluents from 1000-MW(e) Power Reactors

	Type of activity	
	Mixed fission and corrosion products	Tritium
PWR		
Amount of activity in effluent, Ci	26.5	7.7×10^3
Volume of water required to dilute to radiation standard,* gal	70×10^9	675×10^6
BWR		
Amount of activity in effluent, Ci	27.5	50
Volume of water required to dilute to radiation standard,* gal	72.5×10^9	4.5×10^6
Long Island Sound natural background radioactivity, Ci		
Inventory	600†	3×10^4‡
Yearly inflow	105†	1×10^4‡

*Applicable radiation protection standard = 1×10^{-7} μCi/ml; does not require analysis for individual nuclides.

†Calculated from measured gross beta concentrations, which are assumed to reflect those of ^{40}K but not those of tritium.

‡Calculated, based on one-seventieth of tritium concentration of 500 pCi/liter, as reported by Wrenn.[23]

Sound suggest that the released amounts may also be small compared with the amounts of natural long-lived activity already present in many rivers, lakes, and bays receiving reactor effluents. The amount of tritium released, in the order of 10^2 Ci/year from a 1000-MW(e) BWR, and 10^4 Ci/year from a 1000-MW(e) PWR, should be viewed in the context of a reported cosmic-ray production of 4,000,000 to 8,000,000 Ci/year.[24]

The low-level radioactive liquid-waste experience at BNL is not directly relevant to that of a power reactor situated on a large body of water, since the Laboratory is located on the headwaters of the Peconic River, the flow of which is small by comparison with the volume of water required for cooling by a power reactor. However, the release and nearby downstream concentrations of the BNL liquid effluents as shown in Fig. 2, have been comparable to those from power reactors. At the point of release the effluent has been found[25] to contain about 50% ^{137}Cs, 10% ^{90}Sr, and about 10% ^{60}Co. There has been, if anything, a greater opportunity for reconcentration of these nuclides in the locally limited aquatic environment than would usually be the case. As shown in Fig. 3, in the routine downstream surveillance on the Peconic, small amounts of some of the longer lived radionuclides, such as ^{60}Co and ^{137}Cs,

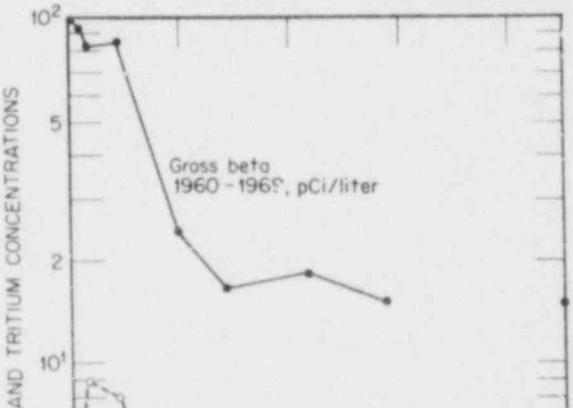

Fig. 2 Average gross beta and ^3H concentrations in Peconic River monthly samples.

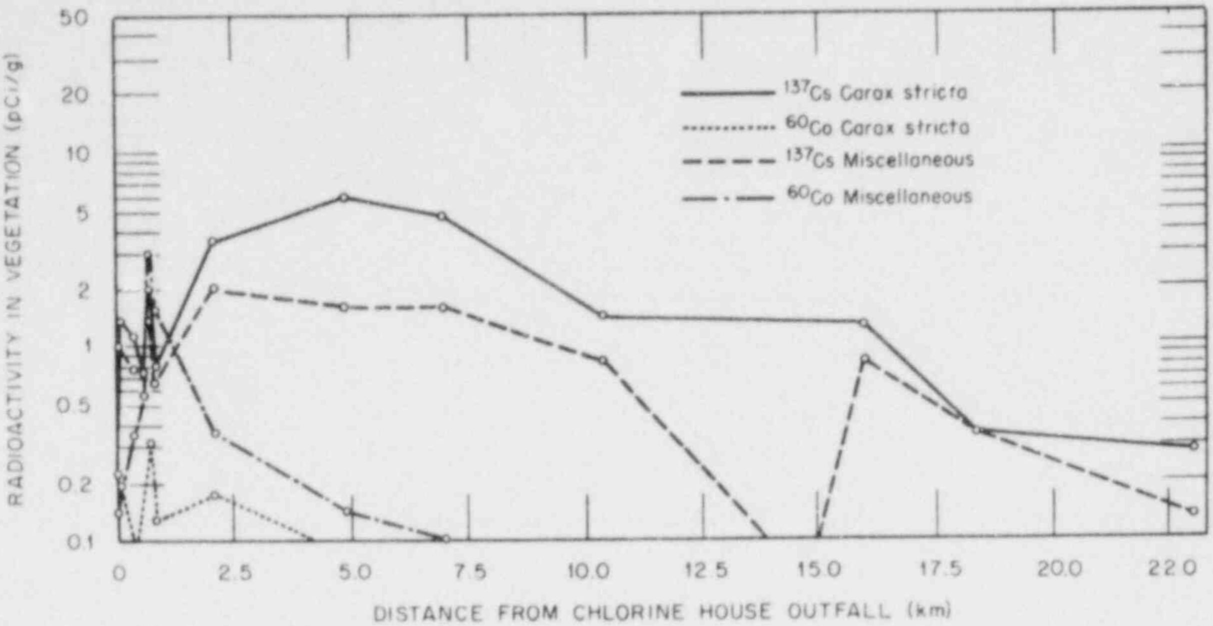

Fig. 3 Radioactivity in Peconic River vegetation in 1969.

known to be present in the BNL effluent, have also been found in plants. Similar concentrations have been found[25] in fish, turtles, and other biota obtained within a few miles below the site boundary. Calculations based on the most generous assumptions about dietary habits suggest that even the most avid angler or watercress fancier could not have ingested more than 25% of the allowable daily intake of these nuclides derived from their radiation protection standards. More reasonable assumptions suggest that the amounts of nuclides actually consumed have been less than 1% of those allowable.

The operating experiences at six power reactors with regard to both gaseous- and liquid-waste discharges were reviewed in 1968 by Blomeke and Harrington.[19] Their study indicated that power-reactor liquid effluents are generally being controlled at a small percentage of release limits, which are based on the radiation protection standard in the receiving body of water. The BNL experience suggests that the accumulation of radioactivity in the aquatic environments of power reactors would be radiologically insignificant. The nuclide of greatest interest, in terms of the anticipated discharge quantities, appears to be tritium. Calculations by way of example can show that, if ten 1000-MW(e) PWRs each discharged 3000 Ci/year of tritium to Long Island Sound, a person obtaining his entire food supply from aquatic animals and plants from the sound would receive a dose increment of 0.07 mrem/year.

RISK ESTIMATES

Some quantitative estimates of these and other risks in terms of the probability of fatal injury or effect per year to an exposed individual are shown in Table 7. The value for 1 mrem/year of radiation was inferred from data published by the International Commission on Radiological Protection (ICRP) that are based on the conservative assumption that effects observed at high dose (in the order of 100 rem) are linear with decreasing dose and dose rate.[26,27] The other estimates are based on Starr's calculations from observed mortality data.[16,28] The risk from the highest radiation levels of a few millirems per year to an individual living adjacent to the boundary of a nuclear reactor site seems trivial in comparison with the many other risks seldom taken into consideration by the populace.

Design options are now available that could reduce the amounts of radioactivity per megawatt of capacity in the effluents of future BWRs and PWRs by one or two orders of magnitude below those now prevailing and used for the comparisons made herein. In view of the already minimal risk connected with the routine release of effluents from plants of current design

Table 7 Annual Probability of Fatal Injury from Radiation and Other Causes

	Individual probability of fatal injury or effect per year of exposure	Refs.
Radiation at 1 mrem/year*	1×10^{-7}	26, 27
Natural disasters	2×10^{-6}	28
Fossil-fueled power plants	4×10^{-6}	28
Electricity	2×10^{-5}	28
Firearms	2×10^{-5}	28
Air pollution†	1×10^{-4}	6
Smoking‡	5×10^{-4}	28
Automobiles	1×10^{-2}	28
All diseases	1×10^{-2}	28

*Estimated from ICRP data, which are based on the conservative assumption that effects observed at higher levels (100 rems) are linear with decreasing dose and dose rate.

†Based on entire population exposed 100% of the time.

‡Based on smoking at a continuous rate.

operated with current practices, significant expenditures or reductions in power-plant reliability to reduce these releases seem difficult to justify. The clamor from political quarters for more restrictive limits on reactor effluents seems especially ironic when the attendant risks are compared with those from firearms and when the difficulties of passage of gun-control legislation are considered.

THERMAL EFFECTS

Although it has come to public attention in connection with the releases of steam-condenser cooling water from nuclear power stations, the so-called thermal pollution is neither new nor unique to nuclear facilities. It has to do more with the growth in numbers and size of steam-turbine generating plants because most suitable hydroelectric sites have already been used. Unfortunately, owing to the inherent nature of the steam cycle, neither fossil- nor nuclear-fueled steam plants use anywhere near all the heat energy released by their fuel to produce electricity, and the unutilized heat is discharged to the environment. The average thermal efficiency is about 33% for fossil-fueled plants,[29] and the ceiling for thermal efficiency is about 40% for a modern fossil-fueled plant. The current light-water-moderated reactor plants are reported to operate at about 32% thermal efficiency.[30] Since essentially none of its heat goes up a stack, this means that a nuclear plant may reject up to 60% more to its steam-condenser cooling water than a modern fossil-fueled station. However, the next generation of nuclear power reactors promises to reach an efficiency of 40% or better.

If there is minimal mixing of the heated-discharge plume, most of the heat released in condenser cooling water is lost to the atmosphere by evaporation within a relatively small zone near each plant. In a recent review of thermal effects, Jaske[31] indicated that impact areas (within which the temperature change is measurable, about 0.75°F minimum increase) of from 2500 acres (~4 square miles) to 3500 acres (~5.5 square miles) should be considered for a nuclear plant. By way of example, the total surface area of Long Island Sound is 939 square miles. If their local thermal effects can be kept within acceptable limits, there should be room for a number of power plants on the Sound and other similarly large bodies of water before alternates for the waste-heat release, such as holding reservoirs or evaporation cooling towers, have to be considered.

SUMMARY

From the evidence to date, the hazard potential of nuclear plants has been greatly overexaggerated by adversaries of such plants. The risks that do exist have been guarded against to a degree that is unparallelled. With regard to routine effluents, nuclear plants produce less air pollution, relative to applicable standards, than do their fossil-fueled cousins. The concentrations of radioactivity in the liquid effluents from nuclear reactor plants are controllable at levels well below radiation protection standards and pose little threat to the environment. Contemporary nuclear plants are somewhat less thermally efficient than modern fossil-fueled plants (although *more* efficient than the average fossil-fueled plant), but the immediate waste-heat problem would seem to be manageable without causing serious environmental problems in large bodies of water. The next generation of nuclear plants, now being designed and tested, promises to be at least as efficient as the best fossil-fueled plants. The AEC and others responsible for the utilization of nuclear plants have been proceeding in a manner that has the public safety and welfare as prime considerations. To date, despite many recent allegations, there is little hard evidence on which to question the judgments of such parties.

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Public Health Risks of Thermal Power Plants

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Abstract: *The results of a study comparing nuclear power plants with oil-fired plants are reviewed and assessed in terms of public-health risks. The study was undertaken as a basic contribution to the state of California's long-range planning on how best to meet the power needs of its growing population. Based on an 8-month evaluation of oil-fired and nuclear plants in urban settings, the authors conclude that the public-health risk from either type of plant is roughly comparable to the hazards to which the public is exposed by uncontrollable natural events—lightning, insect or snake bites, etc. Such deaths occur at an annual rate of approximately one per million of population. A comparison of the risk factors in routine operation of different types of power plants showed that public-health risks from nuclear plants averaged less than one-tenth of the risks from oil-fired plants.*

This article summarizes the results of a comprehensive study[1] comparing nuclear and oil-fired power plants that took a broad view of pollutants and their effects on health. Topics considered in the study included pollutant pathways, risks from steady-state effluents, transient releases, resistance to earthquakes, transportation of nuclear fuels, and acceptable levels of public risk—how safe is safe enough? The work was done for the state of California based on a 1965 policy[2] that "seeks to ensure that the location and operation of thermal power plants will enhance the public benefits and protect against or minimize adverse effects on the public, on the ecology of the land and its wildlife, and on the ecology of state waters and their aquatic life." It is also the policy of the state of California to encourage the use of nuclear energy because such use has the potential of providing direct economic benefit to the public, of helping to conserve limited fossil-fuel resources, and of promoting air cleanliness.

The California State Resources Agency sponsored this study by faculty members of the University of California to provide a factual basis for comparing the public-health risks from fossil fuels and nuclear fuels. The analysis was restricted to oil-fired and nuclear power plants and their associated activities in an urban environment. Gas and coal were not considered, since they are not competitive economic modes for future power expansion in California.

COMPARISON SUMMARY

With both oil-fired and nuclear plants in a typical urban setting, public risks of continuous operation at regulatory limits are in the range of those due to other activities of man which have general societal acceptance. For 1000-MW(e) plants, the risks are in the "low" part of this socially acceptable range for the oil-fired plant (60 deaths per year in a population of 10 million) and in the "negligible" part of the range for the nuclear plant (1 death per year in a population of 10 million).

In both cases the integrated accident risk (averaged over time and all episodic events) is about a hundred-thousandth of the continuous exposure for either the nuclear plant or the oil-fired plant. For the analyzed accidents with equal estimated probability of occurrence, the impact on public health from the oil-fired plant is substantially worse than that from the nuclear plant. For example, the one event in a million years for the oil-fired plant would lead to approximately 700 respiratory deaths in a population center (such as Los Angeles County) of 10 million people, and the one event in a million years for the nuclear plant would result in approximately one death in the same population.

In the worst hypothetical nuclear accident, which has an estimated probability of occurring once in 100 million years, we can assign a maximum consequence of about 5000 cancer deaths per 10 million population (about one-third of the normal annual cancer death rate). Since most of the fatalities resulting from such radiation exposure would be spread over very many years, the effect of such a nuclear-plant accident on public health is unlikely to have much general visibility. It would only be possible to measure the full impact by maintaining lifetime statistics of the exposed population.

For the oil-fired plant, sufficient data are not available to estimate the worse hypothetical case. It is generally known that respiratory ailments can be increased by the synergistic interaction of various "insults" to the system. An extraordinary and rare hypothetical combination of a variety of airborne pollutants, respiratory epidemics (such as influenza), and chronic irritants (including asthmogenic allergens) might substantially increase regional fatalities. Since all these impacts are focused on the respiratory system, it is quite possible that the oil-fired-plant maximum hypothetical accident could cause as many fatalities as the maximum hypothetical nuclear-plant accident—with a probability of occurrence equally low. Omitted from this estimate is the synergistic effect of pollutants from the oil-fired plant other than sulfur dioxide—such as nitrogen oxide, heavy metals (lead, mercury, cadmium, nickel), radioactive elements, carbon monoxide, and carcinogenic compounds. Nitrogen oxide, in particular, may be a serious hazard, but so far little is known about its quantitative health effects. Insufficient data on respiratory effects are available to evaluate the full impact of all the multiple synergistic combinations that might possibly occur.

SCOPE OF THE STUDY

The total public-health risks from electric power should include public injuries and deaths that might arise from the construction and operation of power plants; from the use of electricity; from mining, transportation, and processing of fuel; from disposal of waste products; and from accidents associated with any of these activities. However, this study assumes that the demands for electricity in California will be met; thus it is not an evaluation of the public risks and benefits from electricity nor of the consequences of meeting the demand for it. Also, this study does not consider other areas of social cost, such as thermal discharges, esthetics, utilization of resources, and recreation.

The public-health factors considered include both the risk to an individual (or small groups of individuals) and the risk to the total population. The total (or average) risk must be socially acceptable, with consideration being given to both large- and small-group exposures.

The technology considered in this article is that which can be expected to be available in the near future (next 15 to 20 years) at reasonable costs. Therefore it must either be available now or be operating on a small scale now with reasonable capability of expansion to meet near-term needs.

At the outset, it must be stated that today's coal-fired electric-power plants cannot meet the air-quality requirements of the state and that the technology of pollution control for such plants is not sufficiently developed to assure meeting the needs of the state in the time scale required. Furthermore, it is assumed that California cannot continue to import substantial energy by locating coal-fired power stations out of the state. Natural gas is already in short supply. Accordingly it is necessary to focus attention on oil-fired plants and on nuclear reactors, particularly pressurized- and boiling-water reactors, high-temperature gas-cooled reactors, and fast breeders.

THE EFFECT OF POLLUTANTS ON HEALTH—A PERSPECTIVE

Information on steady-state releases to the atmosphere and to bodies of water is plentiful and is well established for both fossil-fueled and nuclear power plants. However, estimation of the frequency and magnitude of transient or accidental releases is less firm. In either case the correlation of levels of pollutants and public-health risks is primarily based on epidemiological studies, which characteristically represent small samples of the population with many variables that are not as easily controlled as in a laboratory study. Experiments on animals in controlled situations are numerous, but extrapolations to humans do not generally rest on a proven model. Hence the correlation of public-health risks with pollutant levels is on a much less firm basis than the correlation of pollutant emissions with plant size or type.

The central difficulty in comparing the health effects of power plants using different fuels arises from the problem of comparing pollutants with totally different effects on humans. For example, the somatic risks due to sulfur dioxide or radioactive iodine depend not only on the relative quantities involved but also on the nature and severity of their effects on humans. Considering an oil-fired plant alone, the types of pollutants released may change significantly with different fuel supplies.

Despite the lack of precision in our knowledge, some perspective on the relative effects of important pollutants is possible. There are data and known lethal levels that can be used as bench marks for radiation, sulfur dioxide, and nitrogen dioxide. Because of the uncertain data for large populations, the transition from medically perceivable effects to disability and lethality can usefully be indicated as three approximate ranges: natural background, medically perceivable, and lethal. Ranges of medically perceivable effects are about 10 times lower than lethal levels for radiation and sulfur dioxide and about 100 times lower for nitrogen dioxide. "Medically perceivable," as used here, means in vivo clinical measurements on man, in contrast to studies on other forms of life. For all three pollutants the natural background levels are about 100 times lower than the ranges of medically perceivable effects.

There are regulatory limits governing radiation, sulfur dioxide, and nitrogen oxide, each of which applies to an average level to which large populations might be exposed on a continuing basis. However, these are not all implemented in the same way. The limit for average radiation dose to large populations is based on continuous monitoring of reactor-site-boundary effluents. For fossil-fuel pollutants, criteria are focused on off-site ambient levels, which are usually the result of contributions from power plants and other sources, for example, fuel combustion for such other purposes as industrial plants and transportation.

Noting that the AEC limit[3] on reactor-emission levels is the only regulation that is below natural background, it is enlightening to calculate the percent of background permitted by the various regulations. The values are 1, 10,000, and 400% for radiation, sulfur dioxide, and nitrogen dioxide, respectively. Interestingly, much greater excursions above background levels are allowed for pollutants that are less well understood than radiation with respect to their medical implications. This statement is especially true for sulfur dioxide and nitrogen dioxide when information on their possible carcinogenic (cancer-causing) or genetic (altering mutation rate) effects is compared with such information on radiation. This suggests that federal regulations are not consistently or solely determined by the available medical data or public-health criteria. As noted previously, it is relatively easy to compare pollutant levels on a simple stack-effluent basis, for example, but it is more difficult to correlate the various effluents with risks to public health. (Appendixes I and VI of Ref. 1 review this issue in detail.)

The cellular effects of pollutants (stable chemicals as well as radioactive) must also be investigated, and a brief review of the problem will suffice to indicate the ramifications.

Chemical attack on deoxyribonucleic acid (DNA), the genetic material of living cells, can produce mutations—changes in the structure of DNA which are inherited by succeeding cell generations. When the DNA is in a germ cell, the mutation becomes part of our load of mutations; it may result in an increased frequency of oocurrence in children with such major afflictions as cystic fibrosis, sickle-cell anemia, hemophilia, phenylketonuria, or one of the innumerable minor genetic disabilities that are "the differential cause of the death or failure to reproduce of between one-fifth and two-thirds of the persons who escape being killed before reproduction or being prevented from reproducing, by other, purely extrinsic causes."[4] When the DNA is in the developing fetus, the mutation may result in fetal wastage or in one or another of the congenital birth defects that afflict some 6 to 8% of the newborn. The percentage of congenital anomalies varies widely according to the criteria used and ranges from 1 to 14% as reported in a variety of studies.[5-9] When the DNA is in a somatic cell of a child or an adult, the mutation may transform the normal cell to a malignant cell and thus induce a potentially lethal cancer.

At the molecular level, mutations can result from the reaction of a single molecule with a molecule of DNA. Therefore single ionizations can produce mutations or activate latent viruses in individual living cells.

With respect to the cellular effects of pollutants, a general statement that can be made about the magnitude of the hazards associated with environmental agents is that the hazards increase with the level of the agent and the duration of exposure of the population. A more specific statement must be based on detailed data about the action of each agent.

One of the principal modes of action of ionizing radiations on living cells is through the production of free radicals in the water within the cell. These free radicals, chemical species with an odd number of electrons, are highly reactive and attack DNA at many sites. However, radiations are not unique in their ability to initiate free radicals within cells; ozone, for example, when dissolved in water, decomposes to form free radicals. The normal amount of ozone at sea level, 0.02 ppM, if entirely converted to free radicals in the body, would produce about 4000 times more free radicals than are produced by the natural-background radiation levels of about 0.[illegible] rad/year.[10-11] Ozone contents of 0.02 to 0.2 ppM are not uncommon in the Los Angeles basin, and the "alert level" of ozone in smog in Los Angeles is 0.50 ppM. Oxygen is also converted in the body to free radicals by normal metabolic processes. Thus the action of radiation is not qualitatively different from that of other environmental agents, and the risk of increasing radiation levels by the operation of nuclear power stations must be weighed against the qualitatively similar risk of increasing ozone and other pollutants in the atmosphere by the operation of fossil-fuel power plants.

POLLUTANT PATHWAYS

Although little can be said in this brief article about the pathways of pollutants to the public, some of the highlights of the risk-evaluation process can be indicated. Both nuclear and fossil-fueled plants release pollutants to the atmosphere as well as to liquid effluents. Minimization of these releases is common practice, but to expect zero release is unrealistic, even in the future. Thus it is imperative to determine the transport characteristics associated with site meteorology, hydrology, and food chains so that the quantities of pollutants reaching the population can be established.

Meteorological transport is the most important pathway for both particulate and gaseous pollutants from power plants to the population. Such transport leads directly to exposure through inhalation and less directly by ground deposition. Accumulation of detailed meteorological information for a prospective site is a necessary first step. This information includes wind speed and direction, vertical temperature variation (mixing layer thickness), stability class (Pasquill), and their variations with time. Such data acquisitions are already available for the San Onofre, Rancho Seco, and Humboldt Bay nuclear plant sites in California.

The hydrology of the area must be examined from both the standpoint of direct reception of pollutants contained in liquid effluents and also as another link in the chains beginning with meteorology and leading to man. The relative importance of hydrologic transport is strongly dependent on the chemical nature of pollutants and their radioactive or chemical half-lives.

Possible entry of pollutants into food chains or webs can be examined by surveys of the local biogeography and of remote biosystems which could be reached via atmospheric or hydrologic transport. Pollutants of greatest concern are heavy metals and long-lived radioisotopes because other species will not enter food chains or will not maintain their toxicity at the end of food chains, which generally are slow transport paths. This leads to a simplification because relatively few pollutant species need to be followed very far. (Appendix II of Ref. 1 contains a detailed analysis of this subject.)

RISKS FROM STEADY-STATE EFFLUENTS

For a given basis with a fixed volume of air, the question of relative public-health risk attributed to various types of power plants can be posed as follows: How many plants of a given type can be operated without reaching a pollutant concentration level having public-health significance? Quantitative answers to this question can be arrived at in terms of the critical pollutants SO_2, NO_2, and radioactive gases.

Meteorological stagnation of several days' duration is not an uncommon event in several areas of the state. It is a historical fact that air-quality standards are exceeded regularly in some areas and that these occurrences coincide with meteorological stagnation. Increased mortality data for these occurrences are impossible to glean from the public-health data unless the meteorological conditions are extremely adverse and of long duration, resulting in substantial mortality and morbidity, such as the New York, Donora, or London episodes. Nevertheless, lesser occurrences should not be assumed to have no impact.

According to the assumptions used for the study, Los Angeles County can tolerate under current practices 10 oil-fired plants (SO_2), 23 plants fired by natural gas (NO_2), or 160,000 nuclear plants (radioactive gases). Here, each power plant operates at full capacity for 1 day, and no washout or other depletion mechanisms are operative to clean the air during that day. It is notable that 160,000 nuclear power plants of 1000 MW(e) each could operate for 1 day without exceeding an average concentration in the air-basin volume corresponding to legislated limits.

TRANSIENT RELEASES

If the public-health risk of any technological system is to be determined, the frequency and consequences of accidents must be considered. For a well-established system, such as a fossil-fueled power plant, the frequency and magnitude of public-risk accidents can be estimated from historical records. However, since the history of nuclear power plants is short, and there are relatively few such plants, more information is needed to estimate the frequency and magnitude of their releases.

The probabilistic approach to quantifying risk has not been the historical approach to power-plant safety—either fossil fueled or nuclear. Three basic approaches to safety analysis can, however, be identified. The most common is the empirical (or inductive) study of actual performance history to estimate the level of risk of various events. The second is the judgmental (or intuitive) review by experienced professionals to determine if adequate design precautions have been taken. The third, a deductive process, is the estimation of system risk as derived from the reliability of individual components and their interaction. Only the first (empirical) and the third (deductive) approaches provide quantitative results. In the absence of a substantial operating history, nuclear plants have typically been studied by the second (or judgmental) approach. However, the third (deductive) method was used to make a meaningful comparison between oil-fired and nuclear plants. (Appendix III of Ref. 1 discusses this approach in greater detail, with specific calculations for a typical fast breeder nuclear reactor.)

SEISMIC SAFETY OF POWER PLANTS

The methodology used in assessing the seismic safety of power plants (Appendix IV, Ref. 1) provides a basis for determining when typical power-plant designs may be expected to safely withstand the vibratory ground motion to be expected within the state of California. The problems of fault slippage occurring beneath a plant and of tsunamis (seismic sea waves) are not considered here, although they are important considerations in the siting of power plants. Typical nuclear power plants were considered in this evaluation, but the methods could be applied to any type of power plant. This methodology is intended to provide a general basis for preliminary site evaluations. For nuclear power plants, such a study should precede, but cannot replace, the detailed review procedures adopted by the U. S. Atomic Energy Commission.

Results of the seismic analyses indicate that, with reasonable care and attention to detail, satisfactory reactor-containment structures can be designed and built to withstand the earthquake ground motion to be expected at most California sites.

The study also indicates that, in nuclear plants, internal equipment comprising the primary coolant loop (particularly large-diameter interconnecting piping under typical design pressures of 1000 to 2000 psi and temperatures of 600°F) is considerably more sensitive to seismic loading than are containment structures. These systems will require careful analysis, design, and testing for satisfactory performance. For fossil-fueled plants, internal equipment, piping, and fuel-storage tanks are also expected to be critical elements.

Since detailed analytical models of reactor pressure vessels, cores, and control rods are not generally available, no evaluation was attempted during this study. They are potentially critical elements in the dynamic response of nuclear reactor systems and require detailed dynamic analysis. Plant designers and constructors must be prepared to apply new methods of dynamic analysis and to increase the efforts given to experimental verification of power-plant seismic design and construction.

TRANSPORTATION OF NUCLEAR FUELS

A conservative projection was made for the year 2000 (Appendix V, Ref. 1) by choosing the greatest average transportation distance from among the three postulated reprocessing plants in the study, and assuming that every accident that leads to a radioactive release to the environment is a maximum credible accident (all fission gases in the shipping-container plenum are released). The number of serious injuries in the state was found to be less than one in 1000 years for the projected fuel-logistics requirements. This conclusion was based on an average population density and would change in proportion to the actual population density on any chosen route. Two generalizations may be derived from this result:

1. Transportation of spent nuclear fuel does not measurably add to the public-health risks of the power plant.

2. Siting of nuclear power plants does not depend on the location of reprocessing plants, because the two can be decoupled with little or no change in the total risk.

ACCEPTABLE LEVELS OF PUBLIC RISK: HOW SAFE IS SAFE?

Risk, as used in this study, means the quantitative probability of injury (that is, the chance of some specified personal damage occurring in a specified time interval). Public risk is the averaging of individual risks over a large population. The injuries involved may vary from minor annoyances and discomfort (not enough to prevent normal activities), to disabilities that cause reduction in normal productivity (morbidity rate), and to loss of life (mortality rate). Because of the dramatically visible nature of death, public risk is usually conceived of in terms of fatalities or mortality rate. However, the importance to the public welfare of the less visible morbidity rate (disabilities) may be much greater in terms of humanistic, economic, and social values. For example, the annual number of deaths in the United States due to automobile accidents is often quoted with alarm, but one rarely hears of the disabling injuries, hundreds of times as many, which may have an equal or greater social importance.

Since mortality data are most readily available, the quantitative power-plant comparisons presented in the study dealt with the public risk of fatalities, recognizing that this is only indicative of the total risk and that the social cost should include a multiplier to account for associated disabilities. Similarly, a usually neglected but important factor from low-level exposures is the time required for physiologic impairment to develop. If the time for the effects of exposure to develop is long, then only the younger members of the population may have their later life affected (as with smoking). These factors of degree of morbidity, age, and duration of exposure, changing social value as a function of age, and other similar public-health parameters should theoretically be included in any complete study. Unfortunately, basic physiologic and technical data in the air-pollution field are generally so uncertain quantitatively that such a refined analysis is only occasionally justified. Order-of-magnitude answers (that is, within a factor of 10) are usually all that can be expected in such areas of public risk.

A study of the public acceptance of mortality risk arising from involuntary exposure to sociotechnical systems, such as motor-vehicle transportation, indicates that our society has accepted a range of risk exposures as a normal aspect of our life.[12] Figure 1 shows the relation between the per capita benefits of a system and the acceptable risk as expressed in deaths per exposure year (i.e., time of exposure in units of a year). The highest level of acceptable risks which may be regarded as a reference level is determined by the normal U. S. death rate from disease (about one death per year per 100 people). The lowest level for reference is set by the risk of death from natural events—lightning, flood, earthquakes, insect and snake bites, etc. (one death per year per million people).

In between these two bounds, the public is apparently willing to accept "involuntary" exposures (i.e., risks imposed by societal systems and not easily modified by the individual) in relation to the benefits derived from the operations of such systems. The

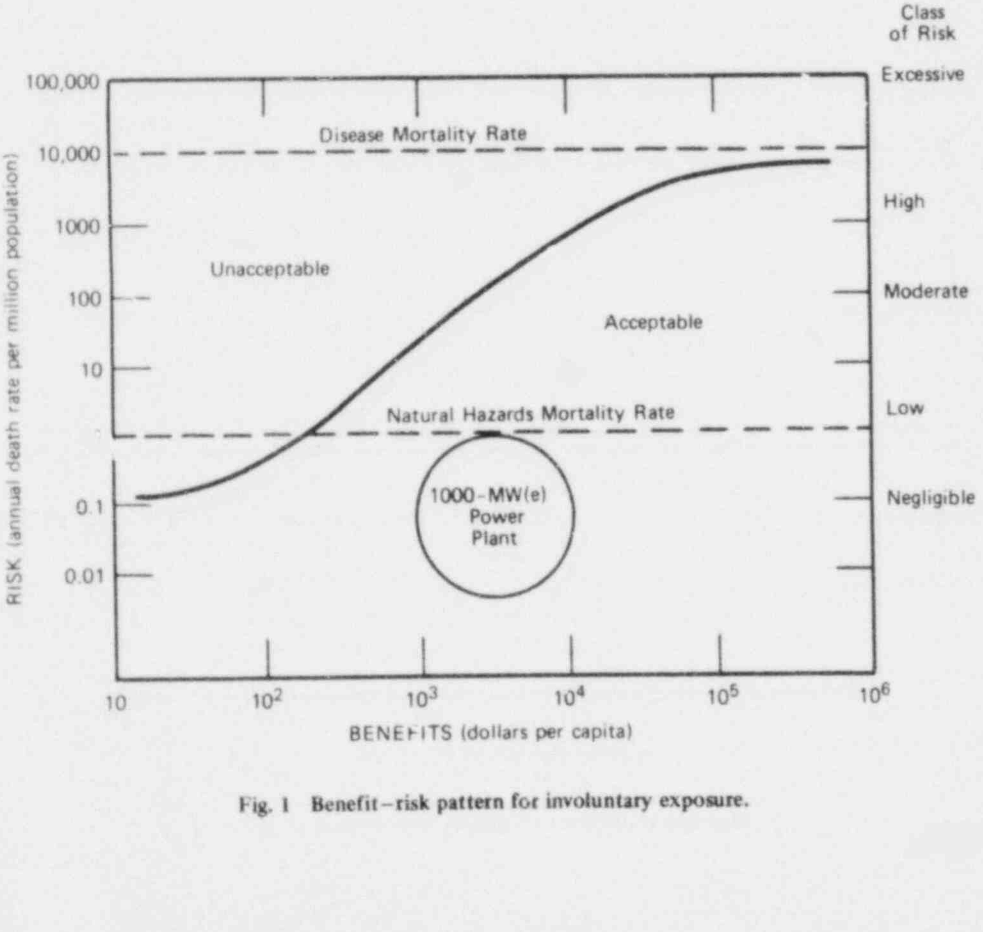

Fig. 1 Benefit–risk pattern for involuntary exposure.

position of electric power plants is well within the acceptable risk range.

PRINCIPAL CONCLUSIONS

If currently available technology is used to protect the public health and safety, the following can be concluded from the study:

The public-health risk from routine operations of electricity-generating plants using nuclear fuel or oil is in the range of the very low hazards to which the public is exposed by uncontrollable events of nature, such as being struck by lightning or bitten by a venomous animal or insect (about one death per year in a million population).

Routine operation of a nuclear plant presents a significantly smaller public-health risk than the routine operation of an oil-fired plant, typically by a factor of 10 to 100.

The public-health risks due to accidental releases from either a nuclear or an oil-fired plant are both of the same magnitude and are about 100,000 times smaller than the risk from routine operation of the plants.

The maximum hypothetical accidents associated with either plant type are not likely to be sufficiently large to have a significant public-health impact when compared with the normal incidence of disease.

Both oil-fired-plant and nuclear-plant structures should be designed to meet the earthquake forces expected at a particular site, and a basis for such a design does exist.

The risk associated with transporting spent nuclear fuel can be made small enough so that the location of the associated fuel-reprocessing installations is a separable factor in siting nuclear power plants.

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Health Effects of Electricity Generation from Coal, Oil, and Nuclear Fuel

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[Editor's Note: This is another in the continuing series of *Nuclear Safety* articles on nuclear power and radiation in perspective. Our complex industrial society is fraught with hazards at every turn—automobiles, polluted air, insecticides, electricity, gases, chemicals, and nuclear radiation—to mention a few. One of the purposes of this series is to portray the impact of radiation in our society in its true perspective.

In this very interesting article on the health hazards associated with electricity generation using various fuels, the authors studied the public-health risks from uranium, low-sulfur oil, and coal power plants. The conclusions they reached regarding the risks associated with each fuel were based on multiple regression analysis in much the same way as other investigators have associated lung cancer with cigarette smoking. However, the editors would like to caution the readers that, although regression analysis is a useful tool that is frequently used in instances involving many interrelated parameters, causation is not proved by such correlations. Rather, the correlations are suggestive of a possible cause–effect relation that must be proven by other means.

Other facts that the reader should bear in mind are: (1) the relatively limited operating experience with nuclear reactors has been so good that no experience has been accumulated regarding the consequences of low-probability accidents (although this relation is being evaluated by the Rasmussen Study, AEC Press Release R-252, June 25, 1973); and (2) effluent releases in both nuclear- and fossil-fueled plants are being cleaned up as a result of recent environmental legislation, and experience with the improving effluent-cleanup technology is limited.

Despite these qualifications, the editors believe that this article brings together such significant information that is needed for such a study, and, given the reservations and assumptions noted, the conclusions are justified.]

Abstract: *Occupational- and public-health effects of generating electricity from coal, uranium, and oil are compared, with particular attention given to accident and chronic-disease rates for fuel extraction and airborne emissions from power and reprocessing plants. It is concluded that uranium offers less of a health hazard as a fuel than coal. The analysis is based on current operating practice; however, advances in technology can be expected to reduce both the occupational- and public-health risks from these fuels.*

The threat of black lung and other respiratory diseases to coal miners, the health effects of air pollution, and the radioactive releases of nuclear reactors have received national publicity in recent years. Each is, to a considerable extent, a consequence of electricity generation. This article focuses on the health effects of generating electricity from three fuels, with particular attention given to light-water reactors (LWRs) and steam plants fueled by coal and to a lesser extent by oil. Since experience with other types of reactors is much more limited, they will not be considered here. Natural gas is excluded from the analysis and oil is only partially treated because they are not likely to be important sources of fuel in the future. Hydroelectric sites are largely used up and thus are of little future incremental consequence. A major topic not analyzed in this article is the optimal growth rate of the demand for electricity.

Coal miners experience accidents as well as pneumoconiosis (black lung) and other chronic respiratory diseases. Accidents also occur in transporting coal from the mine to the generating plant, and, at the plant, additional accidents, such as boiler explosions or the release of noxious fumes, can harm workers. Finally, the normal effluents of the burning—heat, SO_2, NO_X, CO, particulates, and some radioactive substances—pose a threat to surrounding residents.[1,2]

Uranium miners are also threatened by accidents and by disability resulting from inhalation of dust and radioactive particles. Although much smaller volumes of material are transported, there are still potential hazards from transportation accidents. Persons engaged in the milling and fuel-preparation processes are subject to normal industrial accidents and to the risk of radiation exposure (especially from breathing radioactive dust). Nuclear reactors contain large quantities of radioactive substances, a very small proportion of which is released to the environment during routine operation of the power plant. The effluent normally consists of heat, noble gases, tritium, and other radioactive wastes and contributes little to the level of background radiation. There is also a small, but finite, potential for accidental release of more substantial amounts of radioactivity from the power plant. Finally, reprocessing the fuel releases radioactive substances and thus produces additional radiation hazards.

Oil extraction carries the risk of drilling and pumping accidents. The transportation of oil has a small accident rate. The refining operation is susceptible to explosion and fire, as well as to the normal release of air pollutants; for example, petroleum refineries are responsible for a significant amount of

CO, SO_2, and hydrocarbons.[3] Finally, there are generation accidents and normal effluents similar to those associated with coal, although the quantity of emissions is lower per megawatt-hour of electricity.

Morgan,[4] Starr,[5] and Sowby[6] approached the problem of evaluating risks from generating electricity by calculating the probabilities of various accidents or other adverse consequences and comparing these with other activities that people pursue. Some of these calculations are informative but are subject to great reservations since there is no good way of estimating such low-probability events as major nuclear-generator disasters. This is especially true when an attempt is made to incorporate events that are believed to have probabilities of 10^{-3} to 10^{-6} per reactor per year.

The primary approach of this article is (1) to compare the documented occupational-health effects of "extracting" fuel in the forms of coal, uranium, and petroleum, with respect to both accidents and chronic diseases (in terms of disability days per million megawatt-hours of electricity generated), and (2) to compare the calculated public-health effects of the normal operation of power plants fueled with coal, uranium, and oil (both in terms of the dilution volumes required for emissions to meet public-health standards and in terms of estimated dose–response relations for chemical and radioactive emissions). In general, the health effects of spent-fuel transport, radioactive-waste storage, and other radioactive releases associated with the nuclear cycle are treated only qualitatively; insufficient data for quantitative analysis have been accumulated in the short history of many of these operations.

The total analysis results in the conclusion that electricity generation from uranium offers less of a public-health hazard than that from coal or oil. Although the occupational-health effects of oil are less than those of coal, the comparison between oil and uranium is not as clear-cut; however, occupational-health risks appear to be higher for uranium because of radiation exposure to employees and miner silicosis. The framework for the comparison is set out systematically, but, since not all the relevant factors could be estimated with confidence, the analysis must be considered preliminary.

The comparison is based on existing plants, but, since technology is advancing rapidly, this comparison is not likely to be valid 10 or even 5 years hence.[7-9] However, the qualitative conclusions are likely to hold in the future and to be better predictors than the forecasts of untried technologies.

OCCUPATIONAL-HEALTH EFFECTS OF EXTRACTION PROCESSES

There are certain inherent dangers, in terms of both accidents and chronic diseases, in extracting fuels from the earth—that is, in mining coal; in mining and milling uranium; and in drilling for, producing, and refining petroleum. The extent of the risk is shown by the following statistics.

Accident Rates

Table 1 presents comparative data from 1965 to 1969 on injuries and rates of injury for coal-, uranium-, and oil-extraction processes.[10,11] Column 5 presents the disabilities per million megawatt-hours of electricity produced in 1969; this calculation involves assumptions explained below.

In 1969, 237×10^6 man-hours were spent mining coal.[10] At an average severity rate of 8441 disability days per million man-hours, about 2,005,000 disability days could be expected from accidents. The average accident rates for 1965 to 1969 were used instead of the actual 1969 experience in order to smooth the fluctuations that might occur from year to year. Since

Table 1 Comparative Data on Accidents Occurring in Various Extraction Processes from 1965 to 1969

Process	Accidents per year		Injuries per 10^6 man-hours	Disability days per 10^6 man-hours	Disability days per 10^6 MWh, 1969
	Fatal	Nonfatal			
Coal mining	246	10,251	43.5	8441	1545
Uranium mining	8	272	39.8	8702	157
Uranium milling	⅓	59	17.0	1091	
Oil drilling and production	1104*		10.2	1176	135
Oil refining	1060*		5.5	793	

*Includes both fatal and nonfatal accidents.

about 54.3% of the coal mined in 1969 was used for electricity generation,[10] some 1,089,000 disability days would be estimated to result from the amount of coal mined to generate electricity. This coal generated some 705×10^6 MWh;[12] thus approximately 1545 disability days per million megawatt-hours of electricity generated by coal would be estimated to result from coal-mining accidents.

In 1969, 7.80×10^6 man-hours went into uranium mining;[10] thus about 67,900 disability days would be expected from accidents. Uranium milling absorbed 3.59×10^6 man-hours and would be estimated to generate 3911 disability days. In 1969, 11,870 short tons of U_3O_8 were produced domestically,[10] of which about 4700 tons were sold for electricity production.[13] However, not all of this amount was consumed during the year. New reactors were activated, and there was presumably some buying for inventory. The U_3O_8 requirements per electrical megawatt have been published for a number of LWRs[14] and can be used to estimate the consumption of uranium in electricity production. For these reactors, an average of 0.633 short ton of U_3O_8 is required to provide fuel for the initial core and 0.166 ton for the annual reload per electrical megawatt. Thus the annual fuel requirement would be 0.182 ton/MW(e) when averaged over the life of a plant (assuming a plant life of 30 years).† During 1969 the total electricity generated by nuclear plants was 14×10^6 MWh.[12] Thus, assuming utilization at 80% of capacity, an estimated 364 tons of U_3O_8 were required to generate electricity in 1969, about 3.06% of the uranium mined in that year. An estimated 2200 disability days would be expected to result from uranium mining and milling for electricity production, approximately 157 disability days per million megawatt-hours of electricity.

In 1969, some 307×10^6 man-hours were spent in drilling, producing, and refining petroleum.[11] At 1969 levels of employment, 285,000 disability days would be expected to result from accidents in these activities. Since 7.71% of petroleum produced domestically and 6.03% of petroleum refined domestically in 1969 were used to generate electricity,[10] approximately 19,000 disability days would be expected from drilling, producing, and refining petroleum to generate electricity. Since this petroleum generated some 144×10^6 MWh of electricity,[12] 135 disability days per million megawatt-hours would result from these operations.

The contrast between coal and the other two fuels is striking. In terms of estimated disability days per million megawatt-hours, coal had 1545; oil, 135; and uranium, 157. In terms of mining and associated accidents, electricity generated by coal carries almost 10 times the health cost of electricity generated by uranium.

However, a note of caution must be entered. The uranium industry is small enough that the current estimates may not approximate the experience if nuclear power generation is expanded substantially. Many of the values used in the calculation are estimates rather than actual rates.

Chronic Diseases

A large body of literature is focused on establishing an association between coal mining and respiratory disease.[15-28] Although occasional contrary evidence is reported, there is no doubt that such an association exists. However, the incidence of chronic respiratory disease is difficult to estimate since primary reliance has been placed on pneumoconiosis (black lung) as diagnosed by X-ray evidence.[29] This evidence is not highly correlated with respiratory disability.[16,18,25]

Little of the literature reports an increase in disease prevalence or severity of symptoms by years of mining. The dose–response relation is difficult to estimate for a number of reasons, such as the selection process, which causes the more sensitive individuals and those developing symptoms to stop mining. Thus a simple tabulation by years underground should lead to an underestimate of the adverse effects of coal dust. Lainhart[26] reported a linear increase in the prevalence of pneumoconiosis among working miners with 15 or more years of underground experience. He estimated the following formula for the percentage of workers with definite pneumoconiosis: $y = -12.12 + 0.95$ years. Similarly, the incidences of severe dyspnea (shortness of breath) and persistent cough were found to increase with years underground.

Henschel[24] observed that measures of ventilatory function fall more rapidly with years underground than one would expect from aging alone. He found a close association between reduction in ventilatory function and degree of dyspnea, but only a partial relation between X-ray evidence of pneumoconiosis and ventilatory function.

The simple regression shown above can be used to illustrate the chronic disease and presumably the disability cost of coal mining. According to that

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†The amounts of U_3O_8 cited are net amounts and allow for the recovery of uranium from reprocessing spent fuel.

regression, the cost of an additional year of underground mining to workers with 13 or more years of experience is a 0.95% increase of these workers with definite pneumoconiosis. Since each worker mines enough coal to generate 9900 MWh of electricity per year, the disability cost of this electricity for all working miners (strictly in terms of pneumoconiosis) is one additional man in 145 with definite pneumoconiosis.

This estimate is not worthy of great confidence, since it neither controls all the relevant variables nor takes account of other disabilities, such as increased bronchitis and emphysema, or other ventilatory symptoms, such as increased dyspnea. However, the estimate at least illustrates how the calculation should be carried out when better estimates of these factors are available.

It is interesting to contrast this chronic disability rate with the previous estimate of accident disability; for example, mining enough coal to produce 10^6 MWh of electricity is estimated to increase chronic disability by 0.7 additional definite case of pneumoconiosis and to increase accident disability by 1545 days. Thus, if pneumoconiosis resulted in total disability, it could be much more important than the accident rate. Accidents cost approximately 6 man-years of disability per million megawatt-hours, whereas 0.7 case of pneumoconiosis may cost up to 20 years of disability, assuming that pneumoconiosis is totally disabling.

Uranium miners should also be expected to have abnormal rates of chronic disability because of occupational exposure to dust and to radon and its daughters. One aspect of the dust is similar to that for any hard-rock mining: the dust produces silicosis in miners' lungs. A second aspect is more peculiar to uranium mining: the mines are radioactive and therefore expose miners to whole-body radiation. In addition, the dust particles are small and radioactive and thus give an especially high dose to the lungs.[30] Many studies have shown an association between uranium mining and ventilatory dysfunction and between uranium mining and lung cancer.[31-37]

Archer and Lundin[33] estimated a dose–response curve for lung cancer from all available data (European and U. S. miners) and concluded that a linear relation fits the data as well as a quadratic form (at least below 5000 WLM*) and that 1000 WLM will increase the lung cancer rate by 26 cases per year per 10,000 miners. Since the median exposure level of U. S. miners is slightly in excess of 1.0 WL,[30] 1 miner-year is approximately 12 WLM, or 1.2% of 1000 WLM. Thus 1 miner-year is estimated to increase the incidence of lung cancer by 3.1×10^{-5} case per year.

A miner-year produces enough uranium to generate 105,000 MWh of electricity; thus the cost of 10^6 MWh of electricity is 3.0×10^{-4} case of lung cancer per year. This health cost is only with respect to lung cancer and does not include other chronic disability, such as silicosis.† This figure for lung cancer can be compared with the health cost of coal mining in terms of pneumoconiosis. One million megawatt-hours of electricity generated by coal was estimated to cost 0.7 definite case of pneumoconiosis; uranium mining leads to only $3.0 + 10^{-4}$ case per year of lung cancer per million megawatt-hours.

Another way of comparing coal and uranium miners is to examine the total death rates (excluding violent death) for each. Enterline[20] presented data on death rates for coal miners and operatives vs. all male workers, by age, for 1950. Coal miners and operatives had excess mortality ranging from 23% for 20- to 24-year olds to 122% for 60- to 64-year olds. The entire group yielded an excess mortality rate of 67%.

Lundin et al.[34] presented data on uranium miners over the period 1950 to 1967. Expected death rates were calculated for these miners from age–sex–race–cause specific mortality rates for the states in which the mines were located. Excluding violent deaths, uranium miners had 39% excess mortality; among uranium millers, however, total mortality was no greater than expected.[38] Although there was a significant excess in deaths from malignant diseases of the lymphatic and hematopoietic tissues other than leukemia, the numbers were small.

The crude comparison is that coal miners had 67% excess mortality, and uranium miners had 39%. Little confidence can be placed in this comparison since no allowance is made for income levels and other factors affecting mortality. However, it seems likely that the qualitative conclusion is correct; that is, even aside

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*The working level (WL) is 1.3×10^5 MeV of potential alpha energy from radon daughters per liter of air. A WLM is 1 month of mining exposure at this level.

†Investigations during the late 1950s and early 1960s showed that silicosis among uranium miners was only about one-third as prevalent as pneumoconiosis among coal miners.[26,39] However, this was primarily a reflection of differences in length of mining experience between the two groups, the coal miners on the average having much longer mining experience. For workers with more than 20 years of experience, the rate among uranium miners was higher than that among coal miners. The rates for miners with the longest work experience may somewhat reflect higher dust concentrations allowed in the mines during earlier years.

from violent death, coal mining is more injurious to the health than is uranium mining.

A uranium miner produces enough uranium during a year to generate 10.6 times as much electricity as a coal miner produces in a year. This means that, in terms of electricity produced, the excess death rate of coal mining is roughly 18 times that of uranium mining. This factor would be reduced somewhat by the inclusion of other steps in the uranium fuel cycle.

A qualification is needed here since the comparison is essentially between deep mining of coal and deep mining of uranium. Only about half of either fuel is mined undergound.[10,40] Strip mining already supplies almost half of the coal and involves much lower accident rates and chronic disability rates. Insofar as strip mining becomes more important in the future, accident and disability rates will shift in favor of coal. Automation of deep mining would also have a strong effect on these rates. However, the much stricter control measures instituted to reduce radiation exposure of uranium miners should lower the incidence of lung cancer among that group in future years.[30]

OTHER OCCUPATIONAL-HEALTH EFFECTS

Although some data are available on transportation accident rates,[11,41-45] they are not completely differentiated by commodity. Data on the number of fuel shipments can be found in Refs. 40, 44, and 46. Since the number of coal shipments per electrical megawatt is many times the number of uranium shipments,[40,44,46] more accidents and therefore more accident disability must result from coal transportation, even allowing for a shorter average transport distance for coal. The only contradiction would occur if transportation accidents involved breaking the vessel that holds the nuclear fuel (particularly spent fuel) and thus releasing significant radioactivity. No significant radiation exposure has occurred as a result of transportation accidents, and extraordinary care is taken to build transportation vessels that are unlikely to be breached. Brobst[41] has estimated that a truck driver involved in a transportation accident while transporting spent reactor fuel is thousands of times less likely to be injured from radiation exposure than he is from nonradiological crash effects.

Statistics on accidental injury and disability rates for individual segments of the private atomic energy industry, such as reactor operation and maintenance, have been published[47] by the Bureau of Labor Statistics for 1965 to 1970. Data on numbers of employees in these areas are available[48,49] for 1963 to 1970. However, manpower and accident rates for operation and maintenance of fossil-fuel-burning plants are not as well documented. Chronic-disease rates for employees in these activities are also not well documented. The few studies that have examined mortality of public-utility employees or uranium processors have not found rates higher than expected, given the experience of other types of workers.[50,51]

Added cancer mortality risks from some of these activities can be estimated from data on occupational exposure to employees of AEC licensees.[52] The total dose from external radiation reported for a sample of employees involved in activities relating to reactors, fuel processing, waste disposal, and packaging and transporting was about 2800 man-rems in 1969, many times the total exposure to the public from the radioactive stack releases of nuclear power plants.[52,53] An additional 1050 man-rems can be inferred for licensees not included in the sample. (Internal radiation doses were also received by these employees but were not evaluated in Ref. 52 because of the difficulty of determining them.) According to dose–response estimates for radiation-induced cancer which are outlined later in this article, the cost of this radiation exposure would be expected to be about 0.02 to 0.05 death per million megawatt-hours of electricity produced in 1969. However, most of this dose was received by employees involved in fuel processing. Since the amounts of fuel prepared in 1969 exceeded the amounts consumed in generating electricity, and the amount of power-plant fuel reprocessed was less than that consumed, it is difficult to determine the actual mortality risk per million megawatt-hours of electricity. Another problem is that some employees in these activities are not included (such as enrichment-plant employees). Nevertheless, the available data are sufficient to indicate that the occupational-health costs from radiation exposure to employees related to nuclear power production are outweighed by the occupational-health costs to coal miners from accidents and chronic-disease mortality.

PUBLIC-HEALTH EFFECTS OF NORMAL OPERATION OF POWER PLANTS

The normal operation of electric-power plants, both nuclear and fossil fueled, results in the release of heat, radioactivity, and chemicals. Radioactive and chemical effluents have public-health implications, which will be compared. Thermal releases may have various ecological effects, but they have no direct human-health effect and thus are not treated here.

Radioactive and Chemical Effluents

Combustion of fossil fuels produces major quantities of air pollution.[1,2,46,54,55] The generation of electricity from burning coal produces a major proportion of the SO_2, NO_x, and suspended particulates in cities where coal is the principal fuel. In addition, trace amounts of heavy metals and carcinogenic hydrocarbons, such as benzo(a)pyrene, are released.[56-58] Trace amounts of radioactivity in the form of thorium, uranium, and radium have also been found in the ash released from coal combustion, the amount emitted being inversely proportional to the efficiency of the ash-collection mechanism.[59,60]

Most nuclear reactors currently being built are of either the boiling-water type (BWR) or the pressurized-water type (PWR). Most currently operating BWRs release much more gaseous radioactivity, generally in the form of noble gases, whereas PWRs release more liquid radioactive waste, principally tritium. A small amount of radioiodine is also released in gaseous effluent, particularly by current BWRs.[61-65]

The most recently designed BWRs are expected to release much lower quantities of gaseous effluent, because provisions has been made for much longer holdup [illegible] these effluents before release to allow most of the radioactivity to decay, as is currently practiced at operating PWRs. In addition, application of the recently proposed stricter discharge limits can be expected to reduce the quantities of radioactive effluents discharged from the LWRs having the highest release levels.[66] Similarly, coal gasification and air-pollution abatement measures will lead to much lower releases of air pollutants from plants burning fossil fuels.

A number of studies have attempted to compare the radioactive and chemical pollutants released per unit of electricity generated from fossil-fueled and nuclear power plants.[46,54,59,60,67-71] However, the comparison is complicated by the different types of reactors, variations in composition of the fuels, the efficiency of the ash-collection equipment for fossil-fueled plants, differing waste-treatment systems, and adjustments for biological activity and the half-lives of the isotopes released.

Martin, Harward, and Oakley[60] presented a careful comparison of radioactive stack releases from power plants, extending earlier work by Eisenbud and Petrow.[59] The amounts of radioactive material released by oil-burning generators are almost undetectable. When coal-burning generators are compared with nuclear generators, problems arise because the radioactive release takes such different forms. Some of the radium and thorium isotopes released from coal combustion are extremely long lived and chemically active. The radionuclides in the ash which are water soluble are assumed to pose a threat to bone, and those which are insoluble are considered to present a threat to the lungs. For nuclear plants the whole-body exposure from noble gases released from the stack is considered most significant. These isotopes are relatively short lived compared with ^{226}Ra in coal ash.

For coal-fired and nuclear power plants, Martin et al.[60] calculated the dose that a new 1000-MW(e) plant would give to individuals in the vicinity of the plants under specified meteorological conditions. To take account of the different forms of radioactive effluent, they calculated the dose as a fraction of the maximum permissible dose recommended by the International Commission on Radiological Protection (ICRP), with a correction for the effect of different stack heights on distribution of radioactivity. Their results, based on 1968 and 1969 data, indicated that a coal-burning plant would apparently pose about 410 times the threat of a PWR, whereas a BWR would pose about 180 times the threat of a coal-burning plant in terms of radioactive releases through the stack.

Terrill, Harward, and Leggett[54] compared power plants in terms of the volume of air that would be required to dilute their stack effluents each year in order to meet conventionally accepted concentration standards. Hull[67] updated these dilution factors, making use of radioactive emissions from a much larger sample of plants and imposing a more stringent standard on the concentration of chemical pollutants.* On the basis of 1969 releases, these factors corroborated the conclusion reached by Martin et al. that the radioactivity released from coal-burning plants was more significant than that from PWRs but less significant than that from BWRs. Since that time, however, Hull has further updated these factors to reflect 1967 to 1971 nuclear power-plant releases and more recent standards for air-pollutant concentrations.[72] Included in his study were SO_2, NO_2, CO, hydrocarbons, particulates, and various radionuclides; however, only SO_2, particulates, and the radionuclides will receive

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*These studies, based on quantities being emitted from the stack rather than on doses provided, do not allow for differential residence times of pollutants in the atmosphere.

attention in this article. The updated dilution factors for these pollutants are presented in Table 2, except that the discharge quantities for LWRs have been recalculated to reflect only 1971 releases. According to these more recent calculations, SO$_2$ from coal-fired plants is the residual requiring the most dilution.† The SO$_2$ from oil-fired plants requires less than half as much dilution; that from gas-fired plants, substantially less. Particulates from coal-fired plants and radionuclides from a BWR lacking extended stack-gas holdup also require a significant amount of dilution. However, the 1971 radioactive releases from both PWRs and BWRs would appear to be more significant biologically than those from coal-fired plants (unlike previous comparisons) but less important than the release of SO$_2$.

The above comparison is based on concentration standards that are not necessarily equally stringent for chemical air pollutants and radionuclides. Relative to concentrations at which effects on human health have been inferred from epidemiological studies, the concentration standards for radionuclides appear to be more conservative than those for chemical air pollutants.[69] To meet this difficulty, we will attempt to evaluate the relative hazards to individuals of long-term exposure to these pollutants at the specified concentration standards by using mortality risks derived from such epidemiological studies. The relative mortality risks of airborne effluents from fossil-fueled and nuclear power plants will then be estimated. Although morbidity (illness) risks would be expected as well, they are more difficult to quantify and therefore will not be included in the analysis.

Health Effects of Radioactivity

The amounts of radioactive material released from power plants are typically very small relative to background and medical radiation. Although large doses of radiation have been found to increase the risk of death from leukemia and other cancers as well as the risk of genetic damage, little work has been done which gives evidence for effects of such low-level dosage.[75-77]

A number of investigators have attempted to quantify the relation between radiation dose and cancer on the basis of data on Japanese survivors of the atomic bomb, on noncancer patients treated medically with radiation, and on occupationally exposed groups. Assuming a linear dose–response relation, the National Academy of Sciences (NAS) Committee on the Biological Effects of Ionizing Radiation has estimated[78] that an additional 100 mrems of radiation above back-

Table 2 Volume of Air Required To Meet Concentration Standards for Yearly Emission from a 1000-MW(e) Plant

Type of plant	Pollutant	Standard*	Discharge quantity	Dilution volume, 10^9 m^3
Coal	SO$_2$ (3.5% S)	80 µg/m^3	3.06×10^8 lb	1.77×10^6
	Particulates (97.5% removal; 15% ash	75 µg/m^3	9.9×10^5 lb	6.0×10^4
	Particulates (^{226}Ra)	2 pCi/m^3	0.0172 Ci	8.6
	Particulates (^{228}Ra)	1 pCi/m^3	0.0108 Ci	10.8
Oil	SO$_2$ (1.6% [illegible]	80 µg/m^3	1.16×10^8 lb	6.58×10^5
	Particulates (0.05% ash)	75 µg/m^3	1.6×10^6 lb	9700
	Particulates (^{226}Ra)	2 pCi/m^3	1.5×10^{-4} Ci	0.075
	Particulates (^{228}Ra)	1 pCi/m^3	3.5×10^{-4} Ci	0.35
Gas	SO$_2$	80 µg/m^3	3×10^4 lb	170
	Particulates	75 µg/m^3	1.0×10^6 lb	6050
Nuclear				
PWR	^{85}Kr and ^{133}Xe	3×10^5 pCi/m^3	1.6×10^4 Ci	55
BWR	Short-lived radioactive noble gases	3×10^5 pCi/m^3	1.33×10^6 Ci	4.4×10^3
PWR	^{131}I (inhalation)	100 pCi/m^3	0.15 Ci	1.5
BWR	^{131}I (inhalation)	100 pCi/m^3	6.6 Ci	66
PWR	^{131}I (ingestion)	0.14 pCi/m^3†	0.15 Ci	1 [illegible]
BWR	^{131}I (ingestion)	0.14 pCi/m^3†	6.6 Ci	[illegible] $\times 10^4$

*Environmental Protection Agency National Primary Ambient Air Quality Standards,[73] and AEC Standards for Protection Against Radiation.[74]

†A reduction factor of 700 is applied to the inhalation standard for ^{131}I to allow for reconcentration via the ingestion (air–grass–milk) route.

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†The value for sulfur dioxide emissions from coal combustion, based on coal with a 3.5% sulfur content, overstates the level of emissions that is currently tolerated in major cities.

ground per year per person over many years would ultimately produce between 2000 and 9000 extra deaths from cancer per year in the United States, the most likely estimate being 3500. The risk to occupationally exposed groups from a given radiation dose is lower than the risk to the public because of a different age distribution; the mortality estimates for an occupational dose of 5 rems per year range from 380 to 930 excess cancer deaths per million per year. A dose of 1 rem to bone from ^{226}Ra is estimated to produce 0.11 to 0.16 case of bone cancer per million irradiated adults per year. The risk to bone from ^{90}Sr is considered to be lower. The estimate from 1 rem to the stomach is 0.32 to 0.64 death per million per year, and for 1 rem to the remainder of the gastrointestinal tract, 0.22 to 0.44 death per million per year. No estimate was made by the NAS Committee for the risk to skin, because there is insufficient evidence for skin-cancer induction by low dose levels. For the lung, a 1-rem mean dose to bronchial tissues is estimated to produce 1 case of bronchial cancer per million per year. For a dosage to the thyroid, Otway and Erdmann[79] have estimated a mortality risk per rem of one person per million exposed for all ages. Calculations of radiation effects in this article will be based on these estimates, except that no threshold will be assumed.

The 10 CFR 20 concentration standards used in the Martin et al. and Hull studies have been set by the AEC at levels that would limit dosage to exposed individuals from any one radionuclide to 500 mrems/year in the case of exposure to the whole body; for many radionuclides the standards reflect limits on doses to particular organs, with doses higher than 500 mrems/year permitted in some cases.[74,80] Thus continuous exposure over many years to whole-body radiation from noble gases at the concentration limit would ultimately entail an average mortality risk to individuals of 90×10^{-6} per year (according to the NAS mortality estimate). The concentration standard for ^{131}I limits the dose to the thyroid from inhalation of the radionuclide. However, a stricter limit by a factor of 700 is applied to ^{131}I when allowing for reconcentration via the air–grass–milk route. At the latter concentration of ^{131}I in the air, there is a potential dose to the thyroid of 5000 mrems/year to infants from milk and a lower dose to older individuals;[81,82] the average mortality risk to individuals from this concentration would be less than 0.5×10^{-6} per year.

Health Effects of Air Pollution*

A substantial body of literature of laboratory and epidemiological studies of acute exposure to air pollution has established the fact that air pollution causes ill health and increases the mortality rate.[84-86] However, it is difficult to estimate the dose–response curve from this literature. A wide range of dose–response relations are consistent with laboratory evidence and epidemiological evidence from special groups. More precise estimates are needed to determine the public-health effects of pollutant emissions from electricity generation.

Lave and Seskin[85,87-91] have explored this relation statistically, beginning with an examination of the association between the total mortality rate and air pollution in 117 U. S. cities in 1960. The basic regression, taken from Ref. 83, is shown in the following equation:

$$MR_i = 19.607 + \underset{(2.53)}{0.041 \text{ mean } P_i} + \underset{(3.18)}{0.071 \text{ min } S_i}$$

$$+ \underset{(1.67)}{0.001\, P/M_i^2} + \underset{(5.81)}{0.041\% NW_i} + \underset{(18.94)}{0.687\% \geqslant 65_i} + e_i$$

where MR_i = total mortality rate (per 10,000 people) in city i

mean P_i = arithmetic mean of suspended particulate readings in city i

min S_i = smallest biweekly sulfate reading in city i (× 10)

P/M_i^2 = population density in city i

$\% NW_i$ = proportion of the population which is nonwhite in city i (× 10)

$\% \geqslant 65_i$ = proportion of the population 65 and older in city i (× 10)

e_i = error term for variation in the mortality rate not explained by the equation

In this ad hoc regression, 82.7% of the total variation in the mortality rate across the 117 cities is explained. The relation is a linear equation that predicts the

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*Only health effects will be discussed here. Air pollutants have many other deleterious effects, as discussed in Ref. 83.

mortality rate in a city on the bases of (1) air pollution in the city (particulate levels, and SO_2 levels as reflected in sulfate data), (2) the population density, (3) the proportion of nonwhites in the population, and (4) the proportion of the population 65 years of age or older.[92-94] Values are given for the estimated coefficients of the variables; the numbers in parentheses are the *t* statistics for a test that the explanatory variable has no effect (the estimated coefficient is not significantly different from zero). With the exception of population density, all coefficients are extremely significant. Another way of viewing the estimates is to ask how much the mortality rate varies with a 10% increase in one of the variables used in the analysis; these values, shown as "sensitivity coefficients," are given in the following table.

Independent variable	Estimated increase in total mortality rate, %
Mean *P*	0.53
Min *S*	0.37
P/M^2	0.07
% *NW*	0.57
% ≥ 65	6.32

These results show that the mortality rate is significantly related to air pollution and that a 10% increase in air pollution (particulates plus sulfates) is associated with an increase in the mortality rate of 0.90% (0.53 + 0.37). A possible interaction between sulfates and particulates was investigated but was not found to be significant for these data.

Correlation does not prove causation, nor is a multiple regression of this sort more than an indication of an empirical association between air pollution and total mortality (with statistical control for the other relevant factors of population density, nonwhite composition of the population, and the proportion of the population 65 and older). Empirical associations occur frequently and are more often indicative of a particular sample or of a spurious association than of true causation. Although the results of such a statistical investigation should be viewed with suspicion, a variety of tests can be performed to evaluate particular hypotheses about the reason for an observed association. For example, a replication with different data would rule out the association's being due to the peculiarities of a particular sample; explorations with mortality rates for particular diseases or demographic groups would help to clarify the nature of the association and suggest whether it is plausible, given our knowledge of physiology and pathology. Finally, laboratory evidence from animal or human experiments can be used to judge the plausibility of the estimated relation.

To this end, Lave and Seskin have elaborated the basic relation shown in the above equation in a number of ways. The equation was replicated with 1961 and 1969 data; specific mortality rates for 14 diseases were estimated for 1960 (e.g., lung-cancer mortality), and the resulting equations were replicated for 1961. Twenty-eight age–sex–race specific mortality rates were also investigated for 1960 and 1961 (e.g., the mortality rate for nonwhite females during the first month of life). Day-to-day variations in the number of people dying in 5 cities were investigated, as well as year-to-year variations in 26 cities over a period of 7 years. The form of the function was checked by estimating multiplicative, quadratic, and piecewise linear forms in addition to the simple linear form. Finally, a series of tests was performed which should indicate whether the relation was spurious or a true causal one. The sample was split in various ways to see if the regression fit the largest cities as well as the smallest ones; the error term was investigated to see if it had any systematic pattern; other social phenomena known to be related to urbanization but not caused by air pollution (such as crime, venereal disease, and suicide) were investigated and found not to be correlated with air pollution after controlling for other factors; a number of additional explanatory variables hypothesized to affect the mortality rate were added to the regressions.

Neither the equation nor the subsequent work proves that air pollution causes ill health. However, it sheds a great deal of light on the nature of the association and contains estimates of the magnitude of the association in each case. The statistical analysis is aimed not so much at proving causality as at estimating the nature of the relation if it is causal. Since causality can be inferred from the laboratory and epidemiological studies of acute exposures and since the regression coefficients for particulates and sulfates have been reasonably consistent, it is not imprudent to interpret them as estimates of the dose–response relation, even though they cannot be taken as proof in themselves of causality.

The estimates of the effect of air pollution which will be used are those from the 1969 replication, using data for 89 cities, with SO_2 data substituted for sulfates. The regression coefficients will be used to estimate the mortality risk of exposure to air pollutants at the primary concentration standards of the Environmental Protection Agency (EPA) used in Hull's study. According to these coefficients, an additional microgram per cubic meter of mean particulate concentration is associated with an increased mortality of 0.085 per 10,000 per year, and an additional microgram per cubic meter of mean SO_2 concentration is associated with an increased mortality of 0.039 per 10,000 per year.* Thus the exposure for many years to mean concentrations of these pollutants at the EPA primary standards implies an increased average mortality risk to individuals of 638×10^{-6} per year for particulates and 312×10^{-6} per year for SO_2. The primary standards for SO_2 and particulates thus appear to carry many times the mortality risk of the AEC standards for radionuclides.

Relative Mortality Risks from Airborne Power-Plant Effluents

An abstract comparison will be made between the airborne emissions of a 1000-MW(e) coal-burning power plant and a 1000-MW(e) LWR based on the mortality risks estimated above. The method used by Terrill et al. and Hull will be followed in that an arbitrary dilution volume will be assumed for the emission of both plants, 1.77×10^{15} m^3 of air per year, the dilution at which the SO_2 from a 1000-MW(e) plant burning 3.5% sulfur coal is assumed to meet the primary standard. The dilution volume chosen is not important to the conclusions, since both chemical air pollution and radiation dose–response relations are assumed to be linear over the range under consideration, only relative risks are being estimated, and both plants are assumed to be occupying the same site.

The average mortality risk per year for individuals continuously exposed to gaseous effluent at the specified dilution from a plant burning 3.5% sulfur coal with 15% ash would ultimately be expected to be 334×10^{-6} (312×10^{-6} from SO_2 and 22×10^{-6} from particulates). The inclusion of other pollutants in this estimate, such as benzo(a)pyrene, would be expected to add an increment to this risk, and synergistic effects would also play a role. For gaseous effluent from a BWR with a 30-min holdup, the estimated risk per year at the same dilution would ultimately be about 2.25×10^{-6} (2.24×10^{-6} from noble gases and less than 0.013×10^{-6} from ^{131}I, via the air–grass–milk route) and from a PWR, less than 0.0031×10^{-6} (0.0028×10^{-6} from noble gases and less than 0.0003×10^{-6} from ^{131}I). Thus, within the limits of the assumptions made, the emissions from the coal-burning power plant are estimated to present a mortality risk approximately 150 times the risk from airborne effluents of a BWR and approximately 110,000 times the risk from the airborne effluents of a PWR. For emissions of a plant burning 1.5% sulfur coal, the corresponding figures are estimated to be 69 and 50,000 times, respectively (assuming the same ash content), and, for emissions of the same plant removing 75% of the SO_2 via stack-gas scrubbing methods, the estimates are 24 and 18,000 times, respectively.

At the same dilution the emissions from a plant burning 1.6% sulfur oil with 0.05% ash would ultimately present an estimated mortality risk to exposed individuals averaging about 119×10^{-6} per year (116×10^{-6} from SO_2 and 3.5×10^{-6} from particulates), about 53 times the risk from BWR stack effluents and about 39,000 times the risk from PWR stack effluents. For 0.2% sulfur oil the corresponding figures would be 8.0 and 5800 times, respectively, and for 0.2% sulfur oil with 75% of the SO_2 removed, the estimates would be 3.2 and 2300 times, respectively.

The dilution-factor method of comparing power-plant emissions can provide only a first approximation of their relative health effects since other factors affecting pollutant concentration or dispersion, such as different residence times in the atmosphere or different stack heights, are completely ignored. Another problem of the comparison is the crudeness of the dose–response estimates for both radiation and air pollution. For the above reasons, not much confidence can be placed in the difference between the calculated mortality effects of emissions from fossil-fueled plants and most current BWRs. However, the difference between the estimates for fossil-fueled plants and PWRs is strong enough to justify a conclusion that the airborne emissions of PWRs (and BWRs, if they are provided with longer holdup facilities) are substantially less dangerous to human health.

Ideally, a comparison of health effects of generating power from different fuels would consider not only the quantities of pollutants emitted per year but also their dispersion patterns, half-lives, and ambient concentrations in the environment. Meteorology and

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*The measure of ambient SO_2, which was most significantly associated with mortality in 1969, was the minimum biweekly reading. However, since the mean concentration was more of interest in the above calculation, the relation was reestimated using the mean SO_2 reading. The regression coefficient for mean SO_2 was not statistically significant, but its magnitude was reasonable relative to the coefficient for minimum SO_2 concentration.

terrain would be important factors to take into account. Population distribution at various distances from a site would have to be known to estimate average doses received by the public.

Such a procedure requires extensive data collection regarding actual sites. Numerous studies have measured concentrations of air pollutants at various distances from fossil-fuel-burning plants.[95] With respect to nuclear power plants, Gamertsfelder has estimated a maximum value for the average annual radiation doses received from 1969 noble-gas effluents by members of the public within various distances of 13 plants.[53] These calculations were based on the percent of noble gases released relative to the amount permitted that year for each plant, the latter being the quantity that, under adverse meteorological conditions, would have been expected to deliver a dose of no more than 500 mrems/year to individuals located at the plant boundary. Population distributions and wind speed were taken into account. Although comparison of the results of these separate studies for fossil-fueled and nuclear power plants would be desirable, it would be difficult to carry out because of differences in meteorology and other factors at the individual sites and will not be attempted here.

However, these comparisons are precisely what should be done in an environmental impact statement for a new power-generating facility. That is, the effluents of power plants of alternative designs and fuels should be more carefully evaluated to estimate the doses of noxious materials which would be experienced by the public. These doses must be evaluated for their public-health effects using dose–response relations such as those discussed above.

An attempt in this direction has been made by Bergström,[96] who compared anticipated emissions from power plants of alternative designs being considered for sites in Sweden. Expected population exposures to radiation from a nuclear power plant and to SO_2 from a plant burning 1% sulfur oil were compared for a range of sites by means of dose–response curves he estimated for both types of exposure. According to his calculations, the health effects of the nuclear power plant would be smaller than those from the oil-fired station by a factor of 10^4 or more. Since the dose–response curves he estimated were derived from acute rather than long-term effects and since population exposure to SO_2 was calculated indirectly, on the basis of dispersion characteristics of tritium, these estimates need to be further refined. However, they serve to indicate the type of comparison that needs to be made.

A maximum value for mortality from noble-gas effluents of nuclear power plants can be obtained by using Gamertsfelder's calculations, referred to above. Adjusted according to 1971 release rates, the average dose per year received by the population within 50 miles of a 1000-MW(e) plant at a typical site would not be expected to exceed 0.36 mrem per person for a BWR or 0.020 for a PWR, with an estimated risk of 0.065 or 0.0036 extra death from cancer per million exposed persons per year for a BWR and PWR, respectively. For an average population of 2,500,000 within 50 miles of the LWRs, 0.16 extra death or less from cancer would be expected per year from noble gases from a typical 1000-MW(e) BWR and 0.009 extra death or less in the case of a PWR.*

The maximum dose to individuals from ^{131}I, via the air–grass–milk route, can be estimated in the same way.† In 1971 the estimated maximum dose (to the thyroid) from ^{131}I discharged by a nuclear power plant averaged about 0.6 and 2 times the maximum dose (to the whole body) from noble gases from a BWR and PWR, respectively.‡ If the average doses from ^{131}I and noble gases are assumed to be in the same ratio as their maximum doses, the ^{131}I doses would be expected to add less than 1% to the mortality from LWRs.

Liquid Effluents from Nuclear Power Plants

Liquid releases from nuclear plants were omitted from the above analysis because of the difficulty of evaluating average exposure via this route. The radionuclide released in greatest quantities in liquid discharges, particularly from PWRs, is tritium, which is considered to be one of the least hazardous isotopes because of the low energy of its beta rays.[99-101] Environmental surveillance studies in the vicinity of Dresden 1,

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*These calculations are based on very conservative meteorological assumptions. More realistic assumptions would reduce the mortality estimates.† The proposed restriction of maximum dosage from LWR effluents to 5 mrems/year would also serve to reduce the mortality estimates.[66]

†Maximum doses actually expected to be received by individuals have been estimated for a number of radionuclides from Dresden 1 by Blanchard et al.[97] using more realistic assumptions regarding radioactive dispersal. Pathways considered were external radiation exposure, inhalation, and consumption of milk, leafy vegetables beef, fish, and drinking water.

‡Although radiation from noble gases has been detected in the air in the vicinity of Dresden 1 nuclear power station corresponding to a dose rate of 5 to 15 mrems/year, the concentrations in milk of ^{131}I from either Dresden 1 or Yankee nuclear power stations have been too low to be detectable.[64,65,98]

Yankee, and Indian Point 1 nuclear power stations[64,65,102] have not been able to detect any significant radiation exposure to the public from aquatic samples which can be attributed to these power plants.§ However, experience at these plants is not necessarily representative of the situation at other plants.

The radioactive releases from nuclear power plants constitute only a minute fraction of the total radioactive material produced within the plants. Most of this radioactivity is produced within the fuel elements, and nearly all the radioactivity is retained there until the fuel is reprocessed; most of the remainder is concentrated and processed as waste for disposal elsewhere. However, both tritium and the noble gases are very difficult to control by conventional waste-treatment methods. Although the quantities currently being released are not considered dangerous over the short run, tritium and ^{85}Kr can be expected to accumulate over time and present more of a problem in the future.¶

PUBLIC-HEALTH EFFECTS OF OTHER RADIOACTIVE AND CHEMICAL RELEASES ASSOCIATED WITH THE URANIUM CYCLE

The above comparisons concerned effluents from normal operation of power plants only. In addition, further analysis must be concerned with the potential hazard to the public from reactor accidents and the possibility of environmental contamination from stored waste. The radioactive and chemical releases from uranium mining and milling, fuel-preparation processes, and spent-fuel reprocessing must also be considered in estimating the total health effects of atomic power.

Accidental Releases from Power Plants

A potentially serious, but statistically unlikely, source of radiation exposure to the public is a major reactor accident.[104,105] Care is taken in designing nuclear power plants to build in redundancies and other features to lower the probability and potential effects of such accidents. The safety record for nuclear power plants has been excellent thus far; however, it is still too early to assume that the safety of all of these systems has been proven and that a serious accident is precluded. One safety area in which reliability has not yet been conclusively demonstrated is the emergency core-cooling system in the event of a loss-of-coolant accident.*[106-108] However, the possibility of serious accidents is not unique to nuclear plants, there being the potential for boiler- or storage-tank explosions at fossil-fuel-burning plants, with consequent release of air pollutants to the environment.

Morgan and Struxness[80] have estimated the probability of a reactor accident that would release 1% or more of the total fission inventory to the environment to be between 10^{-4} and 10^{-5} or less per year per reactor; at this level of probability, less than one such accident on the average might be expected to occur among 200 reactors per 50 years. Starr, Greenfield, and Hausknecht[69] have estimated the total mortality risk from reactor accidents at 6×10^{-5} cancer death per 10×10^{6} population per year per 1000-MW(e) reactor. This risk compares favorably with their corresponding estimate for accidents at oil-fired plants of 2×10^{-4} respiratory death per 1000-MW(e) plant per year for the same population. Since only mortality from leukemia or thyroid carcinoma was considered in the case of reactor accidents, their estimate may be low. Nevertheless, the order of magnitude of this estimate is very small compared with the mortality risk from routine effluents.

Major radioactive releases might also occur in the event of certain externally caused disasters, such as earthquakes or aircraft accidents. Although nuclear power plants are designed to withstand most of these events, it is conceivable that such an accident might exceed the intensity anticipated in the design and cause the reactor containment structure to be breached.[79,110] More work needs to be done on estimating population risk from such accidents.

Accidental releases may also occur in connection with other stages of the uranium cycle, such as fuel transport and reprocessing. Risks to the public should be estimated for these accidents as well.

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§Estimates of maximum doses from the liquid effluents of these plants range from 0.03 mrem/year to the whole body from Indian Point 1 (from fish),[102] to less than 0.3 mrem/year to the whole body from Yankee (from fish),[65] to 0.4 mrem/year to the thyroid, 0.02 mrem/year to bone, 0.003 mrem/year to the gastrointestinal tract, and 0.01 mrem/year to the whole body, from Dres[illegible] 1 (from fish and drinking water).

¶A number of systems are under development which may virtually eliminate either liquid or gaseous radioactive release to the environment from nuclear power plants.[103]

*Various opinions on the adequacy of the emergency core-cooling system and of interim criteria set for reactors by the AEC to compensate for possible deficiencies in this system were expressed at the rule-making hearings[109] of the Atomic Safety and Licensing Board (RM-50-1) during 1972

Storage of Radioactive Wastes

In addition to population risks discussed above, there are also risks from the storage of radioactive wastes. Gamma radiation from stored wastes has been measured[65] in the vicinity of Yankee nuclear power station, with an estimated exposure rate of about 3 mR/year at the nearest town and essentially zero at 2 km. Storage of a proportionally higher amount of wastes by a 1000-MW(e) plant in a similar geographic location might be expected to entail about 0.001 additional death per year to local residents (on the basis of the NAS estimate for mortality risk and assuming a local population of a few hundred). This risk would, of course, be higher for a more populated location and a flatter terrain.

Low- and intermediate-level radioactive wastes are periodically transported to commercial burial grounds. These facilities are located in sparsely inhabited areas and are carefully monitored to prevent release of radioactivity to surrounding areas. No migration of radioactivity from the burial sites has thus far been detected; consequently no significant radiation exposure to the public is expected.[40]

The storage of high-level liquid wastes produced at reprocessing plants presents a potentially greater problem. Large volumes of these wastes are generated, containing most of the fission products from the spent-fuel elements. Since these wastes are very high in activity and have long half-lives, their accidental dispersal would create serious public-health problems. To date, such wastes have been stored temporarily in tanks on the sites where they were generated. However, this method of storage is unsatisfactory in the long run because the tanks must be given continual surveillance and replaced when they fail.[111]

The extent of this storage problem has been diminished by the development of solidification techniques, which reduce the volume, mobility, and solubility of these wastes considerably.[111,112] Among the proposals for the ultimate disposal of solidified waste, burial in bedded salt formations is being given the most consideration. However, since this method has not yet been proved satisfactory, construction of an interim near-surface storage facility is planned by the federal government.[40] It is safe to say that the waste-disposal problem has not yet been completely solved.

Effluents from Fuel Reprocessing

Considerable quantities of low-level radioactive effluents are released from the single presently operating commercial reprocessing plant. The radionuclides released in greatest quantity have been ^{85}Kr and tritium. However, in terms of population dose, the ^{90}Sr, ^{134}Cs, ^{137}Cs, and ^{129}I released are also worth attention.[113-119]

In general, these releases have been more serious than those from nuclear power plants. Although the activity of ^{85}Kr released per year has been comparable to or lower than the activity of noble gases released by a typical BWR, the ^{85}Kr is much longer lived. In addition, the quantity of tritium released has been about twice the average amount released by individual PWRs. The ^{90}Sr and ^{139}Cs have been released at rates hundreds or thousands of times the rates at an individual BWR or PWR.* The amounts of radionuclides found in environmental samples near the reprocessing plant have been more significant than those found near Dresden I or Yankee nuclear power stations; in particular, such radionuclides as ^{90}Sr, ^{137}Cs, and ^{106}Ru have been detected in streams and in the flesh of local deer and fish, and ^{129}I has been detected in milk from local cows.[64,65,98,119,121]

Martin[119] has calculated population doses from the most significant radionuclides for 1971, updating an earlier study by Shleien.[122] For the population within 50 miles of the plant, a submersion dose of 46 man-rems was delivered from ^{85}Kr in the air. From a submersion dose of this magnitude, a dose of 0.64 man-rem can be inferred to the whole body, 28.5 man-rems to the skin at a depth of 0.07 mm, and 1.1 man-rems to the lungs.[52] For other radionuclides, Martin estimated population doses of 20.8 man-rems to the whole body (16 from ^{3}H in drinking water and 4.8 from ^{134}Cs and ^{137}Cs in fish and deer), 0.8 man-rem to bone (from ^{90}Sr in fish and deer), 0.1 man-rem to the gastrointestinal tract (from ^{60}Co in deer), and 30 man-rems to the thyroid (from ^{129}I in milk).[119] Population doses of this magnitude would entail an estimated mortality risk of 0.004 death (between 0.0001 and 0.0002 death from ^{85}Kr and 0.0038 death from other radionuclides).

Because of the relatively long half-life of ^{85}Kr, a radiation dose would also be delivered to the population beyond the 50-mile radius. Martin estimated a submersion dose of 300 man-rems to the world wide population for the first year following the 1971 release

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*Recently installed equipment has reduced the amount of these two radionuclides released.[114-117] In addition, other reprocessing plants under construction have been designed in such a way that there will be no routine discharge of liquid effluents to the environment. (Tritium will continue to be released through the stack.)[120]

and 16.1 times that amount as the long-term population dose,[119] from which a whole-body dose of 68 man-rems, a skin dose of 3000 man-rems, and a lung dose of 116 man-rems can be inferred.[52]

In 1971, 68.8 metric tons of fuel were reprocessed,[117] about twice the amount of fuel discharged per year from a 1000-MW(e) LWR.[40] If all the fuel reprocessed had come from power plants, the long-term population doses from reprocessing per annual operation of a 100-MW(e) power plant would be 34 man-rems to the whole body, 1520 to the skin, and 59 to the lungs. However, much of the fuel reprocessed comes from AEC reactors and has a lower burnup per metric ton than does spent fuel from power plants. Correcting for the higher burnup of fuel from power plants, 30,000 MWd per metric ton of uranium (vs. a burnup of 11,500 MWd/metric ton for fuel reprocessed in 1971),[119] these doses would be 90,[†] 4000, and 150 man-rems, respectively.[‡] Such doses would entail an estimated mortality risk of about 0.02 death. From radionuclides other than ^{85}Kr, the corresponding risk (calculated in the same way) would be about 0.005 death. Thus the total mortality risk from reprocessing effluents per annual operation of a 1000-MW(e) power plant would be estimated at close to 0.03 death, which, although low, would be about three times the mortality estimated for a 1000-MW(e) PWR from stack effluents and would add a significant increment to the risk from nuclear power plants.[§]

Since substantial amounts of reusable uranium are recovered from the reprocessing of spent fuel, this process in effect serves as a substitute for the mining and milling of uranium ore. According to the AEC,[40] the recovery of fissile material from an annual fuel requirement of a 1000-MW(e) LWR is equivalent to the conservation of about 30,000 metric tons of uranium ore, or about 60 metric tons of U_3O_8. The mining and milling of that amount of U_3O_8 would have been expected to cost about 0.05 death from accidents and about 7.6×10^{-4} case per year of lung cancer. Thus the additional cancer mortality risk incurred from reprocessing effluents is probably outweighed by reduced mortality from uranium mining and milling.

Effluents from Other Processes

Radiation exposure to the public from the current effluents of uranium mines and mills and plants involved in feed-materials production, isotopic enrichment, and fuel fabrication is not considered significant compared with doses from power-plant or reprocessing-plant effluents.[40,52] For example, it has been estimated that the total population dose from current uranium-mill effluents per annual fuel requirement produced for a 1000-MW(e) power plant is no more than 0.06 man-rem, primarily[40] from airborne ^{230}Th. Other effluents having potential health significance are NO_x from combustion of natural gas in uranium mills; fluoride from feed-materials production, isotopic enrichment, and fuel fabrication; nitrates and ammonia from fuel fabrication; and hexavalent chromium from isotopic enrichment.[40]

SUMMARY AND CONCLUSIONS

A comparison of the health effects of generating electricity from alternative fuels requires that the systems effects of the fuel cycles be considered. For example, the cycle for coal consists in exploration, mining, transportation, power generation, and ash removal: for nuclear fuel the processes for exploration, mining, milling, fuel preparation, transportation, power generation, and disposal of radioactive wastes are included (as well as a subcycle in which reprocessing of spent fuel substitutes for the mining and milling of fresh ore). The entire cycles must be compared for their health effects rather than simply the power-generation phase.

Some tentative conclusions emerge from a comparison of the main components of the cycles for coal and uranium. Occupational-health effects from accidents and chronic diseases are substantially greater for coal mining than for uranium mining and milling per megawatt of power generated. Although complete data are not available on accident and disability rates for other phases of the fuel cycles, the differences between coal and uranium are unlikely to be important when

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[†] This estimate of long-term whole-body dose to the worldwide population (3×10^9) is not far from the AEC estimate of 120 man-rems for the eventual annual whole-body exposure to the entire population of the northern hemisphere (4×10^9) from ^{85}Kr per 1000-MW(e) LWR.[123]

[‡] Proportionality between burnup and fission-product inventory of the fuel has been assumed in these calculations. Differences in composition between fuels from AEC reactors and commercial reactors have been ignored.

[§] This estimate does not include radiation doses which will be received in later years from tritium or from the exceedingly long-lived ^{129}I. In addition, most spent fuel from power plants has been cooled for much longer than the required 150 days before reprocessing.[119] Higher releases of radionuclides, such as ^{131}I, can be expected if a shorter cooling period is used in the future unless compensating waste-treatment measures are taken.[130] Fortunately more stringent precautions are being taken to reduce releases of the radioiodines.[119]

compared with the estimated differences from mining and milling.

Comparing the effluents from power generation is more difficult. Both nuclear and coal-burning power plants discharge radioactivity into the environment in amounts that have little effect on background-radiation levels; the small proportion of radium and thorium in coal which is released into the air seems to be less significant than the noble gases and ^{131}I from a BWR or PWR. When liquid effluents and effluents from reprocessing plants and other phases in the uranium cycle are added to the comparison, it becomes still clearer that the total radioactive release from the uranium cycle is more significant than that from the coal cycle. However, coal-fired generators are a major source of chemical air pollutants, which have been shown to be harmful to health.

Thus a comparison of the total health effects of generating electricity from the two fuels depends on weighing the adverse effects of air pollution from coal combustion and excess accident and chronic-disease disability from coal mining against the excess radioactivity released from the atomic power industry. To accomplish this, one would need dose–response curves for both the radioactive and chemical effluents. Estimates of both dose–response curves have been published, although there is still considerable debate on the effect of low-level long-term exposure to either air pollution or radiation.

In the work reported here, airborne releases were compared in terms of the dilution volume of air that would be required to meet recommended concentration standards and in terms of relative mortality risks to individuals exposed to these effluents at a specified dilution, as estimated from the dose–response curves. In the most conservative comparison considered, a PWR appears to offer 18,000 times less health risk than a coal-burning power plant, and a BWR with a 30-min holdup of stack gases appears to offer 24 times less health risk. Including effluents from other processes in the uranium cycle does not change the nature of the comparison, even when atmospheric buildup of ^{85}Kr from spent-fuel reprocessing is considered. In view of uncertainties in the dose–response curves and differences in atmospheric residence times, which were omitted from the comparison, the factor of 24 between coal-burning plants and existing BWRs must be viewed as suggestive rather than conclusive.

Liquid releases from LWRs were not fully evaluated because there are uncertainties regarding the size of the populations exposed by the various pathways and the average doses received. However, since the population dose from these effluents is considered to be much smaller than the dose from airborne releases, it is unlikely that they would have much effect on the comparison.

The conclusion can thus be drawn that uranium offers lower risks than coal as a fuel, in both the extraction phase and the generation phase.

When coal and oil are compared as fuels, it is clear that the latter offers lower risks in both the extraction phase and the generation phase. However, a comparison of low-sulfur oil and uranium is less clear-cut. The differences in the public-health risks from power-plant emissions favor the PWR; however, the lack of complete data for many phases in the fuel cycles makes it difficult to compare the occupational-health risks from these fuels. Nevertheless, the occupational-health risk per megawatt-hour appears to be higher for uranium because of miner silicosis and radiation exposure to employees in the nuclear power industry. We have not attempted to determine which of the two fuels has the more serious overall health effects, because of the limitations imposed by the available data and the many assumptions, some of them arbitrary, made in comparing power-plant emissions.

The relative health risks of airborne power-plant effluents need to be compared for actual sites, controlling for such factors as stack height, meteorology, terrain, population distribution, and atmospheric half-lives of the pollutants emitted. Improved measures need to be obtained for the population doses received by various pathways from liquid effluents. More complete data are needed on radiation exposure to employees in the nuclear power industry. Also necessary are better dose–response curves for both radioactivity and chemical pollutants. Much more work needs to be done to explore the toxic, mutagenic, and teratogenic properties of radionuclides in low concentrations. This work is not likely to be susceptible to laboratory experimentation. Rather, careful epidemiological work is needed to measure the age–sex–race and disease specific death rates for various groups as well as their exposure to various radionuclides and other environmental insults.

The above comparisons have been based on current data and operating practice. Changes in such areas as mining techniques, mine safety regulations, reactor design, and effluent control methods can be expected to alter both occupational- and public-health risks from electricity generation in the future.

* * *

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The AEC Study on the Estimation of Risks to the Public from Potential Accidents in Nuclear Power Plants

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Nucl. Safety, 15(**4**): 375–384 (July–August 1974)

[Editor's Note: This article is based on testimony given by Dr. Rasmussen before the U. S. Congress Joint Committee on Atomic Energy Hearings on Nuclear Reactor Safety, Sept. 25, 1973. The reactor safety study, which has become familiarly known as the "Rasmussen Study," is the first attempt by the U. S. Atomic Energy Commission to make systematic quantitative risk assessments of various potential reactor accidents. Earlier independent approaches to the assessment of low-probability/high-consequence types of events are discussed in Sec. 6.4 of the USAEC Report WASH-1250, The Safety of Nuclear Power Reactors and Related Facilities, July 1973.

The final report from the study, which is expected in the summer of 1974, will provide information useful for better allocation of future safety-research effort and will furnish an independent check on the effectiveness of reactor safety practices. The report should also provide another way of communicating with the public on reactor risks and provide a structure to help bring more logic and less emotion into the discussions. This article will assist in "setting the stage" for this very important report for *Nuclear Safety* readers since it describes the approach being taken in the various study tasks and identifies the types of data that the study will provide.]

Abstract: *The U. S. Atomic Energy Commission initiated a reactor safety study in September 1972 to estimate the probability of occurrence of various potential accidents in light-water nuclear power plants and of their consequences. The study is divided into seven major tasks, including such topics as the identification of accident sequences, the assignment of probabilities, fission-product transport in each accident sequence, fission-product distribution in the environment, health effects and property damage, nonnuclear risks, and interpretation and communication of the meaning of low-probability events to nontechnical readers. A final report is expected in the summer of 1974.*

The principal objective of the U. S. Atomic Energy Commission (AEC) reactor safety study is to determine, within the limits of present-day knowledge, an estimate of the risks to the public from potential accidents in today's nuclear power plants. In most areas of society, risks are determined as a matter of experience, i.e., the events that have occurred and their measurable consequences. Because nuclear power plants have experienced no accidents with immediately measurable damage to the public, we must make *estimates* of (1) the probability of occurrence of accidents and (2) the consequences of the accidents.

The study has a staff of about 50 very competent persons, covering such technical disciplines as reactor safety, fault-tree analysis, data collection, and reliability analysis. In addition, it has contracts for assistance on various portions of the work with several AEC laboratories, private companies, and universities. The study began in September 1972, and a final report is expected by the summer of 1974.

It was possible for the AEC to undertake this study at this time because, during the decade of the sixties, techniques were developed that make predictions of probabilities possible. These techniques were developed principally by the aerospace industry for application to weapons systems and also by the National Aeronautics and Space Administration (NASA) for the space program. They are useful in forecasting system reliability where experience is not available, using data that do exist on components, human factors, and subsystem reliability. In previous studies like the 1957 WASH-740 report[1] and its 1965 revision,[2] the authors were only able to make intuitive and unsubstantiated probability estimates, although they were able to make some quantitative estimates of the consequences of accidents. Apparently the lack of tools to permit the quantitative assessment of probabilities of various types of accidents in part led to "upper-limit" estimates of consequences as opposed to the consideration of a more realistic spectrum of accidents. This upper-limit approach was also taken to ensure adequate indemnification for the public in case of a major accident.

In regard to risk assessment, there are some who believe that events of low probability are amenable to treatment by actuarial statistics, which is, of course, fundamentally incorrect. Actuarial statistics, as used by insurance companies, represent the accumulation of past data to be used as the basis for predicting the likelihood of future events and for deriving costs that might be associated with such events. Such methods

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are not useful for, and in fact are not used by insurance companies in, assessing costs associated with such low-probability events as reactor accidents that have never occurred. Thus there exists no insurance assessment of the probabilities or consequences of reactor accidents. The insurance companies have accepted the fact that the consequences can be very large, and the amount of liability insurance they make available is thus limited to the maximum loss that they feel the insurance pool can sustain. This liability limit has been successively increased over the years from $60 million to $95 million. If the safety record for nuclear power plants remains as good as it is, it is almost certain that the amount of commercially available insurance will continue to increase.

In the course of carrying out this work, it is expected that several secondary objectives can also be met. The study should provide information useful to better allocation of future safety-research effort and should also provide an independent check on the effectiveness of current reactor-safety practices.

GENERAL APPROACH

The study is currently limited to an analysis of light-water power reactors of both the pressurized- and boiling-water types for two reasons: (1) essentially all U.S. commercial nuclear power stations are of these types, and (2) the methodology used to determine probabilities requires detailed engineering plans of the plants. Such plans are not yet available for commercial high-temperature gas-cooled reactors (HTGRs) or for liquid-metal-cooled fast breeder reactors (LMFBRs). If the methodology of the study is proved worthy of further application, the techniques developed by the study will be applied to the HTGRs and LMFBRs once sufficient engineering information becomes available.

One of the major guidelines of the study was that the approach be as realistic as possible. Thus, whenever approximations or decisions are made, "best engineering judgment" is used. Uncertainties are treated by developing realistic probability values of all possible outcomes rather than choosing the worst-possible values. This approach will lead to a prediction of the most likely consequence and the probability of smaller or larger consequences and thus should provide a more complete, accurate view of nuclear accident risks than previous studies that computed only "worst-case" values.

ORGANIZATION OF STUDY

The study is divided into the seven major tasks shown in Fig. 1 and described below.

Task 1. Identification of Accident Sequences

To undertake an assessment of accident risks, we must identify the various ways in which accidents might occur that could affect the public. This approach has been an integral part of the AEC's safety philosophy, and over the years a well-developed set of equipment failures or accident-initiating events has been defined. This study will consider these accident initiators and will search for additional initiating events.

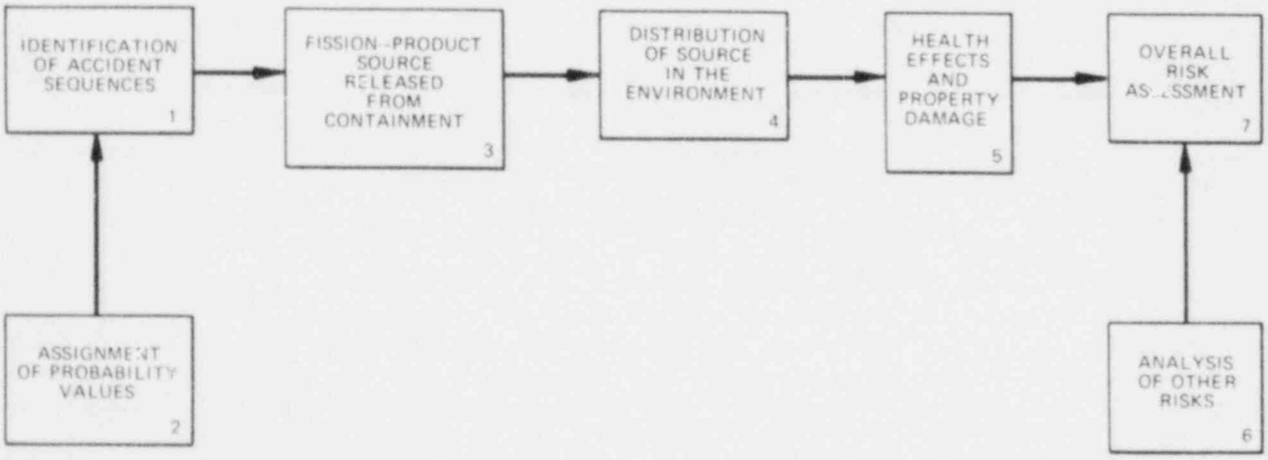

Fig. 1 Basic seven tasks in reactor safety study.

Another part of the AEC's approach to safety calls for the installation of engineered safety features designed to actuate when certain initiating events occur so that the public will not be exposed to excessive radiation. Thus the study must examine the set of initiating events coupled with the success or failure of each of the applicable engineered safety features. This combination of an initiating event and the response of the various engineered safety features can be shown graphically on a diagram called an event tree. Each event tree contains a series of accident sequences that are determined by the initiating event and the operability states of the various engineered safety features (see Fig. 2).

Since there are a large number of accident sequences that must be analyzed, it is necessary to reduce these to a manageable number for analysis. This reduction is done in two stages: first, the sequences are classified into a small number of general categories in which the magnitudes of the consequences for each sequence are comparable. Second, the number of sequences that then require detailed probability analysis can be reduced by neglecting those sequences in each consequence category which have very small probabilities compared with others in the same group. In this way the principal contributors to each category can be identified. The first obvious consequence grouping is between accidents which lead to melting of the fuel and those in which fuel melting does not occur. Accidents in which the fuel does not melt produce minimal health effects and property damage, whereas much larger consequences can occur when fuel melts. Therefore most of the effort in this study is being devoted to the analysis of accidents having the potential for core melting.

Task 2. Assignment of Probability Values

After identifying the accident sequences, we must assign the probability of occurrence of each engineered-safety-system failure in the particular sequence. Since no commercial reactor has ever experienced these

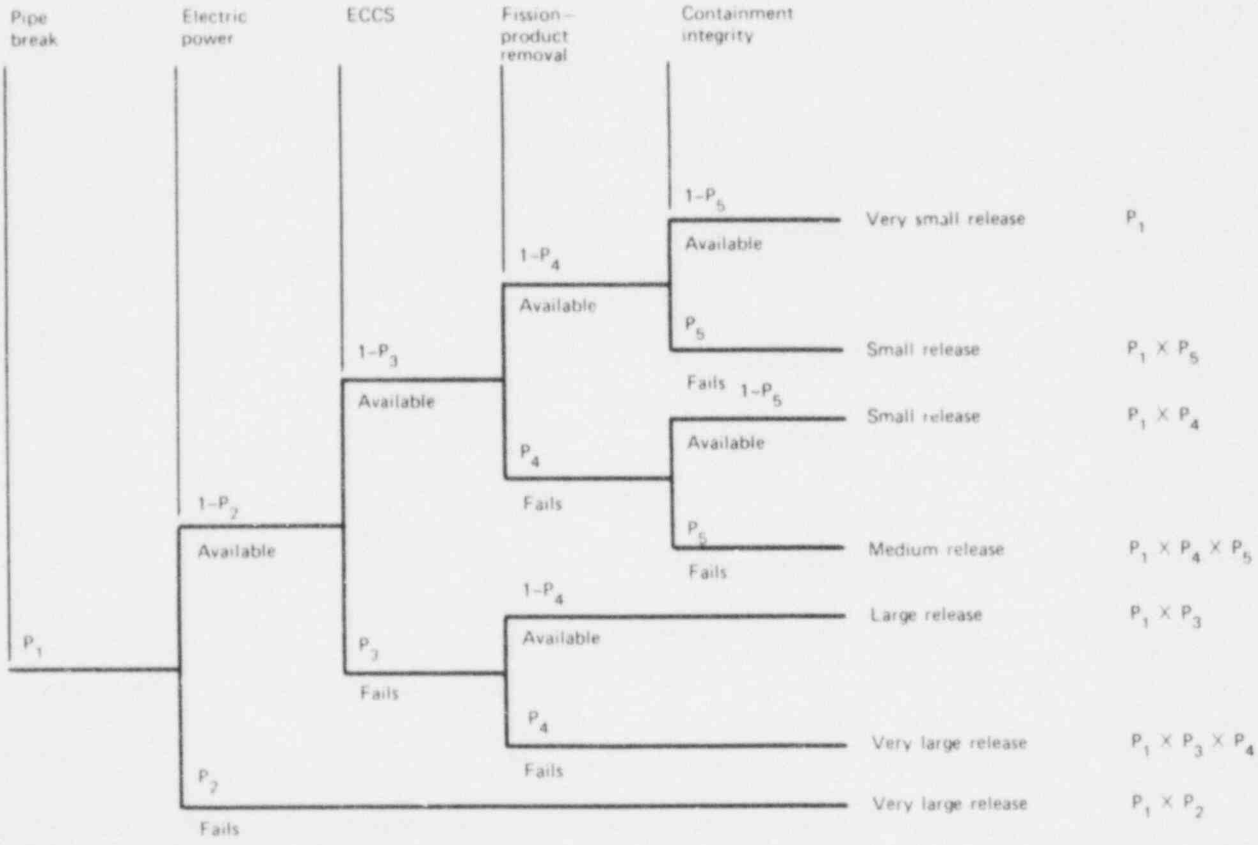

Fig. 2 Simplified event tree for a LOCA in a typical nuclear power plant.

failures, no empirical data on which to base estimates of system-failure rates exist. Thus it is necessary to use techniques that generate system failure rates from failures of components and subsystems. Fault-tree methodologies, developed by the Department of Defense and NASA to identify system design flaws, are being extended to derive probability estimates for both the failure of individual nuclear safety systems and the accident sequences of interest. The failure rates of components and subsystems are determined from industrial experience with products similar to those either in nuclear service or in related use in other industries.

By use of an appropriate analytical model that includes hardware failures as well as failures from operating, test, and maintenance procedures, it is possible to predict an expected value for the probability of the accident. Although this might seem to be highly theoretical, experience has shown that, when the method is carefully used, it predicts failure rates that are in surprisingly good agreement with the limited available data on observed failure rates.

Task 3. Fission-Product Source Released from Containment

This task estimates the quantities of various radioactive fission products that will be evolved from the fuel for each accident sequence. It also incorporates a mathematical model for predicting the fraction of each radioactive isotope that will be deposited on internal surfaces, be washed out by sprays, or be trapped on filters. The final result of this model is a prediction of the quantity of radioactivity that will escape if the containment is violated.

Task 4. Fission-Product Distribution in the Environment

To determine health effects or property damage requires that we first determine how the fission products that escape from the containment become distributed in the environment. This is mainly a problem of predicting how the radioactivity will be transported under different types of weather conditions.

Task 5. Health Effects and Property Damage

This task calculates the effects on public health and the damage to property that can be expected as a result of the radioactive release. Four different consequences of the accident will be calculated: (1) fatalities, (2) injuries, (3) such long-term health effects as latent cancers and genetic effects, and (4) property damage. The calculations will include the expected values as well as the probabilities associated with larger and smaller values.

Task 6. Analysis of Other Risks

For a judgment of the significance of risks from nuclear power plants, it seems important to place those risks in perspective by also examining existing non-nuclear risks. It is useful in making risk comparisons to consider two kinds of risks: (1) high-probability risks that happen often enough so that their frequencies can be measured, and (2) low-probability risks that have not occurred but whose frequencies and consequences can be estimated.

High-probability risks include, for instance, the environmental and occupational health effects due to the generation of electricity by coal, oil, natural-gas, and nuclear fuels. There are various sources of information available to quantify many, but not all, of the elements involved in such risks. For instance, a recent report[3] published by the Council on Environmental Quality (CEQ) contains much useful information in these areas.

In regard to occupational health, Table I shows, for a 1000-MW(e) power plant, the relative occupational health risks from the various types of fuels used. This table indicates that nuclear power plants have significantly less occupational risk than the other types of plants and, in particular, have less than about 5% of the occupational risk of coal-fired plants. Furthermore, the plants may be compared on an acres-disturbed basis, considering the fuel cycle from the fuel source through delivery of the fuel to the power plant. In this

Table I Occupational Health Damage for a 1000-Mw(e) Power Plant*

Fuel	Days lost per year	Deaths per year
Coal	6000	3.30
Oil	2600	0.25
Natural gas	1990	0.20
Nuclear	270	0.15

*These numbers are extrapolated from a recent report by the Council on Environmental Quality, *Energy and the Environment: Electric Power.*[3]

case the acres disturbed are about 7400, 1300, 3500, and 800 for plants fired by coal, oil, natural-gas, and nuclear fuels, respectively. It should be reemphasized that these are approximate extrapolations of figures presented in the CEQ report[3] and are applicable to current plant designs. Such comparisons could change in the future as technological changes are made; for instance, the use of liquefied coal, when feasible, could cause a significant change in the occupational health effects associated with coal usage. Also, introduction of the breeder reactor would cause significant reductions in these risks because much less fuel will be mined, processed, and transported.

It would also be useful to compare the health effects due to the release of effluents from the various types of power-plant fuels. It is interesting to note that the CEQ report does not have such a *health* comparison but only lists the quantities of effluents released. The reason for this is, of course, that, although there is a defined relation between radioactive releases and health effects, sufficient information does not exist to establish such a relation for fossil-fuel effluents.

The foregoing discussion illustrates that, even when risks are known to be occurring, their measurement or quantitative assessment may not always be possible.

The low-probability events that have never occurred include many kinds of technological risks, such as nuclear power-plant accidents, airplane crashes in high population densities, and dam failures affecting heavily populated downstream valleys. Large-scale core meltdowns have not occurred in commercial nuclear power plants, nor have the other types of risks occurred. Yet it is possible to estimate the probability and consequences of such nonnuclear risks. The general probabilities of airplane crashes and dam failures are fairly well known. With this knowledge the probabilities that these kinds of events will happen in locations that would involve large populations can be calculated and the consequences estimated.

It is important in discussing nuclear risks to put them in perspective with other risks to which society is exposed. For this reason the reactor safety study will investigate some existing risks in nonnuclear as well as nuclear areas.

Task 7. Overall Risk Assessment

The principal purpose of this task will be to convey an accurate impression of the risk of low-probability events to nontechnical readers. The average person, when told that an event is of very low probability, such as one in a million, will usually inflate the probability in his mind. This may be one of the reasons that lotteries have become so popular in many states. It is recognized that to communicate an understanding of low probabilities is very difficult, and thus every effort will be made to minimize possible misinterpretation of the results.

PROBABILITY DETERMINATION

As pointed out in the previous section, the assignment of probabilities to reactor accidents first requires decomposing potential accidents into component safety-system failures, each of which can have a probability assigned to it. Two different methodologies are used: event trees and fault trees.

Event Trees

The event tree starts with an event that initiates a possible accident, such as a large pipe break, and develops the possible consequences of this event by considering the response of engineered safety systems that would be called upon as a result of this initial event. Figure 2 shows a somewhat oversimplified event tree for a loss-of-coolant accident (LOCA) in a pressurized-water reactor. The initiating event, in this case a rupture in the primary cooling system, is assigned a probability of occurrence P_1. Next we ask whether or not electric power is available. A probability P_2 is assigned for the failure of electric power sufficient to operate the emergency safety systems. This is shown on the event tree as a fork with two branches: the upper for "available" and the lower for "fails." Since electric power either is or is not available, the probability of having electric power is just $1 - P_2$. If no power is available, none of the safety features will operate; therefore the core will melt, and the result will be a very large release of radioactivity. The probability of this sequence of events is the product of P_1 and P_2. If electric power is available, the next event of interest is whether or not the emergency core-cooling system (ECCS) will operate. Failure of this system is assigned a probability P_3 and success a probability $1 - P_3$.

As may be seen from Fig. 2, this procedure is followed until all plant systems that could affect the course of events of this accident have been considered. Clearly, if a method exists by which the failure probabilities of each system on the event tree can be determined, the overall probability for each sequence can be calculated. An analysis of the effect of the failures that occur allows us to predict the types of consequences expected. Note that the top line in

Fig. 2, which has only the pipe break as a single failure, represents the normally analyzed design-basis accident for reactors. Thus, with all the engineered safety systems working as designed, only a very small release of radioactivity occurs as compared with the bottom line, which involves additional failures and produces a very large release.

After a complete analysis of the event tree, it is possible to generate a histogram of the type shown in Fig. 3. This curve, which presents accident frequency vs. consequences, demonstrates the overall risks to the public and allows computation of expected, or probability weighted, consequences.

The study is developing a series of event trees that are judged to contain the dominant accident sequences for each initiating event. Each tree will yield information of the type presented in Fig. 3. So long as these events are independent, the results can be combined into a final curve like Fig. 3, representing the combined results of all the major initiating events.

Fault Trees

Fault trees provide a method for determining the probabilities needed for the event trees. The logic used by fault trees is almost the reverse of the logic for event trees, in that the fault trees start with an undesired event and identify the ways it may have been caused. Figure 4 shows the first few steps in a fault tree whose top event represents failure of electric power to engineered safety features (ESFs). The first step in the logic recognizes that loss of either d-c or a-c power could cause the failure because a-c power provides the energy needed and d-c power energizes the control circuits needed to turn on the a-c power. These two events are coupled by an "or" gate, which tells the analyst that the probability of the top event is the sum of the probabilities of each event. The figure next develops the a-c power failure. Since off-site power from either the utility network or the station diesels is available, both must be lost before a-c power is lost. These two events are therefore coupled by an "and"

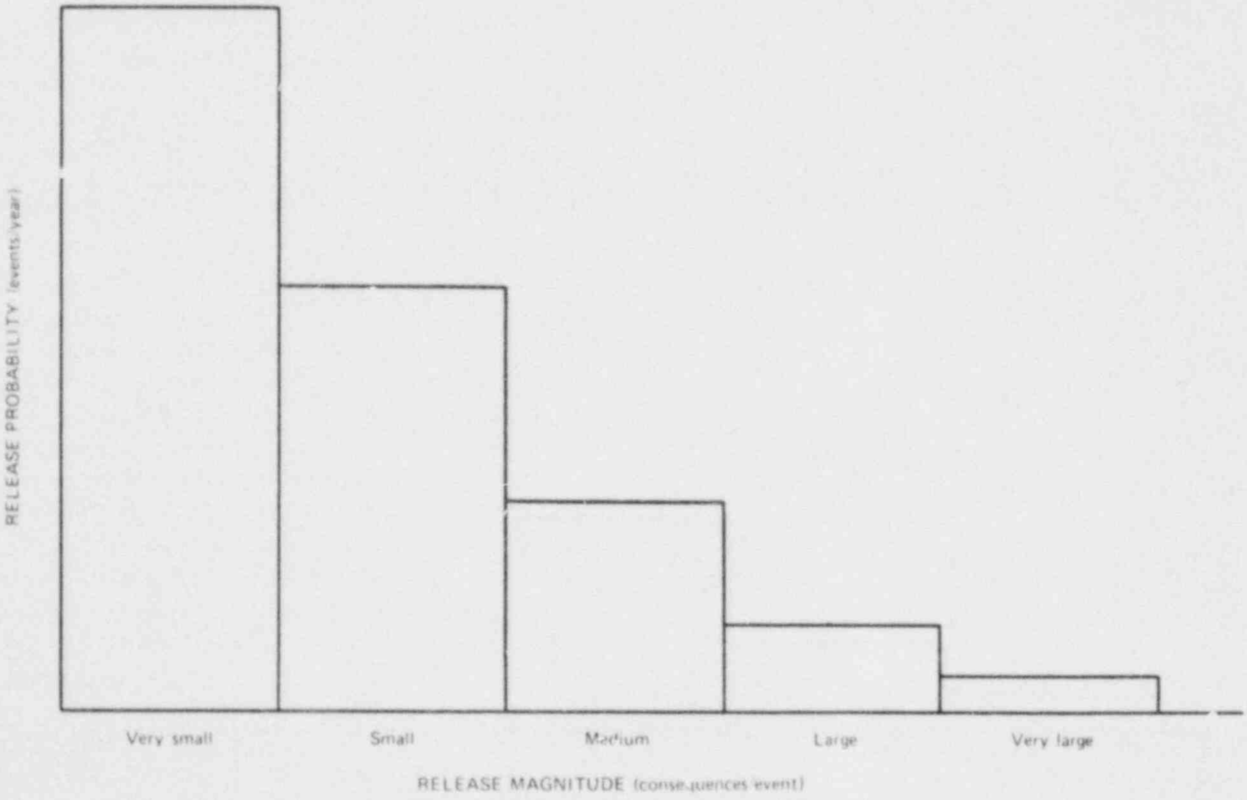

Fig. 3 Histogram of consequences.

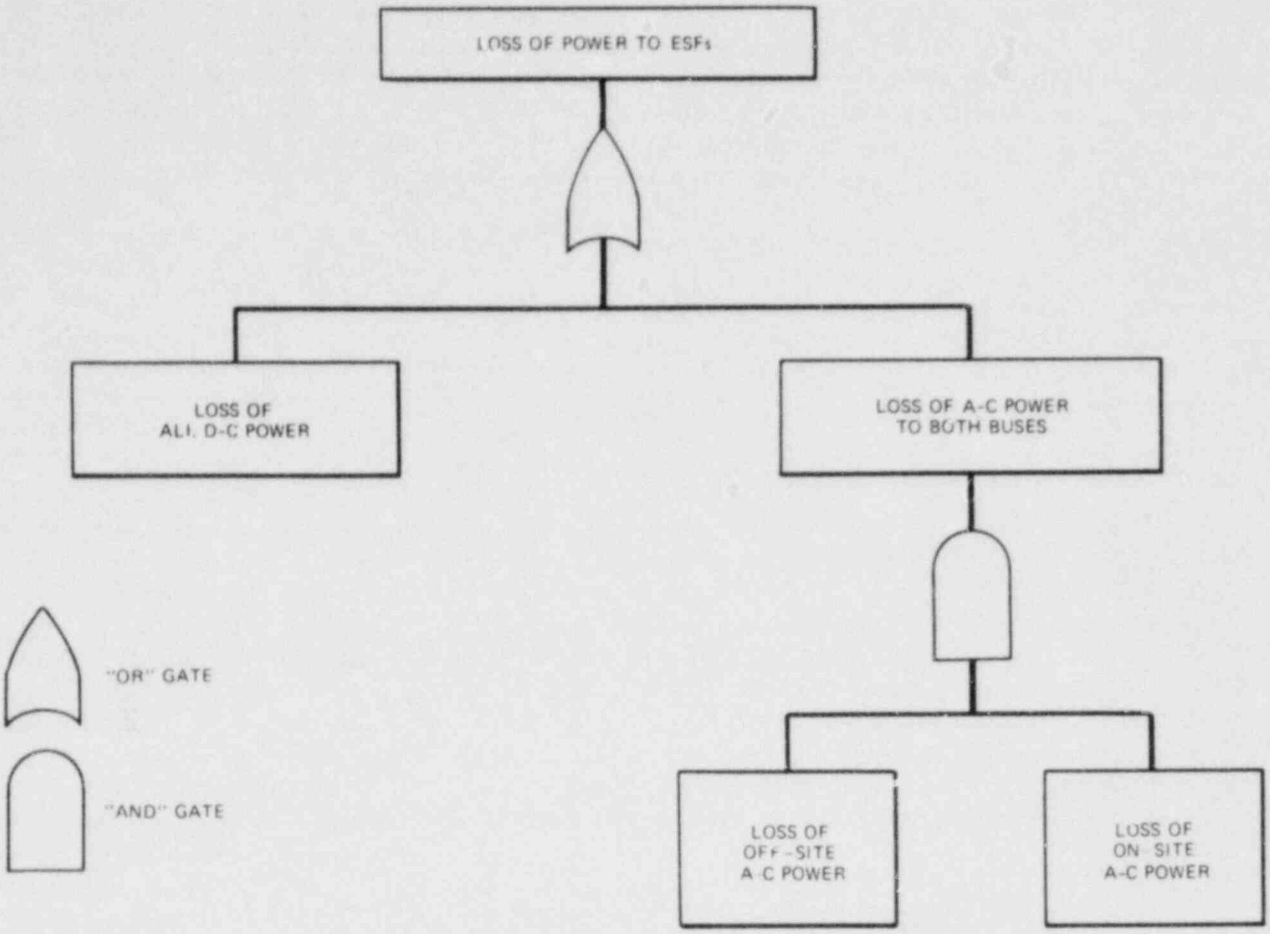

Fig. 4 Simplified fault tree on electric powers.

gate, which tells the analyst that the probability of losing a-c power is the product of the probabilities of losing off-site and on-site a-c power.

With a detailed knowledge of the system, a fault-tree analyst can continue developing the tree until all ways of losing power are identified as a series of equipment failures or human errors. The failure rates of components can then be assigned by reliability experts familiar with the applicable component failure rates in commercial service similar to that in nuclear plants. In the same way the probability of human errors can be assigned by experts in human factors.

Clearly, the exact failure rates due to human error and equipment failure are not known. Thus each assigned probability also has an assigned error that represents how precisely this value is known. In some cases these errors may be a factor of 10 or larger. The failure rates used in the study are based on the analysis of large data banks that have to be accumulated by reliability analysts. Once the failure rates of the various components and their errors have been assigned, a computer is used to calculate the probability of occurrence of the top event on the tree and its error. This value is then used in the branch of the event tree which was used to define the top event in the fault tree.

To be useful for risk analysis, a fault tree must be constructed in sufficient detail to identify all the different causes of failure that contribute significantly to system failure. This is a tedious and time-consuming process for a facility as large as a reactor. The accuracy of the fault tree does depend in part on the skill of the analyst. Despite this drawback, experience has shown that fault trees do provide a logical approach to analyzing system failures and do yield consistently good results when used by skilled technicians who understand the system being analyzed.

The study has been fortunate in acquiring about 15 people skilled in these techniques. For the most part, these people are on loan from Boeing Company, Aerojet Nuclear Company, Sandia Laboratories, and Lawrence Livermore Laboratory. When this study started, there were no fault-tree analysts available within the AEC staff. One of the problems that would have to be overcome before this technique could have widespread use in the nuclear industry is the shortage of trained analysts.

CURRENT STATUS AND CONCLUSIONS

The project has been in progress for over a year, and with one exception (task 7) all the tasks are well under way. There are a number of event trees being constructed for both pressurized-water and boiling-water reactors. Those concerned with the LOCA are nearing completion, and various versions of all the system fault trees that are needed to quantify the probabilities involved in the LOCA have been drawn. About half of these are in the process of quantitative analysis. Two probabilistic atmospheric-dispersion models are under development, one a fairly simple model adequate for short-distance calculations and the other more involved for long-distance calculations. Calculations are now being performed to define health effects due to various levels of doses from various isotopes. Work on the definition of risks due to dam failures, toxic chemicals, and airplane crashes is about 70% completed.

The final task, a quantitative overall risk assessment, requires the results of the other tasks and remains to be done. The analytical work should be completed early in 1974; however, preparing a draft, circulating it for comment, and then integrating the comments into the final report will take several months. The final report on the project should be available in the summer of 1974.

As a result of the work done so far, some general conclusions have been reached.

We are convinced that the above-described approach is capable of providing useful estimates of the risk to the public from reactor accidents. Although these risk estimates will include uncertainties in the magnitude of probabilities and consequences, to date we have found no case where the uncertainties are large enough to destroy the usefulness of the values obtained.

Two of the most common criticisms of the quantitative methodologies we are using are (1) that the reliability data required are not known with sufficient precision and (2) that they do not account for the effects of human interaction and operating procedures on system availability. We have found that, although some parts of the data required are in fact not well known, the effect on the uncertainty of the overall results is nevertheless small enough to make the results useful for the purposes of this study. In addition, we have found that the methodology is sufficiently flexible to allow the effects of human errors and operating procedures to be meaningfully computed. In fact, in some systems these two factors are large contributors to system unreliability.

The methodology being used will predict the most probable consequences of a given accident as well as the probabilities that smaller or larger consequences may result. Therefore a much better understanding of the spectrum of possible consequences will be provided. It seems that the understanding most people have of serious nuclear accidents has been greatly distorted by the "worst-case" analysis used in previous studies. In particular, these worst-case analyses have ignored a number of factors that would significantly reduce the consequences in any real case. Specifically those analyses have assumed that a higher fraction of the radioactivity is released from the fuel than experiments indicate and have ignored some natural processes by which radioactive material would be deposited inside containment. They have also ignored the very important factor that, in an accident where large quantities of radioactivity are released, the self-heating of the radioactivity itself causes the gases that are emitted to rise, thereby reducing the dose. Further, in many of the previous worst-case estimates, no credit is taken for the shielding effects of buildings. Such analyses tend to consider physically impossible cases and have probably overestimated the most likely outcome of severe accidents by factors of 10 or more.

Finally, many people have great hopes that this study will solve some of the major obstacles we currently face in the matter of public acceptance of nuclear power. Although we share this hope, we believe it is probably somewhat optimistic. No matter what results we obtain, some people may be comforted and some may be alarmed. One very difficult problem will be that of being able to effectively communicate the probabilistic ideas needed to fully understand the study. However, the study should provide another way of communicating with the public on reactor risks and should provide a structure to help bring more logic and less emotion into the discussions. A short study like this can be viewed only as a first step to a totally complete analysis of the problem. By the same token, we are sure that the work we will complete by the summer of 1974 will cover enough ground to be of significant use. Once it is complete, many people will find ways to improve it, and the AEC will find that continuing work along these lines will be useful.

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1. Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants, USAEC Report WASH-740, March 1957.
2. AEC Releases Final Draft of Reactor Safety Report and Working Papers on 1965 Accident Study, AEC Press Release R-252, June 25, 1973.
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An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants

Adapted from the draft Summary Report of WASH-1400

The Reactor Safety Study was sponsored by the U. S. Atomic Energy Commission[1] to estimate the public risks that could be involved in potential accidents in commercial nuclear power plants of the type now in use. It was performed under the independent direction of Professor Norman C. Rasmussen of the Massachusetts Institute of Technology. The risks had to be estimated, rather than measured, because although there are about 50 such plants now operating, there have been no nuclear accidents to date resulting in significant releases of radioactivity in U.S. commercial nuclear power plants. Many of the methods used to develop these estimates are based on those that were developed by the Department of Defense and the National Aeronautics and Space Administration in the last 10 years and are coming into increasing use in recent years.

The objective of the study was to make a realistic estimate of these risks and, to provide perspective, to compare them with non-nuclear risks to which our society and its individuals are already exposed. This information may be of help in determining the future reliance by society on nuclear power as a source of electricity.

The results from this study suggest that the risks to the public from potential accidents in nuclear power plants are comparatively small. This is based on the following considerations:

a. The possible consequences of potential reactor accidents are predicted to be no larger, and in many cases much smaller, than those of non-nuclear accidents. The consequences are predicted to be smaller than people have been led to believe by previous studies which deliberately maximized estimates of these consequences.

b. The likelihood of reactor accidents is much smaller than that of many non-nuclear accidents having similar consequences. All non-nuclear accidents examined in this study, including fires, explosions, toxic chemical releases, dam failures, airplane crashes, earthquakes, hurricanes and tornadoes, are much more likely to occur and can have consequences comparable to, or larger than, those of nuclear accidents.

Figures 1-1, 1-2, and 1-3 compare the nuclear reactor accident risks predicted

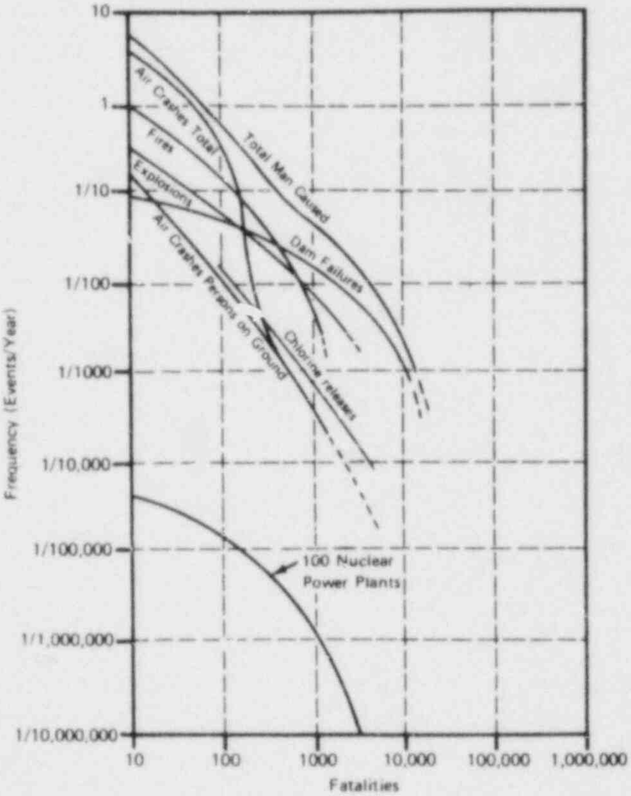

FIGURE 1-1 Frequency of Fatalities due to Man-Caused Events

Notes:
1. Fatalities due to auto accidents are not shown because data are not available. Auto accidents cause about 50,000 fatalities per year.
2. Approximate uncertainties for nuclear events are estimated to be represented by factors of 1/4 and 4 on consequence magnitudes and by factors of 1/5 and 5 on probabilities.

For natural and man caused occurrences the uncertainty in probability of largest recorded consequence magnitude is estimated to be represented by factors of 1/20 and 5. Smaller magnitudes have less uncertainty.

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[1] The work, originally sponsored by the U.S. Atomic Energy Commission, was completed under the sponsorship of the U.S. Nuclear Regulatory Commission, which came into being on January 19, 1975.

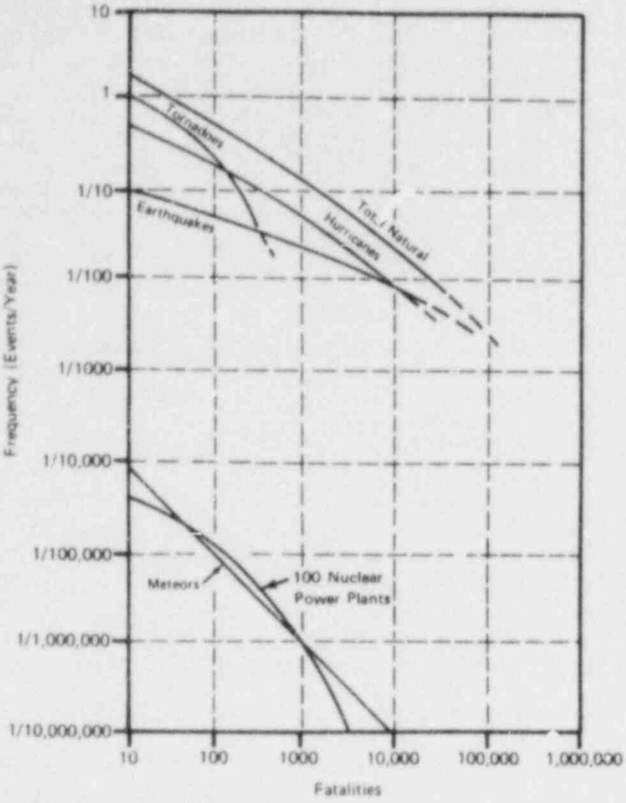

FIGURE 1-2 Frequency of Fatalities due to Natural Events

Notes:
1. For natural and man caused occurrences the uncertainty in probability of largest recorded consequence magnitude is estimated to be represented by factors of 1/20 and 5. Smaller magnitudes have less uncertainty.
2. Approximate uncertainties for nuclear events are estimated to be represented by factors of 1/4 and 4 on consequence magnitudes and by factors of 1/5 and 5 on probabilities.

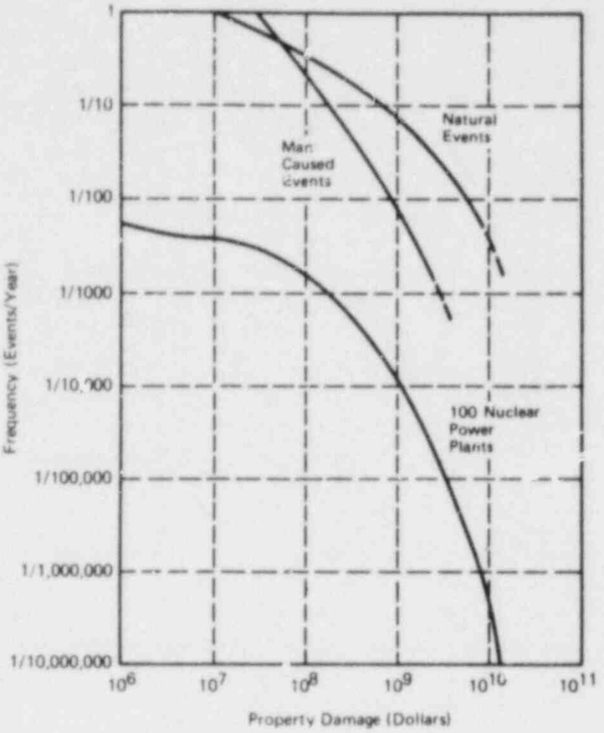

FIGURE 1-3 Frequency of Property Damage due to Natural and Man-Caused Events

Notes:
1. Property damage due to auto accidents is not included because data are not available for low probability events. Auto accidents cause about $15 billion damage each year.
2. Approximate uncertainties for nuclear events are estimated to be represented by factors of 1/5 and 2 on consequence magnitudes and by factors of 1/5 and 5 on probabilities.
3. For natural and man caused occurrences the uncertainty in probability of largest recorded consequence magnitude is estimated to be represented by factors of 1/20 and 5. Smaller magnitudes have less uncertainty.

for the 100 plants expected to be operating by about 1980 with risks from other man-caused and natural events to which society is generally already exposed. The following information is contained in the figures:

a. Figures 1-1 and 1-2 show the likelihood and number of fatalities from both nuclear and a variety of non-nuclear accidents. These figures indicate that non-nuclear events are about 10,000 times more likely to produce large numbers of fatalities than nuclear plants.[1]

b. Figure 1-3 shows the likelihood and dollar value of property damage associated with nuclear and non-nuclear accidents. Nuclear plants are about 1000 times less likely to cause comparable large dollar value accidents than other sources. Property damage is associated with three

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[1] The fatalities shown in Figs. 1-1 and 1-2 for the 100 nuclear plants are those that would be predicted to occur within a short period of time after the potential reactor accident. This was done to provide a consistent comparison to the non-nuclear events which also cause fatalities in the same time frame. As in potential nuclear accidents, there also exist possibilities for injuries and longer term health effects from non-nuclear accidents. Data or predictions of this type are not available for non-nuclear events and so comparisons cannot easily be made.

effects:

1. the cost of relocating people away from contaminated areas,
2. the decontamination of land to avoid overexposing people to radioactivity.
3. the cost of ensuring that people are not exposed to potential sources of radioactivity in food and water supplies.

In addition to the overall risk information in Figs. 1-1 through 1-3, it is useful to consider the risk to individuals of being fatally injured by various types of accidents. The bulk of the information shown in Table 1-1 is taken from the 1973 Statistical Abstracts of the U.S. and applies to the year 1969, the latest year for which these data were tabulated when this study was performed. The predicted nuclear accident risks are very small compared to other possible causes of fatal injuries.

In addition to fatalities and property damage, a number of other health effects could be caused by nuclear accidents. These include injuries and long-term health effects such as cancers, genetic effects, and thyroid gland illness. The early illness expected in potential accidents would be about 10 times as large as the fatalities shown in Figs. 1-1 and 1-2; for comparison there are 8 million injuries caused annually by other accidents. The number of cases of genetic effects and long-term cancer fatalities is predicted to be smaller than the normal incidence rate of these diseases. Even for a large accident, the small increases in these diseases would be difficult to detect from the normal incidence rate.

Thyroid illnesses that might result from a large accident are mainly the formation of nodules on the thyroid gland; these can be treated by medical procedures and rarely lead to serious consequences. For most accidents, the number of nodules caused would be small compared to their normal incidence rate. The number that might be produced in very unlikely accidents would be about equal to their normal occurrence in the exposed population. These would be observed during a period of 10 to 40 years following the accident.

While the study has presented the estimated risks from nuclear power plant accidents and compared them with other risks that exist in our society, it has made no judgment on the acceptability of nuclear risks. The judgment as to what level of risk is acceptable should be made by a broader segment of society than that involved in this study.

TABLE 1-1 AVERAGE RISK OF FATALITY BY VARIOUS CAUSES

Accident Type	Total Number	Individual Chance per Year
Motor Vehicle	55,791	1 in 4,000
Falls	17,827	1 in 10,000
Fires and Hot Substances	7,451	1 in 25,000
Drowning	6,181	1 in 30,000
Firearms	2,309	1 in 100,000
Air Travel	1,778	1 in 100,000
Falling Objects	1,271	1 in 160,000
Electrocution	1,148	1 in 160,000
Lightning	160	1 in 2,000,000
Tornadoes	91	1 in 2,500,000
Hurricanes	93	1 in 2,500,000
All Accidents	111,992	1 in 1,600
Nuclear Reactor Accidents (100 plants)	-	1 in 5,000,000,000

Radiological Impact of Airborne Effluents of Coal-fired and Nuclear Power Plants

J. P. McBride, R. E. Moore, J. P. Witherspoon, and R. E. Blanco*

Nucl. Safety, 19(**4**): 497-501 (July-August 1978)

[Editor's Note: The following article was adapted by the *Nuclear Safety* Staff from a report of the same title by the indicated authors, which was published in August 1977 by Oak Ridge National Laboratory as Report ORNL-5315. The report and its summary here provide significant data for the continuing comparative analyses of the costs, risks, and benefits of various energy systems.]

Abstract: *The radiological impact of naturally occurring radionuclides in airborne effluents of a model coal-fired steam plant [1000 MW(e)] is evaluated, assuming a release to the atmosphere of 1% of the ash in the coal burned, and compared with the impact of radioactive materials in the airborne effluents of model light-water reactors [1000 MW(e)]. The principal exposure pathway for radioactive materials released from both types of plants is ingestion of contaminated foodstuffs. For nuclear plants, immersion in the airborne effluents is also a significant factor in the dose commitment. Assuming that the coal burned contains 1 ppm uranium and 2 ppm thorium together with their decay products and using the same impact analysis methods used in evaluating nuclear facilities, the maximum individual dose commitments from the coal plant for the whole body and most organs (except the thyroid) are shown to be greater than those from a pressurized-water reactor and, with the exception of the bone and kidney doses, less than those from a boiling-water reactor. With the exception of the bone dose, the maximum individual dose commitments from the coal plant are less than the numerical design guideline limits listed in 10 CFR 50, Appendix I, for light-water reactors. Population dose commitments from the coal plant are higher than those from either nuclear plant, except for the thyroid dose from the boiling-water reactor.*

Studies have been made in the past few years of the amounts of naturally occurring radioactive substances emitted in the airborne effluents of coal-fired power plants[1-5] as well as the radioactivity in the releases from nuclear power plants.[3,6] The potential radiological impact of these substances has generally been evaluated in terms of the radiation protection guides set forth by the Federal Radiation Council, the International Commission on Radiological Protection, and the *Code of Federal Regulations*, Title 10, Part 20. The studies showed that releases of radioactive materials from coal-fired plants and nuclear plants were well within the limits specified in these regulations. However, where estimates were made of the radiological impact of stack effluents of the coal plants, the studies were limited to an assessment of the radiological dose through the inhalation pathway and did not include the ingestion pathway.[3,7] Ingestion is the important pathway when considering radioactive materials such as radium and thorium. Recently, new regulations have been issued which contain numerical design guides for limiting the release of radioactive materials from light-water-reactor (LWR) nuclear power plants to values which are "as low as is reasonably achievable" (ALARA).[8] These values are about 100 times lower than the radiological guides in the previous regulations. Therefore we undertook to reevaluate airborne releases of radioactive materials from coal-fired plants, to estimate the potential radiological impact (doses to individuals and populations) of these releases, and to compare them with the airborne releases and radiological impacts from nuclear plants that conform to the new regulations. The method used was (1) to estimate the annual amounts of airborne radioactive materials released from a model advanced 1000-MW(e) coal-fired plant (the source term), (2) to calculate the radiological doses received via all exposure pathways, and (3) to compare the estimated doses with the design objective guidelines specified in the *Code of Federal Regulations* for LWR power stations (10 CFR 50, Appendix I) and with the estimated radiological doses from the airborne effluents of a model 1000-MW(e) pressurized-water reactor (PWR) and a model 1000-MW(e) boiling-water reactor (BWR). Variables considered for the coal-fired plant were the amounts of radioactive materials in various types of coal and coal ashes, efficiency of fly-ash collection, stack height, and modes by which radioactive materials and radiation are transferred to man (i.e., ingestion, inhalation, direct radiation, etc.).

The maximum individual dose commitments and the population dose commitments are calculated considering the estimated releases of radioactive materials from the model 1000-MW(e) coal-fired and nuclear power plants. The source term for the coal plant is

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given in Table 1 and assumes a concentration of 1 ppm uranium and 2 ppm thorium in the coal and a release of 1% of the fly ash.

Table 1 Estimated Annual Airborne Radioactive Materials Released from a Model 1000-MW(e) Coal-Fired Power Plant (Source Term)*

Isotope	Releases, Ci/year	Isotope	Releases, Ci/year
^{238}U Chain		**^{232}Th Chain**	
^{238}U	8×10^{-3}	^{232}Th	5×10^{-3}
^{234}Th	8×10^{-3}	^{228}Ra	5×10^{-3}
^{234m}Pa	8×10^{-3}	^{228}Ac	5×10^{-3}
^{234}U	8×10^{-3}	^{228}Th	5×10^{-3}
^{230}Th	8×10^{-3}	^{224}Ra	5×10^{-3}
^{226}Ra	8×10^{-3}	^{212}Pb	5×10^{-3}
^{218}Po	8×10^{-3}	^{212}Bi	5×10^{-3}
^{214}Pb	8×10^{-3}	^{208}Tl	1.8×10^{-3}
^{214}Bi	8×10^{-3}		
^{214}Po	8×10^{-3}	**Radon Releases**	
^{210}Pb	8×10^{-3}	^{220}Rn	0.4
^{210}Bi	8×10^{-3}	^{222}Rn	0.8
^{210}Po	8×10^{-3}		
^{235}U Chain			
^{235}U	3.5×10^{-4}		
^{231}Th	3.5×10^{-4}		
^{231}Pa	3.5×10^{-4}		
^{227}Ac	3.5×10^{-4}		
^{227}Th	3.5×10^{-4}		
^{223}Ra	3.5×10^{-4}		
^{219}Rn	3.5×10^{-4}		
^{211}Pb	3.5×10^{-4}		
^{211}Bi	3.5×10^{-4}		
^{207}Tl	3.5×10^{-4}		

*Assumptions: (1) the coal contains 1 ppm uranium and 2 ppm thorium; (2) ash release is 1%; (3) ^{220}Rn is produced from ^{232}Th in the combustion gases at the rate of 1.38×10^{-9} Ci sec^{-1} g^{-1} of thorium; (4) the annual release of natural uranium is 2.32×10^{4} g and of ^{232}Th is 4.64×10^{4} g; and (5) 15 sec is required for the gases to travel from the combustion chamber to the top of the stack.

The assumed release to the atmosphere of 1% of the total ash in the coal burned approximates the Environmental Protection Agency (EPA) regulations for the release of particulates to the atmosphere. The percentage of ash released by other coal plants throughout the United States is, in general, higher than 1% and in some cases more than an order of magnitude higher. Thus the calculated source term represents the radioactive release when advanced technology is used for abatement of particulate emissions. The use of coal containing higher uranium and thorium concentrations and higher ash releases could result in dose commitments between one and two orders of magnitude higher than those calculated.

Airborne releases (source term) are given in Table 2 for a model 1000-MW(e) PWR and a model 1000-MW(e) BWR with recirculating U-tube-type steam generators as given in the *Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors* (GESMO).[9] The radwaste systems for each type of plant contain equipment and features typical of current operating plants; however, the plants are models, and the source terms are not directly applicable to a particular operating reactor.

Table 2 Estimated Annual Airborne Releases (Source Terms) from a Model 1000-MW(e) BWR and a Model 1000-MW(e) PWR*

Radionuclide	BWR, Ci/year	PWR, Ci/year
^{41}Ar	25	25
^{83m}Kr	†	1
^{85m}Kr	150	16
^{85}Kr	290	470
^{87}Kr	200	3
^{88}Kr	240	23
^{131m}Xe	18	82
^{133m}Xe	†	120
^{133}Xe	3,200	12,000
^{135m}Xe	740	†
^{135}Xe	1,100	86
^{138}Xe	1,400	†
^{131}I	0.3	0.025
^{133}I	1.1	0.023
^{14}C	9.5	8
^{3}H	43	1,100

*Source terms for the nuclear plants are from Ref. 9.
†Annual release <1 Ci.

Both the model coal plant and the nuclear power plants were assumed to be located in the Midwest, with meteorology characteristic of St. Louis, Mo.[10] The surrounding population was assumed to be 3.5 million people out to 88.5 km from the facility, the average population distribution around three midwestern population centers.[11] The population density in persons per square kilometer assumed for a radial distance of 8 km from the facilities[11] was 37; from 8 to 40 km, it was 49; and from 40 to 88.5 km, 170.

As shown in Table 3, the maximum individual dose commitments calculated for the model coal plant were greater than those for the PWR, except for thyroid dose, but were less than those for the BWR, except for the bone dose. In general, however, whole-body and all organ doses for both the coal and nuclear plants were within the same order of magnitude.

Whole-body and organ population dose commitments within a radius of 88.5 km, as given in Table 4, ranged in all cases from 50% higher to several times higher for the coal plant than for the nuclear plants, except for thyroid dose from the BWR, which was 50 to 100% higher than the thyroid dose from the coal plant.

Table 3 Maximum Individual Dose Commitments from the Airborne Releases of Model 1000-MW(e) Power Plants (mrems/year)*

Organ	Coal-fired plant†	BWR‡	PWR‡	10 CFR 50, Appendix I guides
Whole body	1.9	4.6	1.8	5
Bone	18.2	5.9	2.7	15§
Lungs	1.9	4.0	1.2	15§
Thyroid	1.9	36.9¶	3.8	15§
Kidneys	3.4	3.4	1.3	15§
Liver	2.4	3.7	1.3	15§
Spleen	2.7	3.7	1.1	15§

*The maximum individual dose commitments are for a midwestern site and are estimated at the plant boundary at 500 m from the release points. The dose commitments are less at greater distances. The ingestion component of the dose commitment is based on the assumption that all food is grown and consumed at the reference locations.

†The dose commitments are essentially the same for all stack heights from 50 to 300 m, including the plume rises resulting from buoyancy of hot stack emissions. A 1% ash release was assumed. The coal was assumed to contain 1 ppm uranium and 2 ppm thorium. Some coals may have higher uranium and thorium concentrations. For the concentration ranges of coals, see Table 3 in Report ORNL-5315.

‡Source terms for the nuclear plants are from Ref. 9. The release height was assumed to be 20 m with no plume rise.

§Design guides for doses from iodine and particulates.

¶Assumes dairy cow on pasture at site boundary for entire year. The thyroid dose estimated in GESMO (Ref. 9, p. IV C-115) for the same source term was 11.7 mrems/year.

Table 4 Population Dose Commitments from the Airborne Releases of Model 1000-MW(e) Power Plants (man-rems/year; 88.5-km radius)*

Organ	Coal-fired plant† stack height, m				BWR‡	PWR‡
	50	100	200	300		
Whole body	23	21	19	18	13	13
Bone	249	225	192	180	21	20
Lungs	34	29	23	21	8	9
Thyroid	23	21	19	18	37	12
Kidneys	55	50	43	41	8	9
Liver	32	29	26	25	9	10
Spleen	37	34	31	29	8	8

*The population dose commitments are for a midwestern site. The ingestion components of the dose commitment are based on the assumption that all food is grown and consumed at the reference locations.

†A plume rise due to buoyancy of hot stack emissions was assumed. The dose commitments are for an ash release of 1% and for coal containing 1 ppm uranium and 2 ppm thorium.

‡Source terms for the nuclear plants are from Ref. 9. The release height was assumed to be 20 m with no plume rise.

The major pathway of exposure for the radioactivity in the emissions from both the coal plant and the nuclear plants was ingestion of contaminated foodstuffs. For the nuclear plants the pathway via immersion in the airborne effluents was also significant. Computer codes developed at Oak Ridge National Laboratory were used to assess the doses.[12-16]

The present survey is limited to a comparison of the radiological impacts of the airborne effluents from coal-fired and nuclear power plants. A comparison of the radiological impact of the liquid effluents from coal-fired and nuclear power plants was not made.

The results of this analysis should not be construed to represent a complete comparison of the radiological impact of a nuclear energy economy vs. a coal economy. A complete comparison would include the entire nuclear fuel cycle for a nuclear power economy (i.e., mining and milling operations, enrichment facilities, fuel fabrication and refabrication plants, fuel reprocessing, and waste management) and an analysis of the impact of other phases of the coal fuel cycle, such as mining and waste management.

The release of naturally occurring radioactivity from coal-fired power plants is in addition to the release of other toxic materials.[5] The results of our study show that a complete analysis comparing the environmental effects of coal-burning power plants vs. nuclear power plants should include the radiological impacts from both types of plants.

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Risks Associated with Nuclear Power

National Academy of Sciences*

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[Editor's Note: The report from which this article is adapted had its origin in 1975 in a request by Philip Handler, President of the National Academy of Sciences, to its Committee on Science and Public Policy (COSPUP), to review the draft of the *Reactor Safety Study*[1] (WASH-1400, also known as the Rasmussen Report). The COSPUP welcomed this charge and decided to undertake a survey of all the types of risks associated with the nuclear power program through a critical review of the literature. At the same time the National Research Council was organizing a Committee on Nuclear and Alternative Energy Systems (CONAES) for a broad study requested by the Energy Research and Development Administration (ERDA), now the Department of Energy (DOE). It was agreed that the literature review proposed by COSPUP would provide information that could contribute significantly to the CONAES study. Accordingly, the COSPUP study was supported largely by funds made available by ERDA and DOE for the CONAES effort; additional support was provided by the National Academy of Sciences. This article consists primarily of the "Introduction" (Section I) and "Overall Assessment" (Section VIII) of the "Summary and Synthesis Chapter"[2] of the COSPUP literature review. The "Summary and Synthesis Chapter" was released in April 1979—before completion of the full report—because of the intensity of current interest in the subject.]

The report from which this article is adapted is a critical review of the literature pertaining to the risks associated with nuclear electric power. The review was sponsored by the Committee on Science and Public Policy of the National Academy of Sciences. While the full report consisting of over 25 chapters has not yet been published, this article presents highlights from the "Summary and Synthesis Chapter"[2] which was released separately. The essential aspects of the scope and limitations of this work include the following:

—Since a really comprehensive review of the many scores of thousands of technical documents in the areas covered could not be attempted in a report of this size, attention has been focused primarily, but not exclusively, on the review literature, i.e., on surveys and evaluations of available knowledge in the field.

—Even this survey of review literature is far from exhaustive; however, the reviewers have striven to take into account all significant points of view in the issues treated, using as sources many items in the primary technical literature and attempting to find the primary sources for assertions that have been made in books and articles written for nonspecialist readers. Issues have been identified in which—after they have been reduced to purely factual terms—there is now essentially no disagreement in the technical community. On issues where significant disagreement, or simply lack of knowledge, persists, the reviewers have usually tried not to pass judgment but have tried to identify the extent of the support for each of the views discussed and to point out a few of what seem to us to be relevant common-sense considerations.

[Readers who are especially concerned with the assessment of relative credibility among divergent judgments by experts may find it useful to review the discussion of biases in Section III.2 of Chapter 1 (Ref. 3) and assessment of controversies in Section V.3 of Chapter 1 (Ref. 3).]

It cannot be stressed too strongly that the information surveyed in this report provides *only one of several equally important inputs* for the making of policy decisions on nuclear electric power. Decisions of this sort are not simply yes or no; they are decisions between alternatives, and such decisions cannot be made without assembling, *for each of the alternatives,* the best available estimates of such things as *benefits, costs, risks, and time scales.* This report provides information only on risks and only for one of the ways of producing electric power. While there is occasional mention of benefits, etc., of nuclear power and occasional mention of risks associated with other methods of producing electricity, such comments are few and far between and are introduced only to provide an orienting perspective.

This report deals with a very wide variety of risk issues that have been classified into four more or less orthogonal modes:

1. Possible harmful *effects* of concern are:
   —Early deaths and injuries (occupational and public).
   —Delayed deaths and illnesses (occupational and public) in the present generation or its immediate descendants.

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*Prepared by the Committee on Literature Survey of Risks Associated with Nuclear Power, W. Conyers Herring, Chairman, for the Committee on Science and Public Policy of the National Academy of Sciences.

- —Deaths and illnesses produced in more distant future generations.
- —Damage to property or means of production.
- —Damage to the environment (e.g., ecosystems, climate).
- —Damage to social or political institutions.

2. Several *kinds of immediate causes* might be responsible for such effects:

- —Routine releases of radioactivity or exposure of workers associated with normal operation of the various facilities making up the nuclear fuel cycle (see below); occasional accidental releases of radioactivity from such facilities.
- —Gradual, although perhaps unanticipated, escape of radioactivity to the environment over long periods of time (e.g., from waste-disposal sites).
- —Intentional employment of materials or facilities of a nuclear power program for the dispersal of radioactivity or construction of nuclear weapons.

3. These immediate causes can be associated with any of a variety of *facilities or processes* in the nuclear fuel cycle. A wide variety of these need to be considered not only because there are many sequential steps in the production of nuclear fuel, its utilization, and its ultimate disposal but also because in each of these steps there are a number of alternative technologies that may be used (see below).

4. Two types of *ultimate causes* may contribute to any of the immediate causes listed above: defects in equipment, or more generally in technology, and shortcomings of the people using it or regulating its use.

Figure 1 illustrates some of the details of the nuclear fuel cycle. The column of boxes and arrows summarizes the principal steps in the nuclear fuel cycles now used, or prominently discussed for future use, for the production of electricity in the United States. These steps extend from the initial mining of uranium (or thorium) at the top to the ultimate disposal of wastes at the bottom. The technologies involved at each stage have been described briefly in Chapter 2 (Ref. 3). Transportation operations are usually required at the places indicated by the arrows. At many stages in a nuclear power program, choices may be made between alternative technologies; some of the more important of these choices are noted in the next to the last column. The principal immediate causes of risk associated with each stage of the fuel cycle are identified at the right and left of the boxes—those associated with routine operation on the left and those associated with accident or malice on the right.

Most of the material presented in this summary is organized into sections according to the "kinds of immediate causes" listed above. This organization cuts across that used for the remaining chapters of the report,[3] most of which have dealt with specific stages in the fuel cycle. The central discussion of risks is presented in a section surveying some of the basic scientific facts required in assessing the various kinds of risks.

The variety of sequential and alternative technologies illustrated in Fig. 1 and the variety of risk issues that may be associated with each technology have dictated that not only the report as a whole but also the "Summary and Synthesis Chapter" from which this article is taken must be fairly long. Presented below, with minor editorial changes, is the concluding section of the "Summary and Synthesis Chapter."

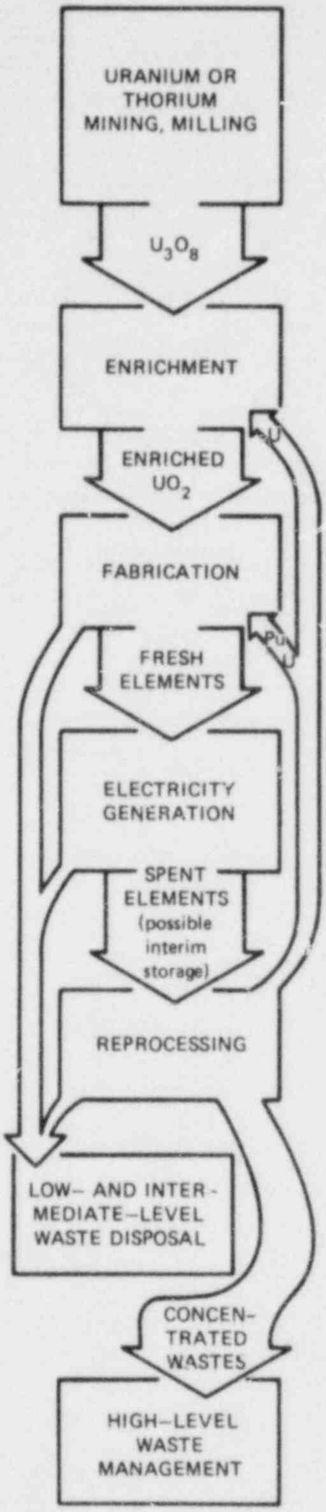
This overall assessment of the risks associated with nuclear power concentrates on risks of radiological origin, augmenting these only with some concerns arising from the weapons potential of nuclear fuels. The risks associated with nuclear power via various types of nonradiological injury to humans are much less important than the radiological risks and also much smaller than the nonradiological risks associated with most alternative means of producing electricity (coal, solar, etc.). Risks of ecological damage due to discharge of waste heat, although sometimes appreciable, are not unusual to nuclear power and can be reasonably well anticipated. The radiological risks to nonhuman life on land and in water have been ignored in this report, since these seem normally to be less serious than the corresponding risks to humans.

To assemble the knowledge of radiological risks to humans into a useful overall picture, we should consider, for each possible source of exposure, the following characteristics:

—The statistical expectation for the population dose equivalent in person-rems that will be delivered by this source per unit of electrical energy generated. (By this is meant the sum of the dose equivalents received by all exposed individuals.)

—The distribution of this dose equivalent in time, particularly as regards present versus future generations.

—The likelihood of catastrophes that will have an economic or psychological shock effect not measurable by the person-rem dose just described.



Routine Occurrences		Nonroutine Occurrences	Principal Available Technologies (U. S. present practice underlined)	Chapter (in Ref. 3)
• radon in mines • surface and groundwater contamination by tailings • radon from tailings • exposure of mill workers	URANIUM OR THORIUM MINING, MILLING		Open-pit or underground mines Th as well as U mining Cover tailings?	16, 17
	U_3O_8			
	ENRICHMENT	• theft of U-235 (if fuel highly enriched)	Alternatives: Gaseous diffusion, centrifuge, nozzle flow, lasers, etc. High or low enrichment	19, 25 25
	ENRICHED UO_2	• theft of U-235 in transit (if fuel highly enriched)		
	FABRICATION	• theft of Pu, U-235 • fire, sabotage	Alternative fuels: UO_2, (U, Pu) O_2, or fuels containing Th	20, 25
	FRESH ELEMENTS	• theft in transit • fire, accident, sabotage		25
• routine radiation release • occupational exposure	ELECTRICITY GENERATION	• accident, sabotage (including spent-fuel storage area)	Alternative reactor types: Light-water, heavy-water, gas-cooled, liquid-metal fast breeder, etc.	11 12–15
	SPENT ELEMENTS (possible interim storage)	• accident, sabotage in transit	Store spent fuel, reprocess it, or discard it?	
• routine radiation release	REPROCESSING	• fire, accident, sabotage, theft of U-235, U-233, Pu	Reprocess or not? Adapt to various kinds of fuels Avoid isolating Pu?	21
	LOW- AND INTERMEDIATE-LEVEL WASTE DISPOSAL	• leakage	Dilute and disperse vs. concentrate and contain	22
	CONCENTRATED WASTES	• accident, sabotage in transit		23, 25
	HIGH-LEVEL WASTE MANAGEMENT	• accident, sabotage • geological change	Choice of type of disposal site Utilization of actinides and some fission products	22

Fig. 1 Principal risks and relevant alternatives in the nuclear fuel cycle.

—The reliability with which these quantities (statistical expectation of population dose and probabilities of catastrophes) can be estimated for a given assumed technology. In other words, how much spread is there between the estimates of highly qualified persons or groups, and how sensitive are these estimates to factors as yet inadequately known?

—The extent to which these estimates can be modified by plausible modifications in the technology used or by such human factors as regulations, procedures, and training. Although it is natural to focus attention on opportunities for improvement, possibilities for regression should also be borne in mind.

—Serious gaps that may exist in our present knowledge of how to quantify the risk, or of possibilities for mitigating it, especially when these gaps might be filled by appropriate research.

Table 1 summarizes the characteristics just mentioned for each of the major sources of risk identified. The central columns give the statistical expectation of the population-dose equivalent per gigawatt year of electricity generated [GW(e)year] for each source of risk; for cases involving accidental occurrences, this means that the population dose delivered when an accident occurs is multiplied by the probability, per GW(e)year, that such an accident will occur. The conversion of these figures, in person-rems per GW(e)year, to ultimate cancer fatalities, genetic abnormalities, etc., is somewhat uncertain; the figure currently most widely used is that, on the average, there will be about one eventual excess cancer death per 5000 person-rems of whole-body dose. Inspection of the table suggests the following overall conclusions:

—Of the risks whose magnitudes can be reasonably accurately estimated, the most serious one is the exposure of future generations to ^{14}C from reactors and reprocessing plants. Prospects for reducing this considerably are good, since it is possible to collect and sequester carbon at reprocessing plants and store it as waste. Release from reactors is several times smaller.

—Of the risks about whose magnitude there is great uncertainty, but which can in principle be quantified, the one that may possibly—although possibly not—deliver the largest population-dose expectation is the exposure of populations in the extremely remote future (time scale of the order of 10 000 years) to ^{222}Rn emitted from abandoned piles of ore tailings. This risk is very uncertain in magnitude, would be vastly decreased in a breeder economy, and would be manifested as an extremely minute change in background radiation on a very long time scale. This latter fact causes some people to consider discussion of the long-term risk pointless, but many would disagree, arguing that person-rem totals are an important consideration however slowly they may be accumulated.

—Of the remaining sources of risk, the one whose range of uncertainty extends to the largest values is reactor accidents. The statistical expectation of population dose from these may be significantly smaller or larger than that from other quantifiable sources. Several lines of research that are in progress or can soon be undertaken offer hope both for reducing the consequences of accidents (e.g., by prevention of overpressure rupture of the containment building) and for reducing the uncertainty in our estimates of the probabilities of serious accidents (e.g., reliability of core-cooling systems, likelihood of steam explosions).

—It is acknowledged that nuclear power programs are neither the cheapest nor the most satisfactory source of material for weapons, and nations that have thus far made explosive devices have not done so using power reactors. Nevertheless, the risks from a possible positive correlation of such programs with the proliferation of nuclear weapons or with terrorism are very disputable and cannot be quantified by technological analysis alone. Some informed evaluations have considered such risks to be small, but others—including the Flowers report,[4] the Fox report,[5] and the Ford–Mitre study[6]—have emphasized the possibility, which cannot be excluded on purely technological grounds, that these risks may significantly exceed all others in the nuclear fuel cycle.

—In none of the cases so far studied in the literature have alarmingly high values been estimated for the time-integrated population dose that people in the future might receive if buried wastes were to be leached by groundwater into the surface environment. Thus, although many authorities have called attention to gaps in our knowledge about some of the factors that bear on the probability and time scale of such eventual leaching, it is not necessary to strive for absolute assurance against escape. One can pursue the much more attainable goal of finding disposal sites for which the product of probability of escape times the consequences if escape occurs can be made reasonably small on the scale of normal-operation consequences.

This last conclusion is supported by a number of studies, and there seem to be no detailed analyses disagreeing with it. However, the relatively recent literature placing quantitative limits on consequences

Table 1 Summary of Risks Associated with Low-Level Radiation Exposures Attributable to the Production of Nuclear Electric Power

Source of risk	Section of Ref. 2	Expectation of population dose, in person-rems per GW(e)year of electricity produced, with present technology		Degree of uncertainty for a given technology	Opportunities for modification	Remarks
		Present generation	Future generations			
Occupational exposure	III	~1600[a]		Probably only a fraction of the value given	Probably modest, but data on variation with types of reactors and their ages are scanty	Mostly from reactor operation; some from mining
Public exposure from normal effluents	III, V.2	$\sim\left\{\begin{matrix}1100^{a,b}\\1350^{a,b}\end{matrix}\right.$	$\sim\left\{\begin{matrix}1700^{b}\\6000^{b}\end{matrix}\right.$	Probably only a fraction of the value given for the case of no reprocessing; a little more uncertain with reprocessing	Larger if escape of xenon[c] or ^{14}C (footnote *d*) is allowed to increase Future-generation doses severalfold; smaller if ^{14}C is captured in reprocessing[e]	Future-generation dose dominated by ^{14}C (half-life 5570 years)
Public exposure from tailings piles	V.1	Very small	Estimates for perpetually uncovered piles range from 1.5×10^5 to 2×10^6; actual values *may* be much less	Very uncertain, as result dependent on future population distribution, weather, and geology, especially with covering by transport of dust	*May* be greatly reduced by covering; surely greatly reduced by reburial, reduced by a factor of ~50 in a breeder economy	Incremental *dose rate* at all times a minute fraction of background; may be compensated at *very* long times by removal of uranium[f]
Reactor accidents	IV.2,3,4,5	*Reactor Safety Study*[g] estimates ~120; absence of major accidents[h] to date gives inequality $<10^4-10^5$	Much less than "present generation"	Conceded to be quite uncertain, with most qualified judgment, favoring values between a fraction of the *Reactor Safety Study* value and 100 times it	Might be appreciably reduced for light-water reactors; probably substantially less for at least some of the other reactor types	
Other accidents	IV.1,6	Very small, according to most studies	Much less than "present generation"	All literature is in reasonable agreement, except for a few workers who speculate on the possibility of higher releases for some transportation accidents[i]	Reprocessing plant accidents can occur only if there is reprocessing; transportation accidents can be decreased by "nuclear parks"	Accidents in reprocessing and perhaps in transportation, although rare, have the greatest possibilities to deliver sizable population doses
Leakage from waste repositories	V.3	Small[j]	Few attempts at quantitative estimation have been made; these have usually indicated small dose expectations even if leakage occurs[j]	Although active acceptance of the conclusions to the left is limited, there seem to be no specific dose and probability analyses disagreeing with them; some unresolved issues concerning likelihood of leakage	Although many of the proposed modes of disposal would yield low dose expectations, very careful site selection might make the expectations far lower still	Most important desideratum is to minimize chance of escape to the environment in the first few hundred years

Proliferation of nuclear weapons among nations	VII.1	Larger if nuclear warfare results; small otherwise	Very diverse judgments exist as to whether and in what manner a nuclear electric-power program will affect weapons proliferation	International centers;[k] coprecipitation of uranium and plutonium or isotopic denaturing of fissile uranium[l]	Suggestions associating nuclear power with proliferation most often do so via enrichment or reprocessing facilities or power reactors using highly enriched fuel
Terrorism	VII.2,3	Small unless successful terrorist acts become quite frequent or succeed in dispersing much more radioactivity than would be possible from a bomb or a spent-fuel shipment	Diverse judgments on motivations and capabilities of terrorists and of their preferences between nuclear and nonnuclear means; no serious antipopulation attempts to date	Can be reduced by avoiding use of highly enriched fuel, by measures similar to those on the line above, and in general by tightened security	Most plausible paths seem to be bomb construction or capture and dispersal of spent-fuel shipments

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[a] Figures given are whole-body doses, i.e., doses delivered at about the same level to all organs of the body. Particular organs sometimes receive rather larger doses; thus the overall probability of cancer induction may be larger, by a modest fraction, than it would be if only the whole-body dose were received.

[b] The upper figure is for the case of no fuel reprocessing; the lower for the case in which all fuel is reprocessed and plutonium as well as uranium is recycled.

[c] Figure tabulated assumes that short-lived xenon isotopes are held up in boiling-water reactors until most of their activity has decayed; past emissions from boiling-water reactors without such holdup have delivered population doses greater by something like 400 or 500 person-rems/GW(e)year. (See Section III.2 of Chapter 12.)[3]

[d] Some foreign reactors seem to produce considerably more ^{14}C than do U. S. reactors, possibly because of the presence of nitrogen. (See Section III.5 of Chapter 12.)[3]

[e] As detailed in Chapter 21 and Section V.3 of Chapter 22 (Ref. 3), it is likely that future reprocessing plants will sequester ^{14}C and store it as waste rather than discharging it to the environment. No such retention is likely for the rather smaller amounts of ^{14}C released from light-water reactors, but some other reactor types may release less of this isotope. (See Chapter 14, Section II.2, and Chapter 15.)[3]

[f] Time scale for the population dose from tailings is $\sim 10^5$ years; that for the decrease in natural ^{222}Rn due to consumption of uranium is $\sim 10^6 - 10^8$ years.

[g] *Reactor Safety Study.*[1]

[h] "Major accidents" defined as those releasing significant radioactivity to the environment.

[i] Although it seems agreed that transportation accidents in which spent-fuel casks are ruptured will be very rare, the severity of such happenings depends greatly on whether one adopts the most favored assumption of release of 10^{-4} of the ^{137}Cs inventory or postulates that as much as 10^{-2} of it can be released.

[j] These conclusions assume waste to be placed somewhere where its probability of escape in the next few hundred years will be extremely small; the feasibility of this is not seriously disputed. At this time, some authorities believe that the future-generation population dose will be small [compared, say, with the figures $10^3 - 10^4$ person-rems/GW(e)year in the earlier rows of this column] whatever the rate of escape; others, while unwilling to reject the possibility of a large population dose in case of escape, feel that the probability of escape in the next $10^5 - 10^6$ years, although not accurately predictable, can be made so small that its product with the dose just mentioned will be small.

[k] Centers at which all enrichment and reprocessing operations isolating high concentrations of fissile uranium or plutonium and all reactors using highly enriched fuel are maintained under international control.

[l] Restriction, under international surveillance, to technologies in which plutonium at no stage appears in pure form, and where fissile isotopes of uranium occur only with sufficient dilution by nonfissile isotopes to make the fuel unusable for bomb construction.

of escape has not yet been sufficiently widely reviewed and assimilated to justify saying that there is at present a consensus, even in the scientific community, about it. Still, it is noteworthy that, in a number of broad studies of nuclear power which have been so organized and conducted as to be able to secure the cooperation of many highly qualified experts representing the full spectrum of opinions, waste management has not been considered a major obstacle.[6-8] One such study,[4] although generally optimistic, is a little more doubtful.

In conclusion, it is extremely important to bear in mind the qualifications noted at the beginning of this summary: the nuclear power risks to which the present report is devoted pertain to only one square in the matrix of kinds of information needed for decision making on energy programs. Even for electrical energy, one must decide among a number of alternative technologies or sources for producing it, and for each of these one must estimate its benefits, costs, time scale, and risks; one must also bear in mind the costs and risks of not producing it. This review has discussed only the risks of a single one of the alternativ

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E. MASS MEDIA AND PUBLIC INTEREST

Nuclear Power in Perspective: The Plight of the Benign Giant

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Abstract: *Premised on the assumption that the public press is both a molder of opinion and a reflector of public interest and critique, nearly 800 items in the daily and periodical press pertaining to the nuclear industry and covering a period of about 1 year were examined for their philosophical and psychological impact on the reader. Accordingly this survey is a retrospective assessment in order of priority of the principal controversial issues confronting the nuclear community. The hope is that, from this work, nuclear advocates and allied interests may find a firmer sense of direction and significant areas where special attention can be most profitably devoted to afford the public the reassurances it needs to feel at ease in the presence of the* energy giant.

Today our country faces an imminent electric-power crisis, and nuclear energy stands ready to accept the challenge. The projected needs for electricity within the next few decades are enormous, and, at this moment in time, nuclear power has the opportunity to fulfill its destiny by being the source of this power for which it is so eminently suited and capable.

Until the late 1960s, nuclear power reactors had been installed and operated with relatively few plaudits or complaints. Considering the successes this energy giant had achieved without encountering any major disquieting reactions from the public, the nuclear industry had little reason to anticipate any opposition. Thus it was that electric-utility companies blithely contemplated utilizing this new technology to meet the energy requirements it foresaw and announced the construction of numerous large nuclear power stations around the country. Suddenly, outcries and rebuffs beset the industry, and its optimism was replaced by bewilderment and chagrin. On the one hand, the utilities offer unlimited nuclear power to the people as the panacea for their future problems concerning well-being, comfort, and economic growth. On the other, voices were raised against the nuclear community which accused it of hidden motives and an assortment of hypothetical ills. The numerous questions posed asked how the installation and utilization of this vast resource will affect our institutions, our society, our health, our environment, and our very destiny and ultimate human existence. These questions have such profound, all-encompassing implications that the nuclear community has been sorely tried to respond. In being challenged on so many fronts, it is faced with the quandary of what issues are most in need of attention and rebuttal.

This attack and rash of denunciations came, not much more than 2 years ago, with considerable unexpectedness. One may aptly wonder at this precipitate concern over the atomic giant, but a probable explanation may have recent origins. Emotions today are apparently most stirred over the concept of *pollution of the environment.* This may be the root of much of the confusion and distrust of the atom and its promises of a viable future. This may have been the wellspring from which all the other quarrels with the industry derived. Many sensitive persons are genuinely concerned with the fate of our planet. Their concern for it and what their offspring will inherit has, no doubt, caused them to feel revulsion for the destruction that man has inflicted upon it, and they feel a compelling desire to thwart any further indignities that would jeopardize conditions on earth even more than they are jeopardized today.

Such concerned people are certainly deserving of admiration and attention. Some people have self-serving interests, many have economic interests, and some are completely disinterested. None can be discounted, but it is to the truly concerned individual that so much is owed in the form of tangible reassurances. Thus it is necessary to learn what problems to them are most worrisome. Even the severest critics of nuclear power submit that the world is facing crisis and find some good in nuclear power, with reservations. It is the side effects of nuclear power and the urgent immediacy of its implementation that apparently are the controversial aspects. On the other hand, the nuclear community concedes that the criticism leveled at it is a healthy thing since it points up the areas where corrective actions might be applied or scientific principles invoked to correct any alleged deficiencies. Then through a declaration of sound assurances, the real or conjectured fear can be allayed or set to rest.

EVALUATION OF THE NEWS MEDIA

What follows is an attempt to provide to the nuclear community and nuclear proponents a weathervane that will indicate the directions of public acceptance and apprehension on nuclear matters. The indicator chosen was the published news. To learn and assess just how well or how badly nuclear power has fared with the public, a meaningful concept of the status of the industry should be attainable by evaluating the situation as seen by the journalist. Thus the frequency with which a given nuclear topic was reported in the press was considered to be indicative of the relative importance of each topic to the public (or, at least, what newsmen believe to be important). Furthermore, the ratio of adverse articles to the total pro-and-con articles was taken as a measure of the magnitude (seriousness) of concern over the issues by "opinionated" people. In other words, this approach takes into account not simply the numerical *popularity* of a subject in the strict sense of the word but also articles that tend to lead the reader to some definite conclusions or convictions on these nuclear-associated topics. These were the two sets of data derived as a basis for recognition of priorities.

Seven hundred and sixty-two articles in newspapers, popular periodicals, and semitechnical magazines published within the past year were surveyed. The articles varied broadly in scope, and the review encompassed sources such as the following: news accounts of speeches by nuclear proponents (AEC Commissioners, utilities' spokesmen, academicians, legislators, and laymen) and of its opponents (conservationists, protest organizations, etc.); general discussions of their contentions; editorials; letters to the editor; and reviews of a particular reactor, or reactors, or the nuclear industry in general. As an integral part of this examination, general-interest articles were also included, e.g., discussions of power brownouts, economics of nuclear power plants, uses of isotopes in industry, warm-water irrigation, and the implications of thermal and radioactive effluents. No articles devoted to "Plowshare" and its adverse or beneficial characteristics were considered, even though nuclear opponents frequently use this project to dramatize the dangers of nuclide release to the environment. Similarly, articles concerned with weapons testing (Alaska and Nevada) or weapons production (Rocky Flats) projects were eliminated, in spite of their popularity with the critics as demonstrations of the "reckless abuses" associated with the atomic energy program. On the other hand, articles devoted to the pros and cons of nuclide waste disposal (e.g., Snake River aquifer) were considered valid, since waste management is an inevitable ramification of nuclear power.

The articles were assigned to a series of 12 categories, selected to reflect the many-faceted aspects of this complex arena, ranging from the real, technological implications to the hypothetical, philosophical idiosyncrasies:

1. Nuclides and wastes
2. Nuclear safety and reactor accidents
3. Insurance and subsidy
4. Safeguards
5. Thermal pollution
6. Siting
7. Environment
8. AEC regulation
9. Antitrust and monopoly
10. Legalistics, law, and legislation
11. Esthetics
12. General

THE SURVEY METHOD

In order to set up more or less well-established criteria on which to base the survey so that in the course of evaluation there would be little likelihood of deviating from the norm, a system of ground rules was established and the category subjects were defined.

Ground Rules

1. An article could be assigned to one or more categories. At extremes, a lengthy review article on thermal pollution would be weighted only once, whereas a simple news release reporting on some organization protesting the placing of power reactors along the shores of a body of water and asserting their potential for thermally and radioactively polluting the water would be listed under three of the categories.

2. Each article was evaluated and assigned an *A* (against), *N* (neutral), or *F* (for) rating according to how the article treated the growing use of nuclear energy for the generation of electricity or other beneficial uses. Generalized descriptions of these assignments are given below:

A. An article reporting the remarks of a nuclear-industry critic or one emphasizing some adverse aspect(s) of nuclear power reactors.

N. An article presenting both sides of some controversial issue associated with the technology. The opposing theses of academicians on the effects of thermal effluents from electric-power plants on the fishes in a body of water are an example.

F. An article setting forth the position of an industry proponent or one giving impetus to the promises, prospects, and benefits of the technology and its innovations.

3. Articles in periodical literature were to be reviewed. Articles in *Newsweek, Fortune, Look, Popular Science, Business Week, Natural History, National Parks Magazine, Scientific American,* and news items in *Construction Digest, Power News, Industrial Research, Electrical World, Product Engineering, Scientist and Citizen,* and *Chemical and Engineering News* are examples of the scope of sources in this area. Such articles are representative of in-depth appraisals, as contrasted to news items, but articles in these media are quite infrequent compared with newspaper items and hence comprised probably only about 5% of the total bulk of the data. Newspaper articles comprised the remaining 95% of the source material. Obviously they were the most abundantly available. Moreover, they were considered to be the most significant criterion of public opinion and reaction to a nuclear-oriented society.

4. Numerous nuclear-oriented publications, technical and otherwise, are supported, subsidized, or simply partial to the nuclear industry. Accordingly, none of these were included in the survey—nor were any official AEC press releases.

Categories

Most of the subject titles are self-explanatory. Thus the obvious will not be covered in the following definitions. Rather, examples are cited that are indicative of the more anomalous situations.

1. *Nuclides and Wastes.* A mayor volunteers to provide an area in or near his community for the establishment of a nuclear-waste burial ground. The issue here is not siting (see below); rather the mayor and his citizenry are showing their disdain for those people who express fear over the presence of nuclides.

2. *Nuclear Safety and Reactor Accidents.* When the statistical likelihood of an actual nuclear accident is given and compared with the chances of other catastrophes, even though stated to be one in one billion per reactor, the critics claim that *one* such accident can happen at any time and that the consequences could be incalculable. Other examples might be the possibility of an accident during radioactive-waste transportation; the locating of a power reactor next to a strategic missile base; and the concern over what precautions are in effect to prevent disaster from sabotage, civil disobedience, maniacal action, or falling aircraft.

3. *Insurance and Subsidy.* Insurance is best illustrated by the contention of nuclear opponents that nuclear power would be economically infeasible for the utilities if it were not for the Price-Anderson Act that provides for partial federal risk assumption. Subsidy would be exemplified by the setting up of a state-supported agency to encourage the progressive development of nuclear technology through tax incentives and the selling, distribution, and control of nuclear fuel elements or the fuel itself.

4. *Safeguards.* The subjects in the *safeguards* category include such topics as the potential for diverting fissile substances into the manufacture of weapons (i.e., nuclear blackmail), the maintenance of correct inventory accounts, and the possible actions of organized crime (i.e., hijacking) due to the high value of the fissile materials.

5. *Thermal Pollution.* Articles devoted to the consequences of utilizing cooling towers in association with a nuclear power plant (e.g., their effect on the weather in the locale) or the use of the thermal effluent to prevent frost damage or to provide warm-water irrigation were included in the *thermal pollution* category. Another article described the predicted shortened lifetime of one of the Great Lakes if all the power reactors planned for it were installed.

6. *Siting.* An article describing the opposition to man-made islands on Long Island Sound for nuclear-power-plant siting was surveyed. Another survey item was a news account of a poll taken by a utility in which it asked the public whether they objected to having a power plant situated on some stream and, if so, would they be willing to relinquish the use of their air conditioners.

7. *Environment.* In instances where a concern for the *environment* was expressed, there was no alternative but to set up a category covering this broad scope. Moreover, sometimes the effects of nuclide releases and thermal pollution were questioned in the context of their total effect on an ecosystem (e.g., contamination and eutrophication of an estuary). Such an article was categorized under *thermal pollution* and *nuclides and wastes,* as well as *environment.*

8. *AEC Regulation.* The *regulation* category pertains especially to the arguments over the dual role—promotion and regulation—of the AEC in its nuclear activities. Articles describing the efforts of some of the individual states to regulate (nuclides, for example) within their borders—and the stance of their counterclaimants—are included under this category and also under the *legalistics, law, and legislation* category below.

9. *Antitrust and Monopoly.* The newest controversial issues are probably antitrust and monopoly. Antitrust is best illustrated by the petitions and lawsuits instituted by small investor-owned utilities that claim

discrimination in being denied participation in the corporate public utility setup of a large nuclear power plant. Monopoly pertains especially to the concern of Congress that energy-resource consortiums may be acquiring extensive holdings on the natural-fuel resources of the country and, through the buying-into or building of their own processing, enrichment, and fabrication facilities, may thereby acquire cartel-like economic power over the country's energy-production resources.

10. *Legalistics, Law, and Legislation.* Articles dealing with questions such as the following would fall under this legal category. If the Illinois Sanitary Water Board grants a permit to a utility to discharge thermal waste into Lake Michigan in conformance with the state's standards, and the Department of Interior sets more stringent standards, who has the prerogative? If the Florida Air and Water Pollution Control Department rejects the siting of a power reactor on an island because it threatens the extinction of several aquatic species, the AEC issues a provisional construction permit for the reactor, and the legalities are being fought out on the basis of the new Environmental Protection Act, what are the legal precedents and how and where will the matter be settled?

11. *Esthetics.* Examples of esthetic considerations would be opposition to locating a nuclear power plant (see *siting*) in the neighborhood of a historical structure or a national monument; or the objectionable nature of the power-generating facilities as they may affect a scenic site (e.g., Big Sur or the coast of Maine). Articles contrasting the architecture of a nuclear power plant with that of a fossil-fueled plant and its associated facilities would be pertinent to this category.

12. *General.* In this catchall category are lumped broad generalized statements and descriptions of power reactors, uses of isotopes, discussions of nuclear technology, etc. Frequently, the articles are abstract in their treatment and are devoted to the philosophical implications of a nuclear economy. The complex diversity of material categorized hereunder is exemplified by articles devoted to topics such as the impact of a nuclear installation (a fuel-fabrication plant or power plant) on the economy of a geographical area, the estimate of extra costs in mills per kilowatt-hour to the consumer for environmental-protection measures, the increase in cost of merchandising bonds that caused a utility to defer plans to build a nuclear power plant, the extrapolated reasoning that people resorted to when they voted to reject a power reactor, and the contentions of critics that the utilities use threats of brownouts as a form of "blackmail."

With these definitions of ground rules and categories, it is now no doubt apparent that the decisions were relatively arbitrary and individualistic. Nevertheless, it is the author's feeling that, in spite of shortcomings and unintentional prejudices, what follows provides some insight into the major areas of concern associated with nuclear energy.

SURVEY RESULTS

Each article was read and given one or more appropriate category assignments. Then I endeavored to envision the reader's probable reaction to the topic being reported and assigned an *A*, *N*, or *F* under the appropriate category(ies). It was this latter judgment that most often presented problems because of its inherent subjectivity. Category assignments, except in the general category, were not so difficult because the articles were most frequently unambiguous.

One Approach—The "Popularity Poll." The results were totaled and are presented in Table 1, where the categories are arranged in order of most entries. The order indicates the subjects written about most frequently and what the news media consider the public is most interested in or concerned with. Of course, the *general* category has the most entries; but

Table 1 Articles Devoted to Subject Categories Associated with Nuclear Technology and an Evaluation of the Expressed Attitude or Inferred Impact on Public Opinion

Category	Evaluation			Total
	Against	Neutral	For	
Nuclides and wastes	142	98	71	311
Thermal pollution	95	68	66	229
Environment	66	72	68	206
Siting	82	63	38	183
Nuclear safety and reactor accidents	55	31	26	112
Legalistics, law, and legislation	63	27	7	97
AEC regulation	32	9	8	49
Insurance and subsidy	24	4	2	30
Esthetics	6	6	10	22
Antitrust and monopoly	13	5	1	19
Safeguards	5	3	0	8
Subtotal	583	386	297	1266
General	93	106	228	427
Grand Total	676	492	525	1693

this is separated from the rest of the table, because it is obviously not amenable to consideration in the same light as the other topics. Based on the *grand total* of all category assignments (1693) and the total of all the articles (762), an average of slightly more than two topics (2.2, to be exact) was discussed per article. From the *subtotal* data it is readily apparent that articles devoted to the subject categories are predominantly critical; the opposite is true when nuclear energy is reported in *general*, with favorable articles being dominant. Nevertheless, it is noteworthy that a comparison of *neutral* articles in the subject categories and in the *general* category shows reasonable agreement: 30% (386/1266) vs. 25% (106/427).

A Second Approach—Poll of the "Opinionated." A second approach is to consider the data from the standpoint of individuals with formalized opinions or those writers who take a definitive stand on a category. Thus, if the number of articles expressing adverse opinions of these nuclear-technology-associated categories are divided by the total of articles, both for and against, the values obtained should give a relative indication as to what concerns these writers most. Data of this type are given in Table 2.

The numbers resulting from the manipulation were termed "relative antipathy quotients." Another treatment of the data might be interpreted as showing how many adverse articles were written for every one that was complimentary. These are called "derogatory disposition ratios."

Table 2 shows that in some instances the statistics are extremely poor in that some of the controversial topics have not been written about to any great extent. Thus, in order not to attach too much significance to these poor data, another column shows the extent of this uncertainty. The data are plotted in Fig. 1, along with the uncertainties. At the bottom again is the *general* material, which must be discussed in a separate context as before.

AN ASSESSMENT OF THE QUANDARY

A "Popularity Poll" of the Categories (Table 1). What subjects are written about most frequently? The number of these should be indicative of those topics of most interest and concern to people. From the number of times (311) the subject of *nuclides and wastes* appeared, it is inferred that people want most to be informed on how their health, longevity, and progeny will be affected by the radioactive materials from a nuclear-power-oriented economy. It follows that the people's predilection for no change in their immediate

Table 2 An Assessment of Relative Antipathy Toward Controversial Problems Associated with Nuclear Technology

Category	Biased articles			Relative antipathy quotients			Derogatory disposition ratio, Against : For
				$A/A + F$ (%)	Uncertainty* (%)		
	Against	For	Total		Σ	Δ	
Safeguards	5	0	5	100	48–100	52	
Antitrust and monopoly	13	1	14	93	66–100	34	13 : 1
Insurance and subsidy	24	2	26	92	75–99	24	12 : 1
Legalistics, law, and legislation	63	7	70	90	80–96	16	9 : 1
AEC regulation	32	8	40	80	64–91	27	4 : 1
Siting	82	38	120	68	58–76	18	2.2 : 1
Nuclear safety and reactor accidents	55	26	81	68	56–78	22	2.1 : 1
Nuclides and wastes	142	71	213	67	61–73	12	2.1 : 1
Thermal pollution	95	66	161	59	50–67	17	1.4 : 1
Environment	66	68	134	49	41–59	18	1.1 : 1
Esthetics	6	10	16	38	15–65	50	0.6 : 1
General	93	228	321	29	25–36	11	0.4 : 1

*From A. Hald, *Statistical Tables and Formulas, Two-Sided 95% Confidence Limits for the Probability θ of a Binomial Distribution*, p. 66, John Wiley & Sons, Inc., New York; courtesy of Forest L. Miller, Statistics Department, Mathematics Division, Oak Ridge National Laboratory, Oak Ridge, Tenn.

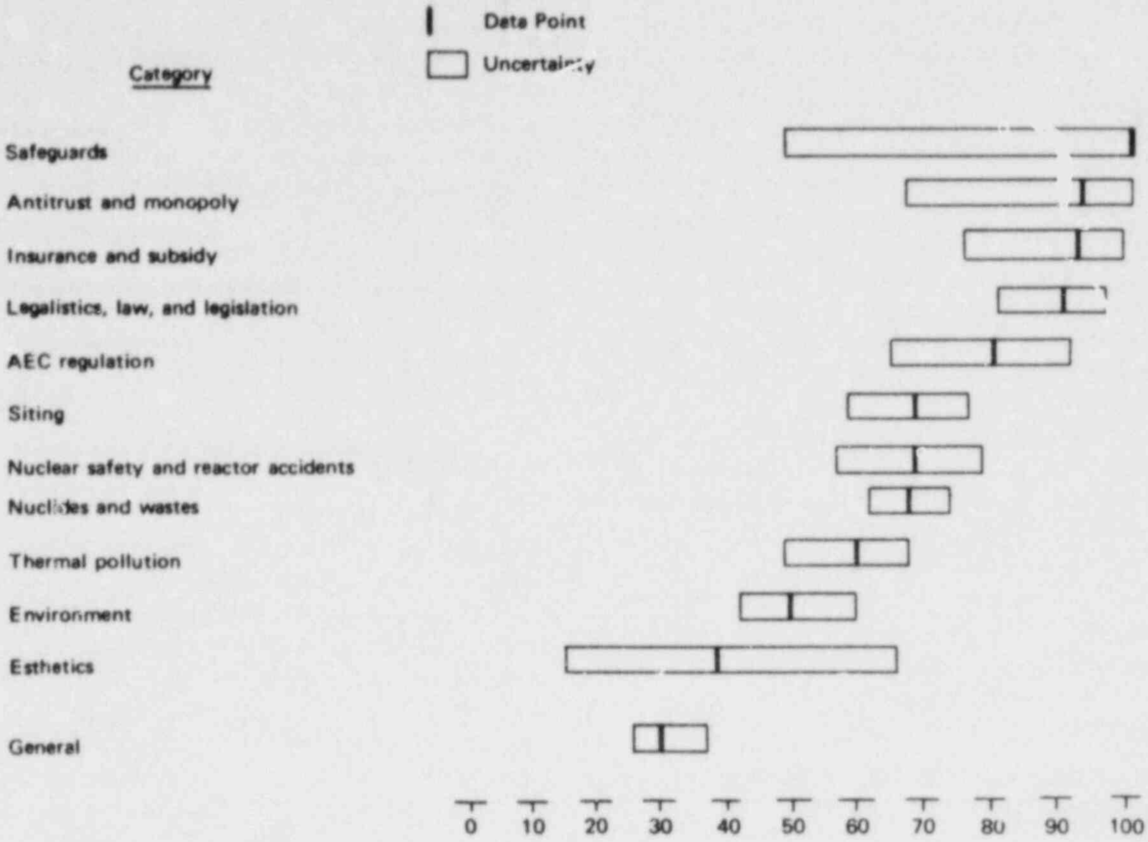

Fig. 1 Relative antipathy quotients from Table 2 and the 95% uncertainty limits associated with the data.

environs (*thermal pollution* and *environment* categories) is the next most important issue, as is borne out by the order in the table.

That *siting* assumes only fourth order of significance might be attributed to "intellectual maturity" on the part of the press and the public. In other words, as a result of having become more conversant and articulate on atomic matters, more precise terminology is being invoked with words such as ecology, mutation, nuclides, biological concentration, and thermal effect. In this light it would no longer be expected that complaints would be on the general basis of siting, except where the term connotes its exact meaning. It is somewhat surprising to observe that *nuclear safety and reactor accidents* are not higher than fifth on the list. This too may be the result of maturity. It appears that the public is sufficiently informed on nuclear power reactors to not be fearful of a disaster occurring during routine operation. In fact, it is my impression that possible actions of psychopaths or the accidental breaching of the reactor containment structure through "acts of God" are the most speculative qualms. *Legalistics, law, and legislation* (sixth place) pertain almost exclusively to the prerogatives of the states in regulating nuclear reactors and all their associated ramifications. The controversial dual role of the *Atomic Energy Commission* in regulation and promotion falls next in line (seventh) to the states' rights issue. That one more or less complements the other is a happy coincidence and can be regarded as corroboration of their respective priorities. The subject of the government providing an *insurance* subsidy (eighth) is not especially conspicuous in the news. Perhaps the people expect Congress or the states to settle this aspect in the courts; or, since subsidies are provided to so many vested interests, it may be that this assistance is not thought to be particularly unusual.

It should be noted that the critical articles far outweigh the favorable, by 583 to 297; however, this will be discussed in detail in the context of Table 2. Since the last three subject categories (*esthetics, antitrust and monopoly*, and *safeguards*) fall so low in the list, any attempt to associate their location with respect to the uppermost categories, with regard to priorities, would have little significance.

Finally, it may be seen from the number of articles in the *general* category that the press is not lax or remiss in giving publicity to nuclear technology.

Poll of the Opinionated (Table 2). The data given in Table 2 and plotted in Fig. 1 are the bases for the "Poll of the Opinionated." In some respects it is unfortunate that more adverse articles were not found for some of the categories, since the statistics leave much to be desired. Nevertheless, in conjunction with the numbers in Table 1, some inferences can be made. Although five articles written on the matter of *safeguards* indicated a need for dire concern (Table 2, 100%), the topic was broached only eight times in the course of 1693 entries (Table 1). So the most that can be said concerning this is that, at least for the moment, it is not a very topical subject, but when it *is* brought up, most of the authors find it an area where much needs to be done. From Table 2 and Fig. 1, the evidence indicates a marked difference in priorities from Table 1. Some of the data are relatively tenuous, but at least two categories are statistically well represented and hence have real significance. These are *legalistics, law, and legislation,* and *siting*. Concerning the former it is inferred that, among writers with a bias, 90% (80 to 96%) favor the position taken by the states. Is it because most of the reporters are hometown boys who are writing what their audience wants to read, or do they really want their state governments to take over the AEC's responsibilities? At least in looking at Table 2 under *AEC regulation*, the percentage drops to 80 and could be as low as 64, meaning that certain of the AEC regulatory prerogatives are not seen in quite so bad a light as Table 1 would indicate. Furthermore, the *AEC regulation* category also often included arguments against AEC regulatory activities.

In contrast to the situation in Table 1, where it placed fourth, *siting* and the environment are uppermost in people's minds (items 6 to 11, Table 2). To explain the new prominence attached to siting under this approach, it is essential to note that the articles are devoted to the debates over locating specific reactors at specific sites, such as Chesapeake Bay, Lake Cuyuga, Lake Michigan, or Eugene, Oreg., for example. In other words, these critiques comprise the bulk of the articles assigned to this category and accordingly resulted in this new significance being attached to the subject of *siting*.

It is interesting to note that in both lists of data, the *nuclear safety and reactor accidents* category follows (or is practically equal to) *siting*. Although this arrangement is retained in Table 2, both supersede the topmost issues in Table 1; i.e., *nuclides and wastes, thermal pollution,* and *environment,* which are in the same order in Table 2 as in Table 1, but they are lower in priority.

There also appears to be a high order of concern about *antitrust and monopoly, insurance and subsidy,* and *AEC regulation*. Even when the "uncertainty" in the numbers is taken into account (and the lowest "antipathy quotients" are assumed to apply), it may be seen that these three categories hold the seeds of more controversy than the categories relating to the environment and to people's health and welfare.

Finally, there are the categories with poor statistical quality. Considering this, not much can be said definitively, except that, of the few articles devoted to *safeguards*, all pointed up deficiencies in the present surveillance and control of fissile materials. With regard to *esthetics*, there is no particular controversy; only 38% of the articles was devoted to criticism, and this value is not far from the *average* of the "uncertainty," namely 40%.

The Lessons Learned

So where does this leave the *nuclear giant*? What have we learned to help in this enigmatic dilemma? It can almost be predicted that when a site for some power reactor is announced writers will focus on it. Some will tout the benefits to be derived from the facility, and others will deplore it and debate the hazards of living in the proximity thereof in the event of a nuclear calamity, since this is the most sensational aspect to attract public attention. Once the public is apprised of the situation, they will initiate questions concerning those subject areas that involve their well-being, with nuclear effluents, thermal pollution, and the effect of the reactor on their environs being considered, in this order. Accordingly it behooves the nuclear industry or utility to approach the public with these factors in mind. However, as the number of reactors grows, the subjects in the statistically poor categories that seem to be of low priority may assume increasing significance. To date they have been largely confined to Congress and the courts, and the press has duly reported on the proceedings. Thus, although the public may become accustomed to and feel more comfortable in the presence of the nuclear giant, the questions regarding these more "nebulous" political, socioeconomic considerations will persist.

At the present time the disputes over specific reactors are being publicized, with the remarks of the opposition being dominant. But much has already been done to provide the general public with representation and the opportunity to participate in planning and decision-making deliberations prior to application to the AEC for facility licensing. For instance, even before the National Environmental Policy Act of 1969 and the AEC's statement[1] of general licensing policy reflecting its obligations under the Act, some utilities were inviting the public to participate in the deliberations and decisions on site selection.[2] The AEC has conducted a number of public meetings[3] to encourage this philosophy of affording the public opportunity to speak out and to promote public understanding of the whole gamut of technical considerations and sociological implications. The Commission is, in addition, considering changes[4] in its procedural process to make knowledge of impending actions, by either it or an applicant, more quickly available and thus smooth the way for early public expression. In fact, the Commission acknowledges, and is encouraged, that certain public-representing bodies have been proposed to give the people an even stronger voice in governmental agency activities, since such a body could be instrumental in expediting a consensus of accord on nuclear matters.

The nuclear industry gives appearance of having learned its lessons well. Many utilities appear to have found a quite reasonable, proper route. They are conducting intelligent advertising campaigns and are establishing rapport with the universities and community civic organizations. They are presenting the public with brief, simple, basic scientific facts that bring the problematical subjects into perspective.

Of course, it would be too much to expect the pathway to total acceptance to be without obstacle. Some misunderstandings are going to persist in the minds of certain individuals. Nevertheless, as ever-mounting numbers of persons become better informed through surmounting the scientific language barrier, it can be anticipated that this majority will become more tractable and amenable to nuclear technology than one that is forced to accept predestined plants under threats of brownouts or blackouts.

CONCLUSION

I do not purport to have any new, striking panacea to offer the industry. I do, however, hope to have given some direction to the question of priorities. A good public-relations job before the fact on the priority issues indicated would seem to be a significant answer to the nuclear community's tribulations.

In this article much attention has been directed to the criticisms leveled at the industry. A look at the number of articles under the *general* category, however, shows matters in a quite favorable perspective. Of 427 articles, 228 were favorably disposed toward nuclear power, and when those *for* and *against* are compared, the ratio is 2.5 : 1. It appears that the trend is more and more in the direction of increasing desire by the electric-utility companies to get onto the nuclear bandwagon. Furthermore, the press implies that people are getting nervous over power outages.

Public action–reaction is a very evanescent thing. Because of the changing kaleidoscope of public opinion, the data submitted here can only be considered to be indicative of current mood. If the utility industry fails to fulfill its commitments for any one or a number of reasons, a subsequent poll might reveal an entirely different complexion and climate for acceptance. In general, the prospect for a nuclear power economy appears to be very good. Moreover, the news media have been, on the whole, reasonably objective, considering the coverage and tenor of neutral and *general* articles. Nevertheless, the unfortunate fact remains that the *against* articles, although perhaps not in the majority, get and retain the public's attention. Much added effort must therefore be expended, by the utility industry and others, to promote and develop full public understanding of these complex and sensitive issues.

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Public Opposition to Nuclear Power: An Industry Overview

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Abstract: *The recent history of public and press attitudes toward nuclear power and its effect on the environment can be traced in the results of polls, panel meetings, debates, etc. Although opposition is not the rule, the quick response by the nuclear industry to the environmentalists' positions has helped to improve public relations. Since nuclear technology is involved in these complex problems, its leaders must do all they can to inform the public and to respond with candor to important questions so that mutual trust and understanding may prevail. Such openness may at first seem self-defeating, but in the long run it will succeed.*

The American public is demonstrating an intense concern for its environment. It is unlikely to accept any unnecessary infringements and increasingly believes that it should have a major voice in determining what infringements are in fact necessary. Moreover, there is increasing distrust of the authority of government, business, and even scientists. As this distrust grows, it diminishes the ability of science and industry to meet the growing needs of our international economy.

The new-found national awareness of our deteriorating environment and the emphasis on participating in major industrial and technological decisions are by no means directed principally at nuclear energy. Virtually every large-scale industrial activity is being questioned and criticized by some members of the public and press. In many instances, such as the U. S. Earth Day activities of Apr. 22, 1970 and 1971, nuclear power plants have received much less criticism than fossil-fueled power plants and other industrial activities. Accordingly, it is quite difficult to estimate the actual magnitude and effects of public opposition to nuclear power. Recognizing the absence of comprehensive data, I will briefly trace the recent history of public and press attitudes toward nuclear power as seen from industry's point of view.

If we were to retreat to early 1969, about 18 months in time, we would find little indication of any public opposition to nuclear power. Aside from the early and quite specialized controversies surrounding Consolidated Edison's proposed Ravenswood plant,[1] Detroit Edison's Enrico Fermi experimental breeder,[2] and Pacific Gas & Electric's Bodega Bay plant,[3] there was little public or press concern about the rapidly expanding nuclear power industry. In 1968, utilities ordered 17 nuclear power stations with virtually no adverse public reaction. Nearly all the scant opposition in the AEC's public hearings appeared on legal or economic gounds, rather than on health or environmental aspects. A California poll taken a year earlier showed 60% favoring nuclear power, and the voters in Eugene, Oreg., approved a nuclear power plant for its municipal utility by a 4-to-1 majority.

The first indication of change in this peaceful situation came rather unexpectedly in early 1969 from an article, entitled "The Nukes are in Hot Water," in a national sports magazine.[4] That article shocked much of the nuclear industry, for it was the first story in a mass-circulation medium that attacked nuclear power on *environmental* grounds. The article proved to be only a preview of things to come. Before the end of the year, two other mass-circulation weekly magazines, several of our most prominent newspapers, and many other publications carried articles sharply critical of the environmental effects of nuclear power. Two new books rounded up every possible criticism,[5,6] including many long discredited ones, and although neither was written by a person technically qualified to examine the subject, both are still considered standard reference sources by some conservation groups and members of the press.

Throughout, 1969, the public's changing attitude was evident in a number of other developments. Several bills were introduced in Congress calling for a moratorium on nuclear power plants. A couple of planned nuclear stations in the East were postponed after being opposed by well-organized local conservationists, primarily on thermal grounds.[7,8] In response to these events, the attitudes of the AEC and the nuclear industry about public opposition began evolving. A milestone in understanding the public's view of nuclear power was made possible in late 1969 by an AEC decision to hold a public meeting in Burlington, Vt., to discuss nuclear power with local residents.[9] As it turned out, the meeting evolved into a debate between the AEC and national-laboratory scientists on one side and several professors and scientists described as "conservationists" on the other. The panel brought together prominent critics of nuclear power from the Midwest, East, South, and Southwest, and the audience included several hundred local residents. The debate and the questions from the audience were, for much of the industry and the AEC, the first direct exposure to the criticisms of nuclear power and to the misinformation and fear that surround the subject. This meeting and a later one sponsored by the University of Minnesota[9,23] indicated, by the relatively small audience turnouts, that, although worry about nuclear power was not widespread in either community, concern among many residents was quite deep. We realized more than ever that opponents of nuclear power included not only professional rabble-rousers and special-interest groups but also a number of concerned and educated citizens who had not heard all the facts about nuclear power or, having heard it, nevertheless had serious questions about its safety and environmental impact.

Many other recent developments have reflected this distrust of nuclear power or added fuel to it. Two Lawrence Radiation Laboratory scientists began telling politicians and the press that federal radiation guidelines should be made 10 times more restrictive.[10] The Minnesota Pollution Control Administration decided that the AEC's guidelines were too permissive and attempted to impose much more stringent requirements with respect to radionuclide releases from reactors within the state of Minnesota. Also, politicians from Long Island to Alaska adopted the perils of nuclear energy as a frequent subject of discussion throughout the recent election year.

These surface indications of public opposition to nuclear power bring to mind a natural question: Are they isolated developments that represent only a small minority of the public, or are they the surface indications of a great iceberg of resistance that has not yet come to light? Are the "nukes" really in hot water?

OPPOSITION NOT THE RULE

We cannot scientifically determine what percentage of the public holds what degree of opposition to nuclear power, but we do know of enough cases of disinterested parties *favoring* it to realize that opposition is by no means the rule. First, we need only to consider the large number of nuclear plants now operating, under construction, or being planned which have not received any significant public resistance. Numerous plants are now operating or under construction that have avoided any serious public criticism. Similarly, we should consider the Los Angeles area, which has outlawed fossil-fueled generating plants because of air-pollution problems. We can point to the Massachusetts Audubon Society, one of the oldest conservation organizations, which has encouraged the use of nuclear power because of its environmental advantages. Further, the California Resources Agency has reported[11] to the Governor that "nuclear energy possesses a tremendous advantage over fossil-fueled plants with respect to the effect on the environment."

Most polls on the subject also indicate that the public is by no means as opposed to nuclear power as some critics would have us believe. A Lou Harris poll[12] in Washington State in May 1970 showed 70% "not opposed" to nuclear power and 6% "strongly opposed"; only 22% were "not opposed" to fossil-fueled plants and 38% "strongly opposed." A national survey conducted for a private nuclear firm in late 1969 produced similar results. When asked what their reaction would be toward a nuclear power plant and a coal-fired plant in their area, about 65% favored nuclear-powered plants and 20% opposed such plants; 22% were "for" coal-fueled plants and 68% were "against." A nationwide poll[13] conducted for the Edison Electric Institute in 1969 showed that 50% of the U. S. population, not including Alaska, Hawaii, and areas served by public authorities, favored nuclear plants in their areas, and 27% opposed them.

Such scattered findings indicate that the opposition to nuclear power plants—often considered virtually a national characteristic—may not be nearly so widespread as some publicity makes it seem. However, this fact alone is no cause for complacency. As we have seen repeatedly in recent years, it does not take a majority of the public in opposition to an activity to significantly affect it, nor does it take a majority of the most informed technical community. A vocal minority, combined with the powers of the press and politicians, can have a major effect on nuclear power or any similar activity.

We must not ask merely whether a majority of the public opposes nuclear power but, rather, how seriously its development is being affected by that opposition, no matter what its size.

EFFECTS OF PUBLIC OPPOSITION

From a developmental point of view, there has been no serious effect from public opposition to nuclear power. The technology of nuclear power has been put into use by industry at an unprecedented pace, primarily because, as AEC Chairman Glenn Seaborg has pointed out, its development came along at the perfect time from the point of view of environment and fossil-fuel conservation. It is easy to forget how quickly nuclear power has progressed from an AEC research-and-development effort into a huge industry. As recently as 5 years ago, only eight nuclear power reactors had been built in the United States, and those eight included such prototypes as Shippingport and Dresden. Today, however, there are more than 100 nuclear reactors in operation, under construction, or on order and these reactors represent a total capital investment of some $15 billion. This phenomenal growth in the nuclear power industry seems proof enough that nothing has seriously affected its development.

A provocative survey of the nation's nuclear utilities made in February 1970 bore out this interpretation. John F. Hogerton, Executive Vice-President of The S. M. Stoller Corporation, examined 70 nuclear power projects with respect to public resistance for the Atomic Industrial Forum's Topical Conference on Nuclear Public Information. Hogerton[14] concluded that public opposition had not retarded the growth of nuclear power and had generally not been a major factor in the "slippage" of nuclear power plants. The utilities he surveyed listed labor problems, licensing delays, and late deliveries of pressure vessels as more significant contributors to the slippage of plant schedules than public opposition. Hogerton did note that in two or three cases public resistance played an important role in postponing or canceling planned projects and that this "could easily become a major factor in the future."

Although the nuelcar power industry may not have been slowed significantly by public pressures, the pressures have been real and increasing, and, to the information men in the industry, they have loomed quite large. A recent survey of nuclear information specialists conducted by the Atomic Industrial Forum's Public Affairs and Information Program indicated that the nuclear information community does indeed believe that public opposition has had significant effect on the nuclear power industry.[15] When asked, "To what extent do you believe public opposition and adverse public information are affecting the nuclear industry?", 27% answered "very seriously"; 44% said "seriously"; 28% said "moderately"; and only 1% replied "hardly at all." The nuclear information specialists were also asked whether the effect of public opposition to nuclear power would become more or less serious in the next couple of years, and 66% replied "more" and 17% said "the same."

The results of these two surveys seem at first contradictory. The one says there has been no effect on the nuclear power industry from public opposition and the other that there has been a serious one, but the two are reconcilable. John Hogerton's survey concentrated on delays or cancellations of power plants caused by public opposition; the responses to the Atomic Industrial Forum poll took a broader view—that of all significant effects the controversy has had on the industry, and there have been many. It may be that the activities of conservationists, the press, professors, and other groups have not threatened the further development of nuclear power, but they have certainly, as the survey asked, "affected" it. Hogerton himself pointed out that public intervention has increased governmental regulation of nuclear power plants and that public opinion reflects the weakened credibility of the nuclear power industry and the AEC.

The effects on the nuclear community from public opposition can be seen in many other ways. The public's overall concern for maintaining an environment as pure as possible—of which the concern over nuclear power is just a relatively small part—has contributed to expanded programs in research and development, environmental activities, and public affairs on the part of utilities, manufacturers, the AEC, and other organizations in the nuclear community. For example, the AEC has established a new Office of Environmental Affairs that is concerned not only with the environmental effects of the AEC's own facilities but also with expanding environmental research activities, passing the results on to industry, and informing the public about the environmental effects of nuclear power.[16] The Congressional Joint Committee on Atomic Energy conducted an unprecedentedly thorough set of hearings that has become the most valuable single source of information on the subject.[17] Many utilities have added environmental specialists to coordinate their ecological activities, and some, such as Northern States Power and Northeast Utilities, have begun new procedures for widening the public's participation in their major decisions. Westinghouse Electric Corporation has created an Environmental Systems Department, initiated environmental research programs with Consolidated Edison and Commonwealth Edison, and conducted a month-long School for Environmental Management at Colorado State University. The Atomic Industrial Forum has established a new Committee on Environmental Law and Technology, chaired by Dr. Merril Eisenbud, and has expanded its Public Affairs and Information Program to serve the information needs of the nuclear community, the media, and the public. The nation's utilities have formed the Electric Utility Industry Task Force on the Environment.

A NATIONAL PROBLEM

Even if public opposition and press attention in the past 2 years have not significantly retarded the development of the nuclear industry, they have nevertheless affected it in many other ways, some of which can be viewed as beneficial. A similar paradox is that public and press criticism of nuclear power is a national problem that does not exist in most areas of the country. This seeming contradiction can be easily explained. The principal criticism of nuclear activities has come from national magazines and television networks, national conservationists, and national special interest groups. In most local areas the opposition has not been against nuclear power in general, but rather against particular plants on particular sites, be they nuclear, fossil fueled, or hydroelectric. Nuclear opposition is thus a problem that affects the entire nuclear community, although it may not be evident on most local levels.

There are two important lessons to be drawn from this observation. For one, we can anticipate that in the next few years more and more of the national criticism will be reflected on local levels. Every critical article in the national media can be expected to sway a certain number of its audience, who may then become active against nuclear plants in local communities. The other lesson is that the organizations best equipped to meet this opposition are nationally based groups, such as the AEC, the Atomic Industrial Forum, and the American Nuclear Society. Members of the nuclear industry must not be lulled into false confidence by a lack of local opposition; every article in a national magazine can affect a community as severely as an editorial in the local newspaper. Accordingly, the industry should support and work with its national organizations, especially during this time of national interest in the environment.

THE ENVIRONMENT AND INDUSTRY

The "overview" of the public opposition to nuclear power could not be complete, of course, without mention of the over-all environmental movement of the past year. The scope and passion of the public concern have been not only national but to a considerable extent worldwide and have by no means concentrated on nuclear power. Here I will discuss briefly what this movement means for the nuclear industry.

Of course, I am qualified to discuss this only from a personal point of view based on limited observations. In general, these observations have led me to the belief that most responsible industry, including the nuclear community, has welcomed the movement and encouraged serious efforts to improve our environment. The respondents to the Atomic Industrial Forum poll[15] strongly supported this interpretation. When asked, "How should the nuclear industry react to environmental activities?", 98% replied "offer assistance"; 27% said "offer financial support"; 3% answered "respond only if properly requested"; and only 1% said, "hope they will overlook nuclear power."

The nuclear community's involvement in environmental aspects could also be seen in the Earth Day activities of Apr. 22, 1970. Hundreds of representatives of government, industry, and laboratories involved with the development of nuclear energy appeared at Earth Day meetings throughout the country, and some firms directly participated in the planning and funding of these events. These items convince me that a large part of the nuclear industry recognizes our world's very real environmental problems and is eager to help solve them. As Sherman Knapp,[18] President of the Atomic Industrial Forum, has said:

> We who are responsible for providing the nation's electricity are as shocked and saddened by our nation's befouled air and water and land as are conservationists. We are eager for our grandchildren to have open space to play in and clean water to drink. And while most conservationists can only debate and lament the problems, we are in a unique position of being able to help the situation by making the environment our number one consideration as we plan, build, and operate our plants.

Concerned though it is about the quality of our environment, the nuclear community, like much of the nation's industry, has had considerable difficulty in placing the problems and proposed solutions of the environmental crisis in a broader perspective. As Dr. Seaborg has pointed out, many ardent "environmentalists" do not seem to realize that the interrelations involving an industrial society are as complex as those comprising nature's ecology. They seem to think that industry could simply turn off a faucet marked "technology" and that all our environmental problems would end. There is more to man's environment and more to the "quality of life" than trees and air and open space, as vital as they may be. There are, for example, labor-saving technologies, without which modern man, like the U. S. frontiersman of 100 years ago, would have neither the time nor the means to enjoy his surroundings. Our natural environment must be considered in relation to our man-made one, of which electric energy is a vital part. As Dr. Seaborg[19] has said, "The environment of a city whose life's energy has been cut—whose transportation and communications are dead, in which medical and police help cannot be had, and where food spoils and people stifle or shiver while imprisoned in stalled subways or darkened skyscrapers—all this also represents a dangerous environment which we must anticipate and work hard to avoid."

The fact that environmental pollution is to some extent inevitable should not lead us to complacency about the subject; rather, it should spur us to try more vigorously to reach the most passionate conservationists with the unhappy facts about these complexities. Unless more of them begin understanding such fundamentals as the fact that all energy conversion, including that of our own bodies, unavoidably creates a certain amount of pollution, industry is in danger of being cast in the role of the villain of society. Already we can see some professional conservationists polarizing the country to the point that everyone who dispassionately discusses such complexities is forced into an antienvironment camp.

ISSUES AND THE FUTURE

The environment will no doubt remain a major issue of controversy and action in the United States for some years to come, and in this respect the nuclear industry is in a favored position. Nuclear power is the least harmful method of generating electricity now practical, and its growth will help slow the degradation of the environment. However, even if more of the public and the press begin recognizing the environmental advantages of nuclear power, the controversy around this technology is not likely to disappear soon or even diminish. The expenditures of the nuclear industry are too great and the facilities too prominent to allow it to leave the public eye. Therefore it might be useful to speculate about the principal issues of controversy that the nuclear power industry is now facing and how these issues might evolve in the near future. I realize that some of the issues are technical ones that I am not qualified to discuss in detail, but I would like to look at them briefly from a public-acceptance point of view.

Radiation Standards

The issue that now seems the most controversial is the effects of low-level radiation, in conjunction with the adequacy of federal radiation guidelines. This topic is indeed creating a great amount of heat among the press and many members of the public, but it is also an issue that could conceivably all but disappear in the near future as such eminent bodies as the International Commission on Radiological Protection, the National Council on Radiation Protection and Measurements, and the Federal Radiation Council review all known data about radiation effects. Whatever radiation standards are ultimately set, I am confident that commercial nuclear power plants can operate well within them. This seems to be an issue that a strong effort to obtain public understanding could help bring to an end as a major point of contention, because much of the strong feeling has no connection with the real world of nuclear power plants. The effects on the population of the Federal Radiation Council guidelines of 170 mrems a year, whatever they could theoretically be, can hardly be associated with the localized effect of a nuclear power plant, which adds radiation of less than 5 mR/year (equivalent to a dose of 5 mrems/year) at its site boundary. When the public and the press understand this vital distinction, an issue that now seems crucial could pass from sight.

Thermal Effects

The issue of thermal effects is undoubtedly the one which will be with the nuclear industry the longest and is the most difficult to explain. Much of the public, like *Sports Illustrated,* just became aware of the potential problems associated with waste heat in the past few years, and, for many of the same reasons, the AEC and industry did not fully foresee them. From a public-understanding point of view, this issue is complicated by the facts that not only are the answers complex and technical but also are, in many cases, unknown. We simply do not know the effects of every temperature on every type of water body or the environmental effects of every type of cooling tower and pond. What we do know, however, indicates that the problems are by no means as severe as some of our critics imply with words like "fish fry" and "boiling rivers," and in some thoroughly documented cases, such as the Connecticut River, there have been no observable adverse effects.

Perhaps the most critical public-information problem involving this subject is the pressing need to put thermal discharges into perspective. In the press, in much conservationist literature, and even in material from some government agencies, the words "thermal pollution" are invariably linked with the phrase "nuclear power," as if waste heat were unique to nuclear plants. Nuclear plants are generally less efficient (about 32%) than fossil-fueled plants (about 40% for the best ones). However, the liquid-metal fast breeder reactor and the high-temperature gas-cooled reactor are fully as efficient as fossil-fueled plants, and yet in the press it is always just the "nukes" that are in "hot water."

There are a number of other issues which are not now prominent but which may become so in the near future as more and more of the nation's large nuclear power plants go on line. The reprocessing, transportation, and ultimate storage of radioactive wastes from these plants will probably undergo increasing press, public, and political scrutiny as the activities in those parts of the fuel cycle expand, and the nuclear industry and the AEC must be prepared to discuss these subjects in a concise and persuasive manner to meet the expected criticism and misinformation.

Government Indemnity

A number of other charges frequently made against the nuclear community are essentially political rather than technical. Perhaps the most frequent is that concerning the federal indemnity of the United States for large accidents involving nuclear material as legislated in the Price–Anderson Act[20,24] of 1957. One of the ironies of U. S. nuclear development is that this law, enacted to guarantee public protection, has become a major point of contention for critics of the nuclear industry. We must learn to educate the public to the fact that far from being a subsidy to the industry, this law basically assures the public's financial protection in the unlikely event of a large accident. Many critics do not seem to understand the basic fact that not a dollar of government money has been expended because of Price–Anderson and that, in fact, the Treasury Department has collected more than $1 million in fees that utilities pay the government. When this law expires in 1976, we can expect a renewed outburst of criticism of it, and we must learn to present our case, whatever it may be, logically and concisely. Although this is essentially a political question and there is a wide range of opinions, even within the nuclear community, we need to emphasize that it is not the nuclear industry that is being protected by this law so much as the public.

Credibility

Another broad issue that has always been a major factor in the criticism of the nuclear community is the public's general distrust of "the establishment" and its "credibility." The word of any official institution is viewed with distrust by many persons today, and not totally without reason. As Louis H. Roddis, Jr.,[21] President of Consolidated Edison and past President of the American Nuclear Society and the Atomic Industrial Forum has said,

> Once assurances that carried an official seal were all that was needed in a more trusting time. But that day is over. People are less ready to believe what politicians tell them. That isn't new. But they don't believe scientists either, and they have some good examples to point to. . . So when we wave nuclear power's fine report card in the public's face, can we reasonably expect it to be believed?

If we are to be believed, we must carefully guard against any action or statement that might further erode public confidence and "credibility."

NATIONAL GROWTH RATE

One issue of controversy that seems to rival the nuclear community's credibility as most crucial in the long run is the increasingly frequent call for a slowdown in our nation's overall growth rate. The natural limits of space, land, water, energy, and other resources are being interpreted by more and more persons as meaning that the country, and the world, cannot expand its population and standard of living indefinitely. President Nixon's State of the Union address phrased it this way:

> In the next 10 years, we'll increase our wealth by 50%. The profound question is: Does this mean we'll be 50% richer in a real sense, 50% better off, 50% happier?

And, more directly related to the nuclear power field, Philip Sporn,[22] former President of the American Electric Power Company, in a review of the nuclear industry for the Joint Committee on Atomic Energy, asked:

> Why must there be an increase in electric energy production? Has a cheap and plentiful electric energy supply become a luxury our environment can no longer tolerate?

These are questions that all responsible leaders of government and industry must seriously consider. Why indeed must the United States continue its phenomenal growth?

The major part of the answer, of course, is that despite all the social movements to the contrary, our population is continuing to grow at a rate that alarms many experts. Worldwide, this is one of man's most pressing problems, with our population of 3 billion persons expected to double within 35 years. Because of its natural resources and lower birth rate, the United States, however, is not facing a problem of such magnitude. Nevertheless, during a week, the U. S. population increases by about 42,000, and by 1980 we will have added some 25 million more persons than we have today. As Sherman Knapp has said, "These 25 million in the next 10 years represent not only that many houses and automobiles and schools and jobs, but that much more pollution—no matter how we produce the goods and services and electricity that they require."

Even though many members of the nuclear industry recognize the problems connected with endless growth, there is little that they can do unilaterally to solve them. Electricity is the most democratic of all products. A single watt cannot be sold until a customer pushes a button to turn on a light, or a television, or a factory. If utilities are to fulfill their responsiblity to the public, they must provide the power whenever that switch is turned on—no matter how quickly the population is growing or how rapidly the standard of living is increasing. Otherwise, no matter how pure they may have maintained the environment, they will have failed. So even as we deplore and work to end the perilous population growth, inefficient uses of energy, and indiscriminate industrialization, we must educate members of the public to the fact that, if the nation's electricity demand is lessened, it must be *they* who turn off the switches.

THE TECHNOLOGY GAP

The problems of population growth and expanding standard of living are just two of many complexities that the nuclear community and other advanced technologies must better communicate to the nontechnical public. The gap in perspective and understanding between industry and technicians on the one hand and the public on the other widens with each new scientific or technological discovery, and if both sides do not soon begin building bridges, it may become unspannable. The public cannot be expected to put its trust in an industry as long as it does not understand the complex technology involved, nor even the complex social and political framework within which it must operate. The nuclear community must increase its efforts to inform the public not only about reactors and radiation but also, and perhaps even more importantly, about the broader perspective that to a great extent guides the industry, including such factors as energy demand, comparative environmental effects of all types of electricity generation, rising costs, increased regulation by government agencies, and critical shortage of economically available fossil fuel. Such fundamental factors as these must be appreciated by the public before it can begin to understand industry decisions and contribute to them meaningfully.

At the same time, the industry's public affairs and community participation programs must feed back the public's concerns, fears, reactions, and suggestions. They must seek not only to inform the public but also to become two-way conduits that will also inform the nuclear community. Only through this mutual understanding can we begin bridging the technological gap.

RESTORATION OF TRUST

As American industry, government, and other "establishments" move toward this more open philosophy of dealing with the public, the change will not be nearly so great for most segments of the nuclear community as for other major activities. The AEC and the nuclear industry have always operated in a uniquely open fashion, despite the cries of "secrecy" occasionally heard from some critics. Since the beginning of the private nuclear industry in the United States, every major project has undergone several open reviews by AEC staff and independent committees, at least one public hearing in the vicinity of the proposed plant, general "fishbowl" licensing and regulation procedures almost unheard of in any similar industry, and public announcements at every step of the regulatory process. The industry and the agency can be proud of their openness and willing involvement in debates. What other major federal agency has ever consented to discuss controversial issues with its most severe critics at public meetings as the AEC has done in Vermont, Minnesota, and other locations, and what other industry leaders have participated in debates and discussions with leading opponents as we have in Atomic Industrial Forum conferences, governmental public hearings, and other public meetings?

At times, of course, this openness seems to be self-defeating. It often means that the critics are given more press and public attention than they could receive without the nuclear community's recognition of their charges. However, I am convinced that in the long run this very philosophy will be one of the major factors in the resolution of the nuclear controversy. We all realize that we are dealing with a unique technology—conceived in secrecy, born in warfare, and developed in fear. It is only natural that the public's attitude toward nuclear application is more suspicious and reluctant and less logical and objective than its attitude about technologies without this dark history. Whether nuclear plants can operate safely could be completely irrelevant if public fear, justified or not, caused the public to reject them.

Public opposition to nuclear power in the United States may not have significantly slowed the development of the industry, but, as we have seen, it has affected it in a number of ways, and there is a chance that its effects could soon become much more serious as some 95 large nuclear power plants now planned and under construction complete their hearings and licensing procedures. It is a technology that represents not so much an environmental problem as a solution, and, as such, nuclear power must be supported vigorously by the governments and industries of all nations. However, because of its history and unfavorable associations, we, as representatives of this nuclear technology, must go farther than most industries in emphasizing safety, candor, and public participation in decisions. We must show that we are interested in listening to all responsible critics and seriously considering their objections. I am convinced that this method of operating may seem to further complicate our jobs in the short term but will, in the long term, lead to the public's confidence and trust.

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Critical Mass: Politics, Technology, and the Public Interest

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[Editor's Note: At the request of the editor, the authors present a summary and appraisal of Critical Mass '75—the meeting of nuclear opponents convened by Ralph Nader. This article differs from most in *Nuclear Safety* in that, rather than dealing with technical issues, it attempts to provide insight into the nuclear opposition as coalesced by Nader. As the article suggests, most opponents are not interested in resolving the basic technical issues—having already adopted the position that nuclear power is unsafe—and are concerned primarily with how to stop nuclear power. Toward this end, the nuclear opponents focus on a number of issues, both "primary" and "instrumental," that are used in various strategies in their opposition to nuclear power. The public, as well as the nuclear community, would do well to understand these issues—real or imagined, technical or otherwise—as well as the strategies in which they are used in the attack against nuclear power.]

Abstract: *Critical Mass '74 and '75, national conferences of opponents of nuclear power convened by consumer activist Ralph Nader, were held in Washington, D. C., in mid-November 1974 and 1975. Sessions of these conferences were devoted to making the case against nuclear power development in the United States and abroad as well as to delineating strategies for citizen action against the nuclear alternative. The conferences pointed out the broadening of opponents' concerns from merely technical issues to a wide spectrum of social, economic, political, and moral issues. The authors, social scientists at the Oak Ridge National Laboratory, discuss the implications of this broadening debate for energy policy.*

INTRODUCTION AND OVERVIEW

"Nuclear energy [has grown] from a dormant to an active social issue, from an issue involved in isolated local controversies to an issue of fundamental national importance."—Ralph Nader[1]

"They [Critical Mass] are organized, they are resourceful, and perhaps most important, they believe they are winning."—*Weekly Energy Report*[2]

"The most serious question now facing nuclear energy is its acceptance by the public."—Alvin M. Weinberg[3]

Critical Mass '74, convened by consumer activist Ralph Nader and held Nov. 15-17, 1974, in Washington, D. C., brought opponents of nuclear power technology together for the first time to discuss ways to better fight the development of nuclear power in the United States and abroad. As observed in *Nuclear News,* Critical Mass '74 "... signaled with unmistakable clarity that the 'strategic retreat' of the intervenors is over."[4] When nuclear opponents reconvened at Critical Mass '75 (held Nov. 17 and 18, 1975, in Washington, D. C.), two trends could be clearly discerned.[5] The debate over nuclear power had passed from technical to social issues, and interventions, once the prime tool used to fight nuclear power-plant construction and operation, had become just one technique in a broadly based campaign of political and citizen action.

Consider Nader's opening comments at Critical Mass '75: "Nuclear power is fraught with, if not dominated by, issues which are institutional and political rather than technical."[5] The problem nuclear power opponents face, he stated, is to "... translate scientific information into the political process ..." and make it a salient *political* issue. Edwin Koupal, Jr., who spearheaded the California initiative movement before his death in April 1976, directed the movement toward effective political action when he stated that "... there will be no more picketing or boycotting ... that's over ... We're going to where it counts ... the ballot box."* Thus the battle lines are drawn. The issue will be addressed in a variety of political forums and on a variety of concerns.

This article describes the personalities, issues, and strategies that have arisen from the Critical Mass conferences based on the experiences of the authors at Critical Mass '74 and '75 and their reading of the antinuclear literature. Our specific concern is to suggest how these issues affect the nuclear power policy debate. We made no systematic survey of proponents' views, however, and therefore do not claim to judge the validity of either the pronuclear or antinuclear stance. However, we do feel that our perceptions and

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*Remarks of Edwin Koupal, Jr., Nov. 17, 1975. These remarks were typical of Koupal's flamboyant speaking style. His job was to sell the initiative process, and he did it quite well.

reactions to these arguments are reasonable measures of public responses.

THE PARTICIPANTS

The 1000 or so persons who attended Critical Mass '75 came from nearly every state in the United States (and from some foreign countries) and represented a broad spectrum of political, social, and environmental groups. The participants ranged from teenagers to the elderly, with most in their mid-twenties. There were as many people in backpacks as in business suits and a few radicals—young and old—mixed in. When they arrived for the conference, they found the meeting hall set up as if for a political convention with placards designating where representatives from each state were to sit. Indeed the conference was in part a political convention as well as a pep rally.

No systematic attempt was made to survey the attendees, but our observation is that many have likely been involved in other movements—Civil Rights, Vietnam, the environment—and are familiar with citizen-action techniques. Many participants spoke of their active involvement in this still-young antinuclear movement.

The thrust of the discussions was twofold: (1) the participants felt that they had to stop nuclear power *now* and (2) they felt that, with the proper allocation of funds and a conservation program, alternative sources of energy can be viable. This latter point is intriguing because we expected more cynicism toward science. There was an overtone of cynicism toward "big" science and "big" technology, but the belief was prevalent that fusion, solar, wind, and geothermal energy sources could be successfully developed.[6]

The varied backgrounds of the participants suggested that Critical Mass is being structured from the grassroots level. Many of the participants spent long hours on buses or trains to attend the conference and were not supported financially by any group. They were enthusiastic and felt that they were winning the battle.

THE SPEAKERS

Mornings at the conference were devoted to a mass assemblage featuring not only Ralph Nader but other speakers who developed the case against nuclear power. It should be noted here that this was entirely the opponents' show.* With the exception of the 10 or more industry representatives in the audience,† the participants and speakers developed not only the reasons to oppose the nuclear option but *how* to carry this out. The first morning was devoted to a wide-ranging discussion of the negative implications of a continuing reliance on nuclear technology. Addressing this issue were: Helen Caldicott, M.D., Children's Medical Center, Boston; David Dinsmore Comey, Business and Professional People in Public Interest; Dr. Hannes Alfvens, Physicist, Nobel Laureate, past-President of Pugwash Conference on Science and World Affairs; Judith Johnsrud, Environmental Coalition on Nuclear Power, Pennsylvania; Dr. Henry Kendall, Union of Concerned Scientists; and Russell Ayres, student, Harvard Law School. With their varied backgrounds, these speakers broadened the discussion from one of pure technology to one concerned with the social impacts of energy generation. Caldicott developed the health issue; Comey touched on economics; Alfvens discussed the plutonium problem; Johnsrud warned of the problems of energy parks; Kendall reviewed the history of the technology, citing its unresolved problems; and Ayres touched on the civil liberties implications of the "plutonium society."

The next morning was devoted to a "Citizens Forum," a device by which persons active in the antinuclear movement could present statements of concern to a panel of Congressmen and lobby for their positions. The makeup of this Citizens Forum is shown in Table 1. The Citizens Forum was an attempt by the movement to say to the Congress that nuclear power is a salient political issue. Koupal contended that the people were ahead of Congress on the nuclear issue and pointed to several hundred thousand signatures on initiative petitions to bear out his contention.

As before, the concerns expressed by the witnesses covered more than technological issues, citing the upcoming initiatives in the west (Oregon, Washington, and California), a recently enacted Vermont statute involving the state legislature in the siting process, the implications of nuclear sales abroad, the ability of social institutions to handle the waste storage problems, and the imbalance in research and development priorities.

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*Proponents did attend Critical Mass '74 and '75, and Ralph Lapp and William Doub accepted invitations to make presentations at Critical Mass '74. The presentations they made—as well as the audience's questions and reactions—well illustrated the lack of dialogue that exists between supporters and opponents.

†The presence of nuclear supporters at Critical Mass caused one workshop leader to curtail his remarks on antinuclear strategy. When a show of hands at this workshop showed five or six supporters in the audience, the workshop leader stated he would not cover all strategies because he did not want the industry to know everything the antis were doing.

Table 1 Citizens Forum Participants

Hearing Panel

Senator Mike Gravel* (D., Alaska)
Rep. Hamilton Fish* (R., New York)
Rep. Edward Beard* (D., Rhode Island)
Rep. Berkley Bedell (D., Iowa)
Senator Dick Clark (D., Iowa)
Rep. William Green (D., Pennsylvania)
Rep. Thom[illegible]arkin (D., Iowa)
Rep. Marth[illegible]eys (D., Kansas)
Rep. Joseph Moakley (D., Massachusetts)
Rep. Toby Moffett* (D., Connecticut)
Rep. Fredrick Richmond* (D., New York)
Rep. James Weaver* (D., Oregon)
Rep. Tim Hall* (D., Illinois)

Witnesses

Edwin Koupal, Western Bloc Organizer
Scott Skinner, Former Director of Vermont Public Interest Research Group
Dr. John Edsall, Harvard Biological Laboratory
Dr. George Kistiakowsky, Science Adviser to former President E[illegible]nhower
Dr. Robert P[illegible] Cornell University
Bjorn O. Gillb[illegible] Environment Center of Sweden
Dr. Carlos Bell, University of North Carolina
Dan Ford, Union of Concerned Scientists

*Asterisks distinguish those who actually attended from among those scheduled to participate.

One significant colloquy took place between Koupal and Congressman Beard (D., Rhode Island). Koupal stated several times that he felt sorry for those states which did not have direct democracy, i.e., the initiative, and that initiative procedures were necessary because legislative bodies are out of touch with their constituencies. Beard responded by saying things were changing, most notably through the new members of the Congress, and that Koupal would do well not to write off the Congress as a viable force in energy policy.

WORKSHOPS

The workshops focused on techniques of citizen action. As the list below shows, there were a number of forums in which citizens could become actively involved. One of the dominant functions of the workshops was to encourage persons of differing perspectives to discuss their problems and successes and to determine ways they could be more effective.

The workshops covered the following issues:

What Are the Alternatives to Nuclear Power?—John Abbotts, Public Interest Research Group.
National Energy Legislation and Citizen Participation in Government—James Cubie, Public Citizen.
Economics of Nuclear Power—Marty Rogol, Public Interest Research Group.
Oversight and Monitoring of Federal and State Agencies—Dan Ford, Union of Concerned Scientists.
Labor and the Nuclear Industry—Sidney Wolfe, Public Citizen.
U. S. Nuclear Trade and Weapons Proliferation—Jacob Scherr, National Resource Defense Council.
Safe Energy Initiatives—Joyce Koupal, People's Lobby.
Energy Issues and State Legislation—Scott Skinner, former Director, Vermont, Public Interest Research Group.
Utility Rates and Nuclear Power—Rich Morgan et al., Environmental Action Foundation.
Citizen Action on Energy Parks—Judith Johnsrud, Environmental Coalition on Nuclear Power.[7]

It was as though Critical Mass was acting explicitly on the exhortations in a recent issue of *Environmental Action:* Critical Mass must "... identify the individuals who already support a moratorium because nothing is so easily dismissed as a group which can't prove for whom it speaks. ... [It] must enlarge its constituency, fast, while the country is still getting only a few [sic] percent of its energy from nuclear power."[8]

STRATEGIES

Opponents are now looking to the state and national political arenas as a focus for their actions. This strategy of politicization is neither new nor radical. The initiative procedure, for example, is permitted by the laws of several states, and many of the citizen strategies discussed have proven successful in other social and environmental conflicts. Such strategies developed from a deep-seated frustration with the regulatory process but do not *totally* abandon working within this process. The key factor is that the regulatory process is now one of *many* arenas in which opponents are operating.

Opponents have characterized the intervention process as a way to achieve minor victories but still see the plants ultimately licensed.[9] They see the hearing process as utilities and agencies of government working "hand-in-glove" and argue that what passes for a national energy policy "... has been made largely by private economic decisions by the nuclear industry."[10] Opponents have thus chosen to focus the issue in ways and on subjects not permitted by the regulatory process.

Such strategies fall into two basic categories: administrative and legislative. Administrative strategies include (1) intervention in regulatory hearings, (2) lawsuits, (3) intervention in utility rate hearings, (4) formation of utility consumer groups, (5) challenging utility advertising under the fairness doctrine, and (6) action in stockholders' meetings. Legislative strategies involve state and congressional legislative lobbying and the use of the initiative ballot.[10]

The most publicized strategy to develop is use of the initiative—a technique by which citizens can determine the issues to be considered and qualify issues to be voted on. This technique has been widely used in California, where the first nuclear moratorium vote[11] was scheduled for June 1976. It is the intent of the Western bloc to bring the nuclear power issue to the ballot and focus national attention on the process as well as the outcome. The proposed initiative petition for the state of Oregon states the following as a condition of nuclear plant licensing: "Imposes conditions on approval of sites and construction of nuclear power plants, not previously finally approved by May 12, 1975, including: removal of all federally imposed liability limits; all safety systems tested and found effective in operation in substantially similar systems; waste disposal found to be permanently without chance of radioactivity escape. Each house of the legislature must by ⅔ vote find conditions met, after extensive hearing proceedings. Governor must annually publish evacuation plans."*

In concert with this initiative drive, a national petition drive for solar energy is being conducted by the Task Force Against Nuclear Pollution, Inc. Petitions are collected nationally but are tabulated by congressional district to provide both a national and local focus to the issue and a convenient gauge of support.†

There is also a substantial media focus. Organizers are conscious of the need to create publicity and have used radio and television public service time by providing local stations with 30- and 60-sec spots to counter utility advertising. Several of these spots have been hard-hitting and memorable comments on the antinuclear issues and citizens' strategies.‡

ISSUES

Strategies are only relevant within the context of the issues that concern movement activists. Table 2 lists many of the major issues addressed at Critical Mass '75. This list includes a variety of social, political, economic, and moral concerns and is evidence of the efforts now being made by activists to broaden the nuclear debate and thus expand their base of support. We have broken the issues into two general categories: primary and instrumental. Primary issues involve all questions related to nuclear power safety; they are primary because the movement would not exist without them. Instrumental issues are those which opponents view frequently as secondary to the safety issues but which are means to mobilize public support against nuclear power. From the perspective of the general public, these issues are probably no less important than the safety questions; indeed that is their utility to the movement.

Table 2 Issues Raised at Critical Mass '75

Primary Issues
Reactor safety
Storage of wastes
Transportation of nuclear material
Breeder reactors
Fuel-reprocessing plants
Energy parks
Potential for nuclear weapon proliferation
Terrorism
Safety of nuclear energy and impact on public health and safety
Instrumental Issues
Responsibility for making decisions on nuclear power
Technical solutions creating greater social problems (e.g., nuclear technology and impact on civil liberties)
Deception of the public by decision makers
Role of government research bodies
Accountability for nuclear power safety
Federal supports for nuclear industry
Cost of nuclear energy
Labor intensity of nuclear energy
Industry credibility
Rising fuel rates and power of utilities
Level of U. S. energy consumption
Need for enrichment facilities
Efforts to speed up licensing process
Siting in rural areas
Federal preemption
The Karen Silkwood incident

Primary Issues

The basic issue for all activists is the safety of nuclear technology. All believe that nuclear power, as

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*The initiative in Oregon is intended as amendments to ORS 453.305 to 453.575.

†These are tabulated each month in *Critical Mass*, the monthly organ of the antinuclear movement ($6 per year, P. O. Box 19379, Washington, D. C.).

‡Information may be obtained from the Public Media Center, San Francisco, Calif.

the technology is presently developed, is unsafe and potentially threatens the survival of our species; many assume that there is no way that nuclear power can be made safe. The issue is a moral, not a technical, one in their opinion, and their political goal is to limit or eliminate nuclear power as an energy source. As Gofman stated: "I would suggest that continued operation of existing plants and the licensing of any new ones represent reckless extremism coupled with an abdication of man's moral obligations to this and future generations. I know of no valid evidence to suggest that nuclear fission power can be made acceptable or that we shall ever need nuclear fission as an energy source. And the essence of the problem at hand is moral, not technical."[12]

Opponents' concern over nuclear safety has many facets. In the past they have focused primarily on reactor safety and particularly on questions of radioactive emissions and probable accidents. Emissions of radioactive materials into the environment are unsafe, they argue, because "all releases [of such materials] into the environment result in some risk to individuals exposed or to their progeny."[13] Furthermore, they stress that the probability of a major nuclear accident is greater than proponents admit. They buttress their position with two judgments: (1) safety systems for reactors have not been tested adequately prior to licensing,[14] and (2) the record of accidents for currently operating plants is ample evidence of the fallibility of the technology presently in use.

But opponents' concern with safety has moved beyond specific questions of reactor safety to those related to all aspects of the fuel cycle. They view the transportation of nuclear fuel through the countryside, the cities, and the airspace as fraught with danger for people and the environment because of the possibility of accidents resulting from inadequate equipment, human error, poor planning, and/or terrorism.

They oppose the plutonium fuel cycle being advocated by many proponents for future nuclear power development. They feel that breeder reactors and fuel-recycling plants are dangerous since major technical questions for each have not been solved to allow for their safe operation. Equally important, opponents know that if the plants were made to operate successfully, they would manufacture and process an almost limitless supply of plutonium, a long-lived source of radioactive contamination. Opponents also believe and publicize the fact that there are as yet no tested solutions to the problem of providing adequate waste storage and disposal of the quality and magnitude required.[15]

Do opponents consider energy parks a solution to some of these safety questions? As they perceive the issue, if a single nuclear power plant is inherently unsafe, then 10 or 40 plants at a single site only compound the safety problems for an area. Judith Johnsrud reflected the feeling of movement activists when she warned politicians that "the road to elective office does not lead through energy parks." Energy parks are both a substantive safety issue and a symbolic issue for opponents. Advocates of nuclear power see energy parks as a means of minimizing risks through colocation and elimination of a vulnerable transportation link. However, since energy parks will contain most if not all of the facilities necessary to complete the nuclear fuel cycle, opponents view them as a convenient target and a representative symbol toward which to mobilize their emotions as well as their efforts.

Opponents discuss safety issues in the international context and from the perspective of the conduct of U. S. foreign policy. They criticize efforts to supply foreign countries with nuclear experts and equipment since such action leads to the proliferation of nuclear weapons. As evidence, they cite India's development of a nuclear weapon using materials available at a small reactor.

Finally, the inadequacy of existing plans for evacuation in communities with reactors in the case of nuclear accident, the potential for human error in the development and operation of nuclear power facilities, and the fear of individual acts of terrorism raised for the participants more unsettling safety issues to be resolved.

Instrumental Issues

The instrumental issues provide more questions of social, economic, political, or moral significance to add to those raised by the safety issues. The instrumental issues broaden the debate, moving it even farther away from the technical safety issues, and provide more opportunities for opponents to challenge nuclear power in a variety of political arenas. They are instrumental in that activists frequently perceive them as a means by which to acquire additional active support when issues of nuclear safety fail. In the final analysis these instrumental issues are secondary to the safety issues.

Opponents believe that the decision on the safety of nuclear power is a value decision that can only be made by each individual.[16] As such, no group of scientists, government regulators, or business executives can provide an adequate answer for all members of the society. Scientists can only explain what the probable risks and benefits might be and cannot tell the public how to weigh them relative to each other; regulators frequently serve the constituency they are to regulate and cannot be trusted; and businessmen serve their own economic interests. With this view, the need to develop a strategy to mobilize the public to participate in the energy policy-making process should become obvious and legitimate, given a commitment to democratic procedures, even to proponents of nuclear power.

One way to mobilize the public is to raise the issue of individual interest and decision-making rights and responsibilities. Thus opponents demand that questions related to nuclear power development be taken out of the hands of businessmen and technical experts and given to the people.

The belief that the public must participate in the policy-making process with respect to nuclear power is further supported by the opponents' view that the experts may not be able to solve the technical problems inherent in nuclear power development without creating greater and more severe social, economic, and political problems.[17] One such problem outlined is the substitution of more controls on civil liberties to ensure safety against theft, sabotage, and blackmail via nuclear fuel and power equipment. Russell Ayres, of the Harvard Law School, has a thought-provoking account of the potential civil liberties problems posed by nuclear terrorism. Tracing the history of civil liberties in times of crisis, Ayres contends that general repression and further denial of individuals' rights is a probable consequence of nuclear power development.[18]

Deception of the public by decision makers on nuclear energy policy is another campaign issue of opponents; they advocate candor and honesty by all public officials and representatives of utilities and the scientific community on all issues related to nuclear power. The belief of opponents that the public has not been told the truth on most matters related to nuclear energy development is, we think, universally held. Opponents cite examples where they claim the public has been deceived (at least temporarily) and information withheld, notably the Browns Ferry incident.[19] They note the admission by the former U. S. Atomic Energy Commission (AEC) that, in the past, the agency had not worked for the public interest.[20] Moreover, opponents charge that governmental research bodies have taken a pronuclear stance. [We are particularly sensitive to this latter criticism since, on our return to Oak Ridge National Laboratory (ORNL), many persons assumed that we would have viewed the participants as kooks or wild-eyed radicals. We think that the effects of any deceptions and admissions by government and industry serve to make every issue that the opponents raise more credible.]

While desiring the right to participate in the decision-making process, opponents want to see industry held more accountable for its actions by eliminating government support to the industry. They are against any form of subsidy to nuclear industry and specifically argue for the repeal of the Price–Anderson Act. They claim that a number of provisions of this act function to make the public accountable for industry's safety and economic errors.[21] For example, the limit of $560 million liability for a nuclear accident means, opponents say, that most people injured would not receive compensation. They likewise argue that the fee of $430 per year for each 1000 kW for thermal-energy capacity as the annual indemnity charge results in a substantial subsidy to the industry by the public since in the private insurance market the indemnity fee would be much higher. The crux of their arguments, and the one which seems to be most persuasive, is that, if industry were held accountable, the realities of the marketplace would exert pressure on the industry to take those actions necessary to avoid getting into situations that might result in crippling costs. Opponents are secure in the belief that industry could not survive a situation of full accountability.

The economic difficulties that the nuclear industry is facing have not been overlooked by the activists either. Opponents note with relish that nuclear power, contrary to predictions of its advocates, is not the cheap energy source its advocates once hoped for. Citing information from an article published in *Business Week*,[22] Critical Mass speaker Comey emphasized these major points which were aimed at challenging the economic viability of the industry: (1) nuclear power is unreliable, since the presently operating plants have not functioned at predicted capacities and have been plagued by numerous shutdowns resulting in enormous additional costs;[22] (2) the continued development of the industry will require the expenditure of enormous capital since capital costs are continuing to rise; (3) industry appears to be more reluctant to undertake such costs without further federal guarantees;* and (4)

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*The nuclear industry is not unique in getting government subsidies, and we do not know if the nuclear industry has received proportionately more money than other industries.

uranium is predicted to be in short supply, with resulting sharp price increases.

Although these issues are intrinsically important in evaluating the costs of nuclear energy, their function for the group is again primarily instrumental. They are used to persuade people who are not responsive to safety issues that nuclear power is an unworthy alternative. We think the new support derived from these economic issues is potentially greater than that from the safety issues. Opponents argue that utility rates for many consumers are rising because of nuclear power development. Indeed, the conference devoted one workshop session to discussing the linkage between rising costs and rising utility rates. We think this argument is persuasive in this time of inflation.

The dollars and cents perspective has yet another focus. Opponents argue that energy alternatives other than nuclear power are more labor intensive.[†] We conclude that the emergence of this issue is a result of the support given the nuclear power industry by several unions which view the construction of nuclear power plants as an obvious benefit to workers. Opponents give little attention, however, to the impact of conservation policies on the structure of the U. S. labor market.

While presenting the issue of industry's economic viability, the activists also challenge the credibility of industry to handle the technology. They point, for example, to the number of shutdowns of reactors which have occurred; the Browns Ferry fire; the cracking of piping systems in boiling-water reactors; the activities and reactions of the Kerr-McGee Corporation in the Karen Silkwood incident;[‡] and attempts by Westinghouse Electric Corporation to renegotiate fuel contracts. With these issues, the antinuclear power movement addresses a fundamental problem inherent to the development of the nuclear energy alternative: that of transferring the knowledge, skills, and precautions of the research laboratory to private enterprise or of commercializing an elite and demanding technology without sacrificing quality control.

In a broader philosophical perspective, the concern over the rise in utility rates is viewed by some as part of the greater problem of the growing power of utilities and indeed of corporate enterprise. A number of documents available at Critical Mass '75 elaborated on this issue by attacking the fuel-adjustment clause and the irregular tax collection policies of the utilities. The overall thrust of the argument is to call for consumer action to challenge corporate control of the economic marketplace, thus moving the nuclear power debate to encompass more basic questions of social organization. Similarly, references to the ideas of Schumacher[23] suggest the movement's link to counterculture philosophies that question the present technological organization of society and its level of energy consumption. These philosophical issues function to provide a network of interlocking interests that unite antinuclear power activists with other major interest groups.

Activists also take a stand on a number of specific strategic issues related to the implementation of the nuclear power policy. These include (1) voting for a nuclear power moratorium, (2) defeating efforts to speed up the licensing process, (3) challenging the policy of siting in rural areas (rural siting is seen as tacit proof that nuclear power is unsafe), (4) challenging the country's need for enrichment facilities, (5) repealing the federal right of preemption (to enable states to adopt more stringent environmental standards),[24] and (6) transporting plutonium through urban areas.

These then are the strategies and issues of the antinuclear power movement as we perceived them at Critical Mass '75. We think that the diversity and sophistication of many of the issues indicate that the movement has the potential to attract a great number of supporters and that its strategies are designed to involve these supporters in active participation.

SOME OBSERVATIONS

Given the above-mentioned strategies and issues, what can we learn about the contribution of this movement to the nuclear power debate? First, the safety issues identified by the nuclear power opponents are the same issues that have been and are of continual concern (with the possible exception of "normal emissions") to nuclear physicists, engineers, government regulators, and the industry. Yet the current

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[†] Nader states: "One obvious impact of this capital outlay [for nuclear] is the loss of jobs. The Project Independence Report indicated that a nuclear economy would require four million man-years of labor while solar energy would create a labor demand for some eight million man-years. Since our economy cannot support the development of both energy resources, a substantial investment in nuclear will, in the long-run [sic] reduce over all [sic] job availability."

[‡] Karen Silkwood, an employee of Kerr-McGee, died in an automobile wreck. Reports in the press indicate that she had been exposed to plutonium and that, at the time of her death, was on her way to discuss plant safety violations with reporters from the *New York Times*. The Silkwood case was one of the dominant symbolic issues against nuclear power at Critical Mass. Silkwood has become the movement's martyr.

strategy of the opponents to broaden the debate by introducing a spectrum of social, economic, political, and moral issues leaves little room for meaningful debate on proposed alternative solutions to the safety questions: solutions would only facilitate the development of the technology. The position of most opponents is clear; there already exists sufficient information to enlarge their suspicions and for many to state unequivocally that the social risks of nuclear power are greater than any perceived benefits to be derived from the continuation of the technology.

How, we may ask, can they come to this conclusion without engaging in a dialogue over technical issues, and how can they appeal to the public for support? We think there are three reasons. First, opponents define the central problem with nuclear power as a moral, not a technical, issue, and argue: Why should one generation burden future generations with unresolved technical problems? Second, the level of debate offered by many proponents frequently does not require a sophisticated understanding of technical issues. Recognizing that there are technical problems yet to be solved, proponents argue that they have faith that "Our human intellect is capable of dealing with this new source of energy."[25] To this, opponents respond that they do not have faith, and they recommend that the public not have faith either. Third, opponents are not looking for answers to further the technology but are looking for ways to stop it altogether.

Would more discussion by scientists of these technical issues renew their confidence and sustain public support? We are doubtful. A cursory review of the technical literature suggests that science has not provided ready solutions to some of the more important problems of the fuel cycle (e.g., waste disposal) and that many general solutions presented in the public debate so far, such as Weinberg's call for a "priesthood of technicians" and a "stable society," are unsatisfactory in that they probably are unattainable.[26] Moreover, there has not been sustained public discussion from the nuclear establishment of these problems, nor does the scientific community speak with unanimity on the question of nuclear power safety.

In the last few years, the public has witnessed the assumption of an antinuclear position by a growing minority of the scientific community; the resignation of several persons in the nuclear industry over safety issues; and internal criticism over reactor safety systems, building enrichment facilities, and energy parks. With these events in mind, the public has considerable reason to agree that the choice of nuclear energy is a "Faustian bargain" and to ask if it wants to make such a bargain.[illegible]

The primary justification for the strategy, which downplays the debate over how best to implement the program, is that the goals of the activist are different from the goals of other citizens or of scientists. Most activists are not concerned with when or how to have nuclear power but how to stop it. In this framework the activist has little choice but to launch a frontal attack aimed at delaying, hindering, or rolling back the program and to challenge the fundamental utility of the nuclear alternative in a national energy policy and the credibility of its proponents.

We do not intend the foregoing text to imply that the opponents' strategies do not foster debate on any technical questions or that all opponents fail to understand technical issues. Much of the literature available at Critical Mass '75 discussed substantive rather than cosmetic issues while referencing numerous technical sources. In our opinion, the conferees were not just listening to "inner voices." Such critics as Barry Commoner have a definite interest in the role of technology in American society and are at the same time quite capable of discussing finer technical points of each energy alternative.[27] Moreover, opponents can respond quickly on those few occasions when proponents debate technical issues in public and challenge their basic assumptions. The Rasmussen report, for example, has elicited detailed technical responses from a number of specialists on a wide variety of grounds.[28]

If there is a major weakness with the debate offered by opponents, it is that the movement, i.e., most of its active members, does not appear to have given much attention to the variety of complex technical and moral problems that might result from using alternative sources of energy or from a massive conservation effort. To criticize activists on this level, however, is somewhat unfair because neither politicians nor scientists have adequately aired these issues in the public arena.

In addition to shifting the debate from technical to social issues, the movement has also increased the number of issues and by so doing has made it more difficult for proponents of nuclear power to dismiss the movement's contentions. Providing answers to one question does not necessarily satisfy the need for information on other issues. Opponents' reactions to the Rasmussen report are a prime example of this problem. Nader writes:[28]

> From the fanfare with which the report was released, it is evident that the AEC and the nuclear industry hoped the report would lay to rest all concerns about reactor safety.

> But these hopes were not realized. The severe weaknesses of the report have contributed to greater skepticism over nuclear power.
>
> At the outset, it should be emphasized that the report, the *Reactor Safety Study* only presumed to cover nuclear reactors themselves. The report did not cover the transportation of radioactive materials by truck, rail and barge; the disposal of radioactive wastes; the fuel reprocessing plants; or uranium mining processes and wastes.

Nader's remarks pinpoint a fundamental problem with the perspective of proponents toward the antinuclear power movement; they tend to think that reactor safety is the only issue, but it is not. There are many issues, nearly all of which are deserving of some thoughtful consideration and research. Until such a time as proponents begin to provide answers and to demonstrate a willingness to discuss these other questions in a variety of public forums, we believe that the antinuclear power movement will continue to grow.

In attacking nuclear power, the opponents have also highlighted the hazards of the process of a federally subsidized transfer of a sophisticated technology from the laboratory into the private sector. In so doing, they have pointed out several interesting and troublesome problems. One is the support of private economic interests given by the government at public cost. The opponents' attack on the Price–Anderson provisions, we think, make this point all too clearly. They ask: Is this support necessary? The need to subsidize solely because private enterprise should not have to bear the costs of failure is the weakest of all arguments since opponents can invoke free-enterprise ideals as follows: the basis of the free-enterprise system is the assumption that independence means the right to fail or succeed on one's own. Government support of the nuclear industry is justified if we assume that there is an overriding national interest that must be met. However, from the perspective of those actively opposed to nuclear power, there is no national interest that would outweigh the health hazards that might result from the development of nuclear power. Certainly, from the perspective of the general public, the answer that the national interest would be served by having energy independence from the Arab world is somewhat convincing. Other arguments that deal with the potential for human misery and social upheaval as a consequence of not having sufficient energy are, we think, more convincing.

Although we at ORNL sometimes hear these arguments in private discussion, we unfortunately find little information in public forums. Surely the advocates of nuclear power will do us all a favor by detailing some of these arguments publicly so that all might better weigh national interest considerations.

However, the most important point, and the one which underlies most of the opponents' criticism of the process of nuclear energy development, is that safety considerations have been secondary to other goals over the years. As a consequence, opponents see their tasks as those of (1) demonstrating that the current technology that evolved from this process is unsafe and (2) undermining the credibility of those who say it is safe. This view explains why they are dogged in their determination to publicize all reactor malfunctions, to expose errors in judgment and design, and to attack personalities and interests strongly identified with the nuclear establishment.

There is no doubt that the basic issues of safety have not received the kind of attention opponents (and many proponents) would like.[29] Whether or not this situation was a consequence of willful decisions by policymakers is yet another question. Recounting the development of the light-water reactor and its emergence as a dominant type for central station power in the United States, Weinberg stated[30] that eventually the technology developed a momentum of its own:

> I mention this history to draw a moral: in big reactor engineering developments, fundamental advantages—at least as perceived *a priori*—do not necessarily determine the ultimate course of events. Developments acquire a force of their own which can preempt the direction of a technology. Newer technologies based on fundamental principles can be bypassed by the momentum of the older system.

This momentum is what opponents now hope to check. If Weinberg's analysis is correct, the task is to change the actions of people who may not really know how or why we have arrived at our current situation. In this light, the analogy sometimes drawn at Critical Mass '75 between the country's dilemma in Vietnam and our present situation with nuclear power does make some sense.

Finally, there is evidence to suggest that the opposition is making some headway in its efforts to alter the course of nuclear power development. The challenges have, at the least, aroused the attention of some decision makers, and in many instances decision makers have been forced to respond in some such tangible manner as monitoring the activities of the activists (e.g., sending representatives of industry to the Critical Mass conference), discussing the issues in a public forum, or giving higher priority to programs designed to meet criticisms of opponents. In our opinion, their most important accomplishment has been to bring to the attention of decision makers the need to consider the adverse affects that a technology may have on its people and their institutions. Consideration of this one question could lead to a more thoughtful approach to the commitment of our national resources. One very useful result could be agreement between opponents and proponents that greater consideration be given to developing mechanisms by which a coherent, safe, workable, national energy policy is defined and implemented.

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    > Richard Spohn, who has worked with Ralph Nader for more than five years and who was recently appointed to head the California Consumer Service Division, brags: "We did studies to determine the best way to get signatures for a petition, and then used that technique." *Politically, shrewd, but is it honest?* (Emphasis added.)

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Education and Public Acceptance of Nuclear Power Plants

G. Delcoigne*

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[Editor's Note: The following article was adapted from a talk by Mr. Delcoigne which was presented at the European Nuclear Society/American Nuclear Society (ENS/ANS) International Topical Meeting on Nuclear Power Reactor Safety held in Brussels, Belgium, Oct. 16–19, 1978. Those familiar with the topic will find nothing new in this article, but the discussion of this topic from the European perspective provides ample evidence of the commonality of the problem on both sides of the Atlantic. Furthermore, the article is well documented not only with textual citations but also by the inclusion of a bibliography. The evolution of the so-called nuclear debate from the late 1960s to the present time is reviewed, and the current manifestations of the antinuclear movement in many countries are described. Despite the emergence of pronuclear groups and discussions in many countries, the author concludes that public education is the crux of the problem, and he discusses the role of the International Atomic Energy Agency (IAEA) in the nuclear debate.]

The current environmental debate entered the international area in the late 1960s when the people of highly industrialized countries were increasingly being confronted with the undesirable impacts of technology and economic activity—polluted air and water, degraded urban and rural conditions, noise and congestion. Nuclear power soon became a prime target for frustrated emotions, and the so-called nuclear controversy started.

A second phase of the movement covers the early seventies to 1976 when the peak was reached. This was an anti-nuclear-reactor period, and a notable change took place in the membership of antinuclear groups. This was the time when lawyers and full-time publicists arrived on the scene. The nuclear licensing process, as such, and court actions by the opposition have been described by a Boston attorney as "a full-employment bill for lawyers."[1]

Today, in a third phase, it is no longer only scientists or lawyers or even technically trained people who are taking part in the nuclear debate—the new critics are a collusion of political activists and people who describe themselves as "enlightened people who care." Nuclear power plants are no longer the only target. In self-criticism the movement named "Environmental Action" calls for a new alliance in these words: "Failure to assemble broad coalitions today will make it much more difficult to organize tomorrow for jobs and against recombinant DNA, laser and other sophisticated weaponry, behavior modification, complex industrial chemistry, and future solutions proposed by scientists and governments laboring in the service of business and industry."[2]

SCIENTIFIC DEBATE?

But, although it deals with highly technological items, is the nuclear debate really a scientific debate? No, it is not, because the role of scientists in this public debate has changed from the primary role, which is the use of the scientist's expert status to give authoritative evaluations on technical and scientific aspects of a question, to a secondary one, which is employing the scientist's specialized knowledge for social considerations.

This is particularly evident in the nuclear controversy where scientists are presented as experts in another field of knowledge than their own and where statements such as the following are usually made: "We are not all experts in the field of nuclear energy, but we do not recognize that we must therefore remain silent on an issue of great social and economic importance."[3] The French ocean explorer Cousteau calls on people to stop land-based nuclear stations in the United States; Commoner (a biologist) testifies before the U. S. Congress on nuclear economics; Gofman (an expert on radiation effects) and Kendall (a high-energy physicist) judge the engineering facts of Rasmussen; and Watson (a geneticist) stands as a witness of nuclear accidents.

Nobel Prize winners are enrolled for or against nuclear power: usually Dr. Hannes Alfven, Nobel Prize winner in physics, is quoted as saying, "No acts of God can be permitted"—which leaves the public with the false impression that reactor designers have not reckoned with "acts of God." On the other side, 10 Nobel Prize winners in the United States "can see no reasonable alternative to an increased use of nuclear power to satisfy our energy needs."[4] Scientists who sign appeals are certainly able to make a competent

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professional judgment in their particular scientific field, but their statements regarding the problems of a different specialization, on the other hand, can only represent a personal opinion, which cannot be promoted to the rank of a scientific expert opinion.

Is the nuclear debate, then, a technical one between experts? The answer is: very rarely, because very few arguments of the opposition have followed the pattern of the net energy theory, for instance, which had its own moment of glory (i.e., one of constant repetition by the media 4 years ago). This controversy has meanwhile been settled—on a technical basis. In 1974, an Englishman, P. Chapman,[5] published an article in which he calculated that, making certain assumptions, during an exceptionally rapid expansion of nuclear energy, more energy would be used in the construction of nuclear power stations and for their fuel cycle than would be gained. The net energy balance of nuclear power stations was thereupon studied by various groups.[6,7] The results of these studies agreed that today's light-water reactors would generate within the first 2 to 3 months of their operation as much energy as had been invested in them. In a later article[8] published at the end of 1975, Chapman acknowledged the correctness of the results of these studies, and this put an end to the controversy. This case—which follows the usual scientific approach of publications reviewed by peers and admission of error—is an exception to the rule in the nuclear controversy.

Since then, several of the older arguments against nuclear power have been partly shelved—thermal pollution, emergency core-cooling systems, and reactor safety. It is perhaps curious how the emphasis in the debate has changed. At one point nuclear power was clearly the main bone of contention. Indeed, one spoke then of "the nuclear debate." Now, however, the accent has switched to the broad energy mix, and the main nuclear issues focus on breeders, waste disposal, proliferation, and the future energy needs of society.

If it is not a scientific or a technical controversy, it is certainly today a major sociophilosophical controversy between industry and the public, aggravated by a lack of understanding due partly to the specialized terminology used and to the present public distrust of some of the institutions the experts represent. The attack is on the industrial society, exemplified by the central generation of electricity, and nuclear power is the prime target. This was not the case in the early sixties, when the antinuclear movement started in the United States. Long before the leaders of today's antinuclear movements began publishing scare stories about what would happen if ounces of plutonium escaped during a noncredible nuclear reactor accident, the nuclear scientists themselves were worrying about atmospheric weapon tests, which dumped 6 tons of plutonium into the atmosphere, half of which is still settling to earth as fine dust today

TODAY'S ANTINUCLEAR MOVEMENT

Today, nuclear opposition groups no longer fight only for the protection of human life and nature but show an inclination toward religious or, on the other extreme, more activist (terrorist) aims. There are names such as "New Directions," "New World Liberation Front," "Another Mother for Peace," and "Mobilization for Survival" in the United States. This last group, called "mobe" for short, has four aims, which are characteristic of other groups also: (1) zero nuclear weapons, (2) ban nuclear power, (3) stop the arms race, and (4) fund human needs.

With some delay, the course of events in the United States has been followed *mutatis mutandis* in most industrialized countries with nuclear power programs. Yet—over time and geographic location—one can notice certain changes in the ranks of the antinuclear critics.

In Austria an appeal is made by "Mothers Against Nuclear Energy," and opposition against the Lemoniz nuclear power plant in Spain is mounting among Basque followers of the more violent Euzkadi Ta Azkatasuna (ETA).

In the Federal Republic of Germany, the Bundesverband Burgerinitiativen Umweltschutz (BBU) claimed to be the fourth largest political party in 1977. The small BBU executive board of only about 50 persons—most of them occupying leading positions in several associations which they themselves help to set up and appearing in different roles whenever there is an opportunity—approved the following action program:

—Disrupt the transport of uranium.

—Hold protest rallies.

—Refuse the payment of electric bills.

—Publish a list of companies with stakes in nuclear power.

This program may have been too aggressive for the passive follower, for the BBU soon experienced splits in its ranks, the chairman resigned, and in 1978 various of the public interest groups were absorbed in more political "Green Lists."

Delaying tactics, which started in the United States, has become one of the most favored instruments used by the opposition in countries belonging to the Organization for Economic Cooperation and Development (OECD). In his latest book, Ralph Nader[9] recommends legal delays as "the most expeditious route to limiting nuclear power." Delays, some of them merely obstructionist, have stretched completion time of a nuclear plant to 10 to 12 years. In the United States the present regulatory machinery requires more than 40 local, state, and federal permits from as many as 50 regulatory agencies for a single nuclear plant.

The result of this opposition has been that governments in some countries, although elected in democratic ways, have been hampered by these small groups in their attempts to introduce major technological innovations in the society. Amory Lovins in his article, "Energy Strategy: The Road Not Taken," wrote: "Even if nuclear power were clean, safe, economic, assured of ample fuel, and socially benign per se, it would still be unattractive because of the political implications of the kind of energy economy it would lock us into."[10]

Just how widely these new ideas are shared is not exactly known, but those who espouse them are very adamant and vociferous, have excellent access to the news media, and exercise political influence in at least two or three western countries. Certainly one of the underlying reasons for the reaction against nuclear power lies in the conscious or unconscious association in most people's minds between the peaceful uses of nuclear energy and the atomic bomb.[11] The psychological *"Angst,"* the fear of any new technology, and the overdramatization of future environmental havoc seem to be growing parallel to the increasing pace of technological development.

These antinuclear philosophies have also become clothed in the good reputations of the organizations which have adopted them, the best example being the involvement of various churches. It started in the United States with the resolution of the National Council of Churches opposing the so-called plutonium economy. Yet, the Lutheran Council of the United States, early in 1976, declared that in any decision rejecting nuclear power, one would need to consider the morality of using a limited supply of fossil fuels to produce electricity; and the World Council of Churches[12] demands that if there is no viable alternative to nuclear energy today the social implications of that fact must be examined. In 1979 the World Council of Churches will hold a worldwide conference on the theme, "Faith, Science, and the Future."

Meanwhile, the Protestant Church in the Federal Republic of Germany is questioning the exorbitant costs of nuclear power,[13] and the Catholic Church in Austria established an "ethical commission" for questions on nuclear power, maintaining that the decision to start a reactor has ethical and moral implications, although Cardinal König stated that technical questions should be left to the experts.

RATIONALE FOR DISSENT

A recent risk-assessment study in Austria showed that differences in attitudes of people who are for or against nuclear power are mainly due to their different beliefs about the environmental impact of nuclear power and its benefits.[14] However, another survey[15] on French attitudes showed that people acquire beliefs about the costs and benefits of nuclear energy which accord with their established attitudes either for or against nuclear power.

The fear of change is inherent in human beings and in established social structures: the impact of Brunelleschi's cupola was discussed for over 50 years by the Florentines, and what was said about trains in the 1840s or about electricity at the turn of the century is very similar to today's horror stories about nuclear energy.

It is important to put this spreading fear of technological risk in historical perspective. Seventy-five years ago, the major insecticide—which was sprayed on everything from apples to grapes—was not DDT, but lead arsenate, or "Paris Green." Women canned food with such preservatives as formaldehyde in high concentrations. Red food coloring was lead chromate—a horror of today's biochemist. The average life expectancy was 40 to 45 years at the turn of the century, and more than 13% of all infants died before their first birthday.[16]

Grosso modo—this is today the standard of living of the majority of people in the world and particularly in developing countries. But in the West where life expectancy is now over 70 and infant mortality less than 1%, the extensive research on "the possibility" that saccharin was carcinogenic led to it being banned 3 years ago in the United States. Additional research by industry has now proved that the possibility was not proved in the case of human consumption.[17]

It is therefore important for the public to understand what is meant by *risk* at a time when all scientific advances come under suspicion and when risk assessment is still a very new discipline. In this regard the distinction between real and perceived risk is quite new[18] and of key importance for our very rudimentary understanding of what can be considered an acceptable risk from technology.

For today's critics, one can see two main explanations: the delayed consequences and the association of nuclear energy with nuclear weapons.[19] The consequences of a slowdown or halt in the planning and construction of nuclear power stations are not immediately felt but will show up 6 to 10 years later. People underestimate or are unaware of the importance of a secure energy supply for the whole economy, and part of the reason lies in the difference in the time frame in which scientists or engineers, as opposed to politicians, must operate. I am convinced, for instance, that those who advocate the banning of artificial fertilizers, one of the greatest environmental pollutants, would never get much support, because the consequences of such a ban would be felt within a year's time and their responsibility for such a decision would still be fresh in the public mind.

The second explanation is the old association between peaceful uses of nuclear energy and nuclear weapons. Yet, there has so far been no case where a country went about developing a nuclear explosive by constructing a nuclear power plant. It should be noted, and made more generally known, that in the 10-year period from 1945 to 1954 three countries developed nuclear explosives, between 1955 and 1964 another two countries did so, and between 1965 and 1974 only one country developed nuclear explosives. In this time span, nuclear capacity in the world grew from 5 MW in 1955 to 54,000 MW in 1974 in 19 countries. From this alone, one could conclude that there is no relation between the expansion of nuclear power and the development of nuclear explosives.

THE INDUSTRIALIZATION ARGUMENT

To put the phenomenon of this "debate" into proper perspective, one should take a look at today's world. These trends result overall from the effects of affluence, safety, and well-being, for they are evident only in the highly industrialized countries with market economies.

Perhaps some new projects today are too big or too dangerous. Innovators and entrepreneurs are asked not only to bear all risks but also to bear the burden of proof—as if only they benefited from their efforts and not society also. Partly as a result of this increased awareness, people now seem to be trying to decrease many kinds of risks that society had been willing to accept in the past. In many cases the dangers are hypothetical but are taken too seriously. There are many programs of "risk avoidance"[20] which seem to have been carried beyond any useful benefit–cost ratio to the point where they have become counterproductive. Thus malpractice suits in the United States—which are supposed to protect and reimburse patients—are now actually causing so-called defensive medicine to be practiced: the quality of medical care falls while its costs rise.

This general criticism against big industry is not confined to the nuclear industry. A similar assault has been in progress for some years against the food industry in the United States, although, *prima facie*, the abundance of food in American life is something to be marveled at.[21] One must point out that little hardship is involved when, "as residents of the Geneva area," you declare that you would like to see "man living in harmony with nature" and therefore ask the French Government to take time for reflection before continuing the construction of a fast breeder reactor at Creys-Malville.[22]

To give a rather typical example of the thinking of certain affluent groups: in the United States environmentalists have stopped a loan to Indonesia for the purchase of 24 dredges to reclaim 8.9×10^9 m^2 (2.2 million acres) of tidal wetlands and mangrove forests on the coasts of Sumatra and Borneo. The purpose of the proposed reclamation was to provide more land for growing rice and other crops for human beings. The suit, however, was based on the danger of siltation, destruction of fisheries, and loss of wildlife.

The developing countries are still primarily concerned with how to gain access to modern technologies on the best terms and how to use technology to further their economic development and self-reliance because, for them, poverty is the worst pollution.

While some groups in our society consider further technical development unnecessary, very little thought is given to the means that must be provided to maintain the present standard of living in the developed countries, not to mention what is needed to raise the standard of living in the developing countries. Very little thought is given to the question of how to secure food and water for a population that will probably reach 6000 million by the year 2000 (Ref. 19).

The Pakistani delegate to the IAEA made the following statement at the 22nd General Conference of the IAEA in September 1978: "The developing countries of the world, representing over two-thirds of mankind, are facing a critical dilemma. On the one hand, there has been an inevitable increase in the price of oil and . . . further escalation in prices becomes unavoidable. The industrialized countries, instead of adopting a firm policy of conservation, are increasing their consumption and preempting the available limited reserves of reasonable-cost oil. It is an irony that at the same time, due to their domestic political considerations, they are slowing down their nuclear power programs, which could have brought some relief in reducing oil consumption. Under the circumstances, when the energy-deficient developing countries turn toward nuclear power, they face the insurmountable hurdles created by a deliberate and calculated policy of denial of nuclear technology, which is desperately needed for their further development."[23]

Countries with centrally planned economies also continued to regard nuclear energy as a necessary and benevolent force. The economic plan for 1976–1980 in the USSR foresees a rate of introduction of nuclear power stations exceeding the rate of development of electric-power generation as a whole. By 1980 the total capacity of nuclear power stations in operation will be about 21 million kW, and capacity will be doubled by 1985. It is envisaged that by 1990 the installed nuclear capacity in the Soviet Union will reach 90 to 100 million kW. One of the major points of the Council for Mutual Economic Assistance (CMEA)* program was the proposed accelerated development of nuclear power generation in CMEA countries.[24] In Romania, for instance, the nuclear power program is being accelerated so as to provide 20% of the installed electricity by 1990 (Ref. 25).

It is significant that doubts about nuclear energy are generally limited to sections of the affluent countries. With one or two exceptions, they are not shared by the governments, regional organizations, or trade unions of the developed countries nor by the developing or socialist countries. Perhaps developing countries and workers' organizations have a firmer sense of the true implications of zero growth. Be that as it may, no government on this earth has yet declared zero growth a political-economic aim.[26]

NEW TRENDS IN OECD COUNTRIES

Despite the problems discussed above, new trends noticeable in the OECD countries include (1) formation of the pronuclear groups, (2) favorable judicial decisions, (3) greater public participation in public decisions, (4) increasing support by government officials and regional organizations, (5) favorable public polls, and (6) educational programs. Each of these is discussed in more detail below.

One encouraging trend has been the formation of public interest groups that take an active interest in the solution of energy problems (e.g., the European Energy Association, A Power for Good in the United Kingdom, and Nuclear Energy Women in the United States).

Another trend is the reaction of the judiciary system in response to the continuous harassment by antinuclear groups with respect to decisions taken in accordance with existing constitutional rules and regulations. This judicial reaction differs with the issues and the laws of each country.

1. In the United States, the Supreme Court stated in April 1978 that "the fundamental policy questions appropriately resolved in Congress and in state legislatures are not subject to reexamination in the Federal Courts under the guise of judicial review of agency action," and in June 1978 it upheld the constitutionality of the Price–Anderson Act.

2. In Japan, a district court in Matsuyama ruled that safety standards at the plant were sufficient and in conformity with Japan's reactor regulatory law.[27]

3. In the Federal Republic of Germany, a court in Hamburg recently ruled against withholding portions of the payment of electric bills, which 350 nuclear opponents had done, arguing on the basic right to freedom of conscience. The court cited the fact that no one can withhold part of his taxes if he disapproves of the nation's defense budget. Even more recently, the administrative court of Oldenburg stated that the limits for the release of radioactive effluents into the River Weser have been so strictly determined that the fears of the plaintiffs of contamination of the groundwater are without any foundation.

There has also been a greater effort toward public participation in decision making. The most famous example comes from the United Kingdom. The Windscale inquiry and Justice Parker's ruling proved that if both parties to an argument could be brought together under an impartial authority, it would be possible at least for the differences to be identified. The impartiality of the Tribunal was recognized by the Counsel for the Friends of the Earth,[28] but this view did not survive the publication of Justice Parker's report; i.e., 4 months later the Friends of the Earth, in their assessment of what they call "the Parker inquiry,"

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*Also known as COMECON.

accused the Inspector of "a marked asymmetry of judgment," of being "insufferably patronizing and inexcusably slipshod," and of "obscurantism."[29]

In another instance of public participation, in New Zealand, where energy planning for the nineties is necessary, the government has issued a publication titled *Goals and Guidelines*, which should serve as a useful background to a continuing and informed public debate on energy matters. The criticism that some aspects of the publication may arouse will be constructive and helpful in improving and refining the energy strategy that the government is now in the process of developing. The government welcomes considered written responses to *Goals and Guidelines* and will assist in the promotion and coordination of the public discussion on its contents. The New Zealand government specified, however, that "its presentation for public debate does not mean that the Government will, or should, refrain from making decisions while, for 12 months or so, the process of public debate and response-gathering and analysis takes place. Some decisions will certainly be required, and must be taken, in that time. Nor does it mean that the Government will not be fully responsible for the decisions made after the responses are received, or that it should or must need any particular response."[30]

Most encouraging of the new trends are the instances where government officials and regional organizations have repeatedly supported nuclear energy:

—At the European Economic Community (EEC) public hearings[31] in November 1977 and January 1978, it was noted that "development of nuclear energy appears to be an inescapable necessity to maintain moderate growth."

—The European Parliament in Strasbourg approved the breeder policy for Europe,[32] and the Council of Europe organized a colloquy on "Energy and the Environment" in November 1977 to improve the quality of information available to parliamentarians in Europe and in preparation for the debate in the Parliamentary Assembly in 1978.

—The economic summit at Bonn in July 1978 concluded that "the further development of nuclear energy is indispensable and the slippage in the execution of nuclear programs must be reversed."

The majority of polls and referenda on nuclear power appear to confirm this trend—in general with a 2 to 1 ratio in favor of nuclear energy. Strangely enough, polls taken near commercial nuclear power stations show more or less the same ratio.

In OECD countries governmental reaction has manifested itself in large-scale efforts in the dissemination of information. However, the results have often been disappointing. Official government-sponsored information campaigns have been carried out and have been counterproductive in Sweden and Austria and also, to some extent, in the Federal Republic of Germany and in Switzerland. On all these occasions, opponents used the campaign to proclaim their own credos. It also became apparent that the "neutral citizen" for whose benefit the campaigns were conducted is usually not interested enough to attend the debates. The only dependable participants are the "concerned citizens" (i.e., those who took the trouble to label themselves as such), and they are usually the opponents—those who have the money and the leisure and have been given the opportunity.

EDUCATION: THE CRUX OF THE PROBLEM

The real crux of the problem is education, or rather the lack thereof. The vast majority of people with whom one comes in contact are largely ignorant about nuclear energy, and education is a long-term process. Few schools have environmental or energy education in their curricula, and probably few teachers are prepared to teach such courses. A recent national inquiry in Canada, based on 2100 individuals over 18 years of age, showed that only 56% was aware that nuclear energy can be used to produce electricity.[33] Another study,[34] which was made in the United States, found that support for nuclear power increased with the education level. On the average, there was 13% more support for nuclear power among those with the highest educational attainment.

Education is primarily the responsibility of government. A small start has been made in the United States where high school and college teachers were invited last summer to participate in a nationwide program of 63 energy-education workshops sponsored by the Department of Energy. A similar program exists in Karlsruhe. However, all educational efforts are not run along the same lines. In the United Kingdom, the Open University has a course titled "Control of Technology," which includes nuclear power. The textbook in the course is *Nuclear Power* by Walter Patterson of Friends of the Earth. The other reference books are the *Sixth Report of the Royal Commission on Environmental Pollution*, *The Fissile Society* by Walter Patterson, *Nuclear Prospects* by Michael Flood and Robin Grove-White, *Fuel's Paradise* by Peter Chapman, and *Soft*

Energy Paths by Amory Lovins. The Penguin list of publications on nuclear energy does *not* include even *one* written by an expert on nuclear energy.

Education on a worldwide basis and in an impartial way is needed about energy questions in general. The same effort that has been made on an international basis in order to arouse consciousness of environmental problems should be undertaken for energy matters. The Tbilisi Declaration made under the auspices of UNESCO in 1977 made clear that environmental education was to be considered a comprehensive lifelong education, revealing the enduring continuity which links the acts of today to the consequences of tomorrow. This will strengthen the programs of environmental education of the United Nations Environmental Program (UNEP).

A recently published World Health Organization (WHO) study titled *Health Implications of Nuclear Power Production*[35] favors nuclear power as compared to alternative energy sources and also noted that the public should be kept fully informed and that public health authorities should participate in the dissemination of information on nuclear power. This trend of comparative energy sources assessment is also seen in governmental[36] and institutional studies,[37,38] and the UNEP has launched four studies on comparative assessment of environmental impacts of all energy sources, i.e., fossil fuels, nuclear energy, and renewable sources of energy.

THE ROLE OF THE IAEA IN THE PUBLIC DEBATE

What is the IAEA's role in the public debate (or controversy, as the case may be)? An immediate objective, of course, is to give correct technical and factual information about energy, and nuclear energy in particular, to the IAEA member states and the public so that the safety, the availability, and the economic aspects of the various energy sources can be seen in proper perspective. This includes information about any safety-related incidents so as to avoid the misrepresentation of facts and their subsequent dissemination. In the same way, efforts are made to offer to those interested the basic facts and main references on topical problems such as nonproliferation, waste management, and decommissioning.

In reviewing this debate, one is struck by the communication gap that exists between the debating parties and the public—it is very close to a generation gap. In a certain sense, one generation has failed to explain to the next the possibilities of the technical world which it has created and its children will live in. Where is the school program that informs our children about the technological innovations of the 20th century and the benefits they can derive from them in everyday life: the advances in industry, agriculture and pest control, communications, space research and its feedback applications, medical analyses and surgery, computers, laser applications, war technology, natural resources, and energy sources including nuclear energy? Whether public acceptance of nuclear power plants is achieved through debate or education or both, "the energy issue will be with us for a long time, because it has become social and political as well as technical."[39] As Marie Curie said well over 50 years ago, "Nothing in life is to be feared; it is to be understood."

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F. THE FUTURE OF NUCLEAR ENERGY

THE FUTURE OF NUCLEAR ENERGY*

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In many ways nuclear energy is a fantastic success: a completely new source of energy now producing, or soon scheduled to produce, about 20 exajoules per year or almost 10 percent of all the energy man now produces. This energy will come from ∿ 525 large reactors in 36 countries. These reactors, if replaced by oil-fired power plants, would require about 10×10^6 barrels of oil per day — i.e., about one-seventh of all the oil produced in the world. Were the output of these plants used for electric resistive heating, in principle 2.5×10^6 barrels of oil per day could be displaced if in electric vehicles, perhaps 7×10^6 barrels.

Despite this extraordinary accomplishment, the first nuclear era seems to be coming to an end in many countries. Will there be a second nuclear era — that is, will nuclear energy occupy a secure niche as a large and permanent source of energy? Or will it simply be an ephemeral bridge to a fission-free future based on the sun, on geothermal energy, on fusion, and on fossil fuels — at least as long as the latter last, or until they are proscribed because of their effect on the climate?

It is impossible to generalize: in Austria, the first nuclear era has already ended or, more accurately, was not even allowed to start; in Sweden a majority voted to end it in 25 years; in the United States, some states have proscribed nuclear energy, and President Carter refers to it as an energy source of last resort. By contrast, in France, Japan, and the Soviet Union, nuclear energy continues to grow rapidly, and plans are going forward for the second nuclear era, based on breeders or other high-gain reactors.

The most plausible futures probably require nuclear energy. A world of 8×10^9 people is almost surely going to demand much more energy than we use today, assuming the energy can be found. R. Rotty of the Institute for Energy Analysis (IEA) and W. Haefele, et al. of the International Institute for Applied Systems Analysis (IIASA), visualize a world that uses 3-4 times as much energy in 2030 as we use now. Were most of this to come from coal, the world would have to mine 25×10^9 or more tons of coal each year. This I deem to be incredible. I would imagine the dangers of nuclear energy would pale by comparison.

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*Presented as the Closing Plenary Address, ANS-ENS Topical Meeting on Thermal Reactor Safety, Knoxville, Tennessee, April 11, 1980.

Yet a nuclear future of this magnitude is also formidable. Even if but one-half of this energy were produced by nuclear reactors, we would be speaking of a world of 7500 large reactors. Is this credible? In short, is a very large second nuclear era possible, even if the world allows the first era -- based on reactors of current type and limited by the amount of relatively cheap uranium — to evolve into the second era, based on reactors that, in principle, can be supplied with fuel indefinitely.

That scenarios are uncertain goes without saying. At the recent Münster conference, Amory Lovins argued that improved efficiency in end use could assure the amenities we now enjoy in a world of 8×10^9 people using no more energy than is used now. This amounts to reducing the expenditure of energy per capita from 2 kW-years per year per person to 1 kW per p[illegible] I shall not be here in 2050, when this happy situation is expe[illegible] take place, so I shall never know whether Lovins will be proven right. Given the uncertainties, to proscribe the second nuclear era now on the grounds that the world can live in relative peace with an expenditure of 1 kW per person is mindlessly irresponsible. Nor can we count on the other options: each is beset with difficulties that all of us are familiar with. Nevertheless, no one can prove that nuclear fission is here to stay: our responsibility as nuclear technologists is to perfect the fission system so that it remains an available, politically acceptable option. Ultimately the future of nuclear energy is a political and economic question to whose resolution we nuclear technologists can only contribute, not decide.

II

I deal but briefly with the first nuclear era, during which nuclear energy is based on already developed reactors. Since a Pressurized Water Reactor, over its lifetime, requires about 6,000 tons of uranium, we had always understood that the first nuclear era was self-limiting. How self-limiting depends on how much uranium can be retrieved at an acceptable price — 10×10^6 tons would support 1,000 reactors for 50 years, for example. Thus we already may have in place 30-50 percent of all the reactors that will constitute the first era. What the ultimate usable price of uranium in current reactors might be is set by the price of energy from competitive sources. If the competition is, say, solar power towers, I suspect the upper limit for the price of uranium is far greater than we now imagine (though the world, paying so much for primary energy, would thereby be a far poorer place). If the competing source is the breeder, the upper limit might be, say, \$180 per pound. (This is based on the breeder eventually costing \$500 per kW more than the non-breeder.)

What can be done in the short run to ensure that the first nuclear era run its originally contemplated course is limited because the reactors and the institutions required to manage the nuclear enterprise are already in place. Two exceptions to this should be noted. First is waste disposal: a vigorous, clear demonstration of actual disposal of high level wastes would probably be as important as any single action to incline the public toward support of nuclear energy. Second, Three Mile Island may have proved, as Dr. Stratton explained at this meeting, that in accidents that develop slowly, the China Syndrome may be a myth: a melt-through with large release of radioactivity may be physically impossible. After all, it was the belief of the entire nuclear community, since 1960, that failure of ECCS would usually induce failure of the containment. If this is wrong, we must re-examine many basic assumptions. Moreover, I call your attention to calculations by S. Zivi that suggest the physical impossibility of the violent steam explosion blowing the top off a Pressurized Water Reactor vessel. These considerations, coupled with the observation that the ^{131}I source term may be grossly overestimated, represent the best of the good news from Three Mile Island. Nevertheless, even in the short run important fixes, though incremental, can and are being made.

Three Mile Island focused the public's attention on what many of us within the nuclear enterprise had realized was the real problem — the Class IX accident. That the enterprise has reacted vigorously — with the Institute of Nuclear Power Operations (INPO), the Nuclear Safety Analysis Center (NSAC), and insurance pools; and that a variety of technical improvements will be instituted can only be applauded. The aim must be to avoid another Class IX accident during the rest of the first nuclear era — not only because the public will hardly accept such an accident, but because, as the current moratorium on nuclear energy suggests, the financial strain on the affected institution is simply too great. No utility president is likely to order a nuclear plant if he believes he is betting his utility on an event (such as Three Mile Island) whose a priori probability might be as high as 10^{-2} per year.

Although reaction to Three Mile Island has not been uniform throughout the world, none can deny that its impact was profoundly felt everywhere. The U.S. utilities have recognized this in setting up INPO. Ha the international nuclear enterprise reacted with equal vigor? Can we be assured that countries with little technological tradition can maintain and operate reactors safely? The industrialized countries have the strongest incentive to ensure that Class IX accidents are avoided anywhere in the world. The same considerations that led to establishment of INPO in the United States are relevant worldwide. Indeed, I would consider the extension of INPO, or something equivalent to INPO, worldwide as an extremely important step in ensuring that the first nuclear era is not aborted. I believe this matter is being taken seriously both by the International Atomic Energy Agency and by the Nuclear Regulatory Commission. *(I recall, during a visit to Pakistan in 1962, discussing with Francis Perrin the capacity of underdeveloped countries to manage nuclear systems. We were encouraged by the successful operation of national airlines in most of these countries: a handful of expert pilots and mechanics are sufficient to operate safely. However, as Three Mile Island has shown, once a Class IX accident occurs, the demands on the technological community become very great — much greater than can be met by the resources of all but the most sophisticated* *countries. Perhaps emergency response teams, combining international experts as well as experts from a nation's nuclear energy laboratory, ought to be established to prepare for such contingencies.)*

III

Are the measures now being taken to assure the continuation of the first nuclear era sufficient to ensure the second nuclear era: the era we visualized as involving perhaps 10 times as many reactors as we now have, many of these being breeders? Again, no one can tell; nevertheless, the argument used by the Swedish aeronautical engineer, Bo Lundberg, in 1963 with regard to the future of air transport, must be heeded. Lundberg pointed out that as the number of passenger-miles flown increased, the probability of accident per passenger-mile would have to decrease correspondingly. Otherwise the accident rate would increase — in his estimate, to several major crashes per day by 2010. Though the probability of a passenger successfully completing a flight remained as good in 2010 as in 1963, in Lundberg's view the public would lose confidence in air travel, and commercial air travel would collapse. He proposed that in the fifty-year period from 1960 to 2010, the fatality rate per passenger-mile would have to diminish from $11/10^9$ passenger-miles to about $.3/10^9$ passenger-miles — a factor of about 40.

Commercial air travel has actually become much safer per passenger-mile — so much so that although the passenger-miles have increased about as he predicted, the absolute accident rate has fallen. Over the last 20 years in the United States, though the number of active commercial transports has increased 19 percent, the total accidents have decreased 71 percent. By contrast, there has been much less improvement in general aviation: the number of fatal accidents in general aviation has doubled as have the number of airplanes. Yet the public tends to view accidents in small planes very differently than it does accidents in commercial transport. The 1270 people killed in 1979 in the United States in many small plane crashes would not be tolerated if they were killed in 10 or 15 large crashes each year.

The experience in air transport should teach us two things: first, that accidents do tend to diminish as experience is gained; but second, that as far as the public's perception is concerned, risk is not simply the product of probability x consequence — i.e., the first moment of the probability distribution of severity of accidents. Somehow, the public accepts many small airplane crashes, but reacts much more violently to a few very large crashes, although the total casualties are the same in the two instances. I would guess that this reaction is at least in part attributable to television: each of us can identify with, and be scared out of our wits by, a large accident that we see in detail on the TV screen. That the accident is a priori extremely improbable is less evident since what we see is an actual instance of the improbable occurring. In short, the public, I would suggest, understands consequences; it does not understand probabilities.

The a priori mean probability of Three Mile Island, according to Rasmussen, is about 4×10^{-4} per reactor year, with a tenfold spread on either side of this mean. If the first nuclear era amounted to 30,000 reactor years, and the mean a priori probability remains 4×10^{-4} per year, there would be, on average, 10 Three Mile Islands over the next 30-50 years, with the range lying between 100 and 1. This I would judge to be intolerable — not merely because the public would lose confidence in nuclear energy long before the tenth Three Mile Island, but because utility executives, whether private or public, would have lost confidence in nuclear energy. To survive the first era, I would suggest that we must reduce the a priori probability of Class IX accidents by a factor of the order of 10 to 100, so that at most there would be very few — say one or two Three Mile Islands, within this period.

IV

I shall not try to describe the many possible measures that can be undertaken to reduce the probability of Class IX accidents, or to mitigate their consequences. Many of these have been discussed at length at this meeting. They include a variety of technical and institutional fixes, mostly incremental. (For example, I have already implied that more careful analysis might rule out containment failures that are now conceded to be physically possible.) The possibility that has not been discussed is the development of reactor systems that are intrinsically less sensitive to meltdowns than are the present types. We are convening a small group of old-timers in the nuclear business (that is, the now rather elderly group of people who were responsible for setting the enterprise along its present course) to discuss whether the current moratorium in the U.S. might be used to advantage to establish criteria that reactors for the second nuclear era ought to meet.

One conjecture that I would put forward is that siting policy itself may have an influence on accident probability. If one concedes, as was assumed in the Rasmussen report when it admonished its readers *not* to multiply accident probability at time T by total reactor-years at time T + t, that the accident frequency per reactor per year diminishes as the *total* number of reactor years increases (according to the so-called cumulative learning curve discussed at length by P. C. Roberts of the United Kingdom), then it seems plausible to me that such learning occurs faster on a large site than it does on a small site, and that, therefore, the accident rate *per* reactor ought to be smaller on the larger site. To take an example, elements of the Three Mile Island sequence occurred at Davis-Besse, Oconee, and Rancho Seco before it occurred at Three Mile Island. Had all four reactors, Davis-Besse, Oconee, Rancho Seco, and Three Mile Island, been co-located, I cannot imagine Three Mile Island occurring. The word would have got around about the ambiguity in determining water level after a small LOCA. To be sure, INPO's and NSAC's main jobs are to ensure that the word gets around — i.e., that accident frequency diminishes fast enough as cumulative reactor years increase to more than balance the increase in number of reactors. I suggest that consolidation of siting would hasten the process, and thus ease INPO's and NSAC's task.

The trend toward consolidating siting is unmistakable: of the 525 reactors, 170, representing one-half the world's nuclear power outside the United States, are now on sites with 4 or more reactors. If this trend continues, then could we not contemplate a world of 5,000 reactors confined, say, to no more than 500 or 1,000 sites? Now if the cumulative learning curve for a multi-reactor diminishes so fast that the probability of accident <u>per site</u> is rather independent of the size of the site, we would be confronting a world in which the overall accident rate is not so different from what we now experience. I am able to contemplate such a second nuclear era with much more equanimity than I can one in which many thousands of reactors are scattered among very large numbers of organizations and sites, and in which the learning rate is correspondingly slower.

I realize that what I have said is conjecture. I put it forth for consideration; I should think that the influence of number of reactors per site on accident rate could be estimated from an analysis of LER's that are already available. This I should think would be useful datum to collect.

V

Much of Western society seems today to be afflicted by an environmental hypochondria that undermines and debilitates every massive technology. Is it possible that this hypochondria will pass, and that the public reaction to nuclear energy will eventually be commensurate with its true risks?

I see two possibilities. The first is that we will eventually be heeded in our insistence that nuclear risks must be judged in comparison to other risks. To take an example, Henry Hurwitz of General Electric has estimated that if the government's goal for conserving energy by better insulation of houses is achieved, then we can expect 20,000 additional lung cancers per year because of the increased exposure to radon in the tighter houses. This estimate is based on a strictly linear dose-response, with no threshold. The expected number of casualties during the next 20 years from insulating homes is therefore much larger than the casualties caused by the very worst Class IX accident that might occur in 20 years. Tightening houses to save energy is more dangerous than is a Class IX accident!

One cannot ignore Hurwitz's calculation: if the public reacted in a way that we here would deem rational, its fears about nuclear energy would surely be allayed by this argument. But the difficulty is the one I have already alluded to: a single incident that might harm many people is far more threatening than are many small incidents that in aggregate affect even more people. Nevertheless, I am optimistic enough to hope that people will eventually place risks of nuclear energy in perspective.

The other possibility is that the estimates of the amount of cancer caused by low levels of radiation could prove to be greatly exaggerated. The large number of cancers supposedly caused by the worst Class IX accident occur mostly among a very large number of people exposed to less than 1,000 mr per year of radiation — i.e., 3 mr per day. If low level radiation could be shown to be <u>much</u> less harmful than is suggested by the usual linear hypothesis (with a slope of 1 cancer per 5 x 10^3 rads), then the spectre of a reactor accident conceivably causing hundreds of thousands of casualties would be extirpated.

Three recent findings bear on this all-important issue. First, in the April 4, 1980 issue of *Science*, Raabe, Book, and Parks have shown that at least for bone tumors caused by radium, there is, in fact, a practical threshold - i.e., the latent period for appearance of the tumor exceeds the life span if the dose is lower than 39 millirem per day. This evidence is consistent with the findings at Nagasaki where low LET radiation below about 50 rads showed no increase in leukemia (even though the exposure was instantaneous); it is not consistent with Hiroshima data where there was a higher irradiation by high LET radiation and linearity perists below 50 rads. It is significant that the third BEIR report of the National Academy of Sciences no longer accepts linearity below 10 rads -- yet most of the 45,000 estimated number of cancers from the worst Class IX accident are attributable to lifetime doses less than 10 rads.

A second possible misconception is the alleged sensitivity of the fetus to prenatal radiation. One of the more dramatic events at Three Mile Island was Governor Thornburgh's order to evacuate pregnant women. The scientific basis for this action lies in the claim by Stewart and Kneale that the doubling dose for childhood cancer is less than 2 rads to the pregnant mother. This claim has been in the literature for about 20 years; it has been a source of dispute ever since it was made. During the past year Drs. J. Totter and H. G. MacPherson of the Institute for Energy Analysis have found a methodological flaw in the Stewart-Kneale analysis: namely, that the controls did not in fact match the cancer cases in many essential respects. In particular, the requirement that the probability that a control received X-rays equal the probability that a non-radiogenic cancer received X-rays was not fulfilled; as a consequence, the findings of Stewart-Kneale were rendered invalid. There is, according to MacPherson and Totter, <u>no</u> evidence that extremely low levels of prenatal radiation increases the probability of childhood cancer.

Finally, I call to your attention the recent article in the *Proceedings of the National Academy of Sciences* by John Totter on the origin of spontaneous cancer. Totter first shows that mortality from cancer, when corrected for competing risks, seems to be independent of a country's state of industrialization, and therefore of its level of man-made pollution. Thus, he argues, one must seek the primary carcinogens not among man-made agents, but rather among all-pervasive "normal" components of the environment. The culprit suggested by Totter is oxygen. His main argument rests on the known fact that one intermediate in the metabolism of oxygen is the superoxide radical, O_2^-; and this radical is essentially the same as the radicals produced by radiation, which of course is known to be a carcinogen. Indeed, the radiomimetic dose continually imposed on each of us because of the flood of O_2^- radical might be between 500 and 2,000 rads per lifetime — i.e., between 7 and 30 rads per year; it is this flood of radiomimetic radicals that, in Totter's view, is an underlying, perhaps the most important, cause of cancer. If one accepts Totter's view, then the lifetime dose of 7 rads of background radiation, even on the linear hypothesis, would account for about one-third to 1 percent of cancer.

It is too early to say how Totter's revolutionary theory on the origin of cancer will be received by the scientific community. Thus far it has been promoted by the President of the National Academy of Sciences, Dr. Philip Handler who, along with Professor Fridovitch of Duke University, discovered the enzyme super-oxide dismutase that protects us from this enormous natural flood of radiomimetic radicals. Nevertheless, the evidence pointing to oxygen as the culprit is tantalizing: oxygen is known to be a mutagen; it has been shown to cause tumors in fruit flies; and it gives a positive Ames test, the assay that is often used to screen carcinogens.

I cannot say where these considerations will lead. I would suggest that they may very well result in our realizing that in fact low-level radiation is far less damaging than even the linear hypothesis suggests, and that therefore most of the fears concerning the lingering effects of Class IX accidents or, for that matter, of conceivable contamination from leaks from waste depositories, are unfounded. If these speculations prove correct, then I should think the Western world will come to its senses with respect to nuclear energy.

I close by drawing from William Clark's perceptive paper on "Witches, Floods, and Wonder Drugs." He likens the current environmental hysteria to the fear of witches that swept over much of Western Europe and America in the 16th and 17th centuries. The symptoms were much like those we now see every night on TV: vague discomforts, cattle dying, babies deformed because of industrial miasmas. Perhaps most striking was the hysterical fear exhibited by 400 Middletowners when the Nuclear Regulatory Commission proposed to vent 60,000 curies of ^{85}Kr from Three Mile Island: the maximum beta skin dose per person would have been 11 mr, the whole body gamma dose 0.2 mr (compared to Totter's estimate of radiomimetric O_2^- dose of between 7,000 and 30,000 mr per year). Witch hunting flourished for two centuries, especially since it was in the interests of the witch hunting profession to find and burn more and more witches. It was not until 1610 that the chief inquisitor, Alonzo Salazar y Frias, became suspicious that the alleged connection between witchery and human ills may have been exaggerated. He ordered an investigation and discovered that although more than 500,000 bona fide witches had been burned at the stake in the past century, nothing else seemed to have changed: people got sick and died, wars and pestilence abounded, crops would sometimes fail. Though he did not proscribe witch hunting, he forbade the use of torture to extract confessions: the result was that witch burning, and then witch hunting, fell precipitously.

I do not wish to leave the impression that a Class IX accident is as innocuous as witches have turned out to be: we know that the LD_{50} is 400 rems of radiation and that in the worst conceivable accident some acute deaths would occur. But we also know that most of the presumptive casualties and the fear of Class IX accidents comes from low level exposure. I would therefore insist that the future of nuclear energy, whether there will be a second nuclear era, will depend upon the public's overcoming its unreasoning dread of our modern witch — exposure to low level radiation. It took the Inquisition more than a century to overcome its fear of witches. I would hope we will lay to rest this modern witch soon enough to ensure that the first nuclear era run its course, and the second nuclear era be allowed to co-exist with the solar era or fusion era.

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