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A SURVEY OF RISKS OF ALTERNATIVE FUEL CYCLES

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ACRS Fellows:
J. M. Griesmeyer
D. H. Johnson
W. E. Kastenberg

## ABSTRACT

Difficulties in assessing the risks imposed by different electricity generation techniques are presented. Specific aspects of the coal, oil, hydroelectric, and nuclear fuel cycles which are difficult to quantify are discussed. This is followed by a review of five recent comparative analyses. The results of these studies are compiled and presented as broad health effect assessments. Review of these studies indicates that the assessed risks of nuclear power are less than or equal to those of the primary alternatives. When the unquantified risk components are then considered, this relative assessment becomes more qualitative, but does not appear to change.

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# 1. INTRODUCTION

The generation of electrical energy has become an integral part of our society. resulting in both positive and negative impacts. Because of changing resources, energy options are subject to evolution which in turn bring about changing impacts on society. An essential ingredient in the formulation of responsible policy regarding choices of energy is an identification and quantification of their impacts for currently deployed and future options.

A measure of the negative impact of technical endeavors such as energy generation is the measure of risk. Although formal definitions of risk have been made [1-3], it is convenient here to be fairly general in its definition. In this discussion, risk is used as a measure of negative impact on society. It may be based on actuarial data (e.g., the number of people killed annually in automobile accidents) or it may be based on calculation using a model (e.g., the potential restriction of land use due to a nuclear reactor accident).

In this report, the current literature regarding the risks of conventional fossil fuel-electric and hydroelectric energy generation are summarized and compared to the risks due to conventional nuclear-electric generation. The major objective is to place the actual and potential risks of nuclear energy generation in perspective, so that they can ultimately be considered in the licensing process. This consideration might also include the allocation of limited economic resources. The use of a more expensive form of electricity production caused by increased licensing requirements which may not be cost effective could also lead to the unavailability of resources which could be used for risk reductions in other aspects of society.

Before proceeding with this summary and comparison, it is useful to comment on such an approach. The consideration of risks from electricity generation technologies in such a generic manner as advocated here should, at the least, provide a coarse measure for the comparison of the social costs of these options. If one option is denied, either through political decisions or due to lack of development of the resource or technology, its risks are replaced by risks from other options. It is important to note in this regard that even conservation may impose risk.

A prime difficulty in the study of energy related risks surfaces in the choice of an unbiased common denominator upon which to base the comparisons. Related difficulties include the lack of an established and accepted methodology for risk comparisons, the multidisciplinary nature of the problem, the different manifestations of the impacts for each option in terms of their associated health effects, and the enormous variance in the uncertainties in the risks of concern. It is fully expected that the treatment of these difficulties will provide the potential for disagreement in the general public as well as in the risk assessment community.

In Section 2, risks of the coal, oil, hydroelectric and nuclear fuel cycles are considered. Attention is given to problematic aspects which are the source of major uncertainties of assessing specific risks. Difficulties in establishing a common base of comparison of the diverse risks are discussed with detailed consideration given to specialized concerns such as the use of expected values for catastrophic phenomena.

Section 3 contains a summary of some recent assessments of the risks imposed by various alternative electricity generating options. The health effects are presented as ranges of expected values which encompass the individual analyses and generally represent accepted values. However, in light of the difficulties discussed in Section 2, the assessments necessarily contain omissions.

The final section of this report contains a brief summary, discussion and some concluding remarks regarding the risks associated with current electricity generating technology.

## 2. FUEL CYCLE RISK ASSESSMENTS

### 2.1 Introduction

An assessment of the risks from each electricity generating option must include consideration of the risks from each portion of the corresponding "fuel" (or full production) cycle. Only when such complete assessments are made and the uncertainties therein evaluated, can objective comparisons of the risks of energy options be made. As discussed below, such completeness may be an elusive goal; however, careful analysis of the quantified and unquantified risk contributors contained in recent analyses of various fuel cycles can provide insight into relative risks.

Elements of a fuel cycle that must be considered in a complete risk analysis would include, but not necessarily be limited to, fuel extraction, transportation, processing, conversion, and waste disposal. Each element may impact public health and safety, as well as the environment, through a variety of mechanisms; and common elements across fuel cycles will have different impacts.

2.2 Sources of Uncertainty: General

Nonrandom uncertainty is present in fuel cycle risk assessment because of the type and quality of the data involved, the nature of the component risks, the selection among and treatment of the varied impacts, and the selective omissions of component risks.

The analyses performed to date have utilized data that can be categorized as follows: a) those based on actuarial information and b) those based on models. In addition, some risks remain unquantified, either through omission of the parent hazards in the overall analysis or because of the lack of fundamental understanding of the particular phenomenon. The type of data used depends primarily on the nature of the risk.

One major aspect in the quantification of risk is a knowledge of human health effects. In particular, the health effects of fossil fuel plant emissions and the health effects of low level releases of radioactive material from nuclear plants contain uncertainty. A recent paper by Hamilton [4] reviews the major uncertainties in the health effects data for both types of emissions. In addition, Hamilton assesses the various criticisms of presently accepted health effects data, shows which are valid and which are not, and finally suggests areas where further research is necessary to reduce uncertainty.

An additional concern in the utilization of data involves its original source. The use of common sources, necessitated by the dearth of independent information on specific effects, raises the possibility of common fallacies cross-contaminating a selection of otherwise unbiased investigations. An example of this concern is found in the dependence in many risk analyses on the data compiled by a handful of investigators reflecting the health effects of air pollution from the burning of fossil fuels.

A related concern is the reliance upon a single analysis of a component risk across risk assessments. For example, the quantification of the risks associated with large accidential releases of radiation from nuclear power plants is commonly based on a single analysis [5] or variations on that analysis.

Three final comments are appropriate in a general discussion on uncertainties in risk analyses. First, at least one investigator [4] has indicated that the marginal health effects of additional energy generating units must be considered; specifically, ambient concentrations of sulfates, especially east of the Mississippi River, are close to levels where chemical damage is seen. Second, synergistic effects have not been adequately considered; for example, the increased use of coal may, through climatic change, influence the failure probability of hydroelectric dams by increasing the magnitude of the maximum probable flood. Third, there is always some uncertainty introduced in not knowing whether all contributions to risk in a given analysis are included; for example, that all sequences are included in determining the risks of accidents.

## 2.3 Problems in the Characterization of Risk

Risks from different technologies of electricity generation involve impacts which manifest themselves in a great variety of ways. The present paper will focus primarily on two such impacts: premature death and non-fatal disease/accidents. No comprehensive attempt is made to discount or convert, in some sense, other impacts such as land use restriction or resource diversion to equivalent deaths or disease. Health impacts from different hazard sources may vary according to the amount of time for effects to surface.

Demographic factors, such as the age distribution of a target population, which are dynamic variables, also enter into the analysis of risk and vary in importance among risk sources.

A difficulty in establishing a common denominator on which to base comparisons surfaces when the question of equity is approached. The receipt of direct, tangible benefits and some degree of control of the hazard suggests that occupationally encountered risks be considered separately from risks to the general public.

As risks to individuals are considered collectively by society, the degree to which that society is risk adverse may be defined. Thus, there is a logical division between individual and societal risks. One aspect of this division is perhaps exemplified by the current controversies surrounding the Zion and Indian Point nuclear power plants. It <u>may</u> well be that the units in question pose individual risks which are not significantly different from the "average" nuclear plant in the United States. However, the relatively large populations surrounding these units <u>may</u> necessitate engineered changes <u>if</u> the societal risk is considered excessive.

Society demands explicit attention be paid to hazards of catastrophic proportions, regardless of their probability of occurrence [6]. Each form of energy producing technology presents such hazards (e.g., in the use of coal or oil, climate modification from released $CO_2$ or extreme ecological modification from acid runoff and rain; for hydroelectric power generation, the rupture of a sizable dam near a large population center; in the use of natural gas, the release of LNG near a population center; and in the case of nuclear power, the release of substantial amounts of radioactive materials resulting in potentially large immediate, as well as delayed, health effects).

These risks, however, must be brought into the overall risk assessment framework (quantified to the extent possible), perhaps employing singular risk aversion factors.

Because of the diverse aspects of risk, expected (or average) values are often employed and they require careful interpretation. While the use of expected values may be informative in specific studies, any temporal or demographic variance, for example, will be obscured. However, the desire for simplicity in the use of a single number, whether standing alone or in a comparative analysis, may well be abandoned in favor of a more complete basis such as frequency-consequence plots for a spectrum of consequences.

### 2.4 Uncertainties in Current Risk Assessments of Available Fuel Cycles.

The specific uncertainties and omissions in currently reported risk assessments of available methods of generating electricity are listed below. These include fossil fuel, hydroelectric and nuclear generated power. No attempt is made to improve the quantification, and no claim is made as to the completeness of the present discussion. The objective here is to demonstrate that all presently available energy generation technologies pose some risk components that are unquantified or are subject to technical controversy.

#### 2.4.1 Coal

Because of the great potential increase in its use, the health and environmental effects of coal utilization have been receiving increased attention [7,8]. In addition, the recent report from the Office of Technology Assessment [9] stated that if additional evidence confirms the present concerns, existing coal consuming facilities will be prime targets for emission regulations. Difficulties in assessing the risk from the use of coal include quantifying:

a) the chronic health effects (dose/response relationships) of the oxides of carbon, sulfur and nitrogen, radon gas, and particulates released at the power plant. The particulate fraction includes trace elements (e.g., vanadium, cadimum, uranium, thorium) as well as organic material.

b) the long-term effects of carcinogens, mutagens and toxic substances emitted in large quantities, including those imposed by long-range transport of sulfates and trace metals.

c) the long-term societal risks of atmospheric buildup of $CO_2$ and the risks to human health from acid rain.

d) the risks of contamination of groundwater from acid or alkaline mine water. Present neutralization techniques involve pH treatment which results in increased water hardness, perhaps introducing other risks.

e) the effect of dust, polycyclic organic material, $CO_2$, and sulfur compounds on coal mine workers. Actuarial data are available; however, the combined effect of new regulatory standards and an increased workforce will be difficult to assess due in part to the long characteristic time constant of the health effects.

f) the risks of groundwater contamination and other chemical releases from coal combustion waste (i.e., coal ash). This waste may represent one-half of the nation's noncombustible solid waste and industrial sludge (by weight) by 1985. The waste is chemically active and also contains radioactive trace elements whose daughters are gases (e.g., isotopes of radon).

g) the risks from mine waste impoundment practices. (In 1972 the failure of a mine waste dam killed 125 people.)

h) the health effects due to releases of chemical effluents from mine waste piles.

i) the multifacted effects from the competition of the entire operation of the coal cycle with local resources. For example, current reclamation efforts are sometimes less than successful due to the long time constant for ecological recovery and adverse rapid processes such as erosion. Health effects of such diversions of resources are difficult to quantify.

j) the marginal risks of a coal unit in a particular geographic location.

Note that of these concerns only the health effects related to (a) and (e) are addressed in the analyses reviewed in Section 3, and even then they are only partially considered.

### 2.4.2 Oil

In order to compare the risks of the oil fuel cycle with those of other energy options, the potential risks from the following activities must be determined: drilling, transportation, refining, utilization and waste disposal. Because the use of oil, in proportion to coal and nuclear, will steadily decline in the future, and because of the competition for its utilization as a transportation fuel, the risks attributable to its use as a power-plant fuel have received less attention.

Those aspects of the oil fuel cycle leading to uncertainy in risk include:

a) the health effects of the effluents (e.g., oxides of sulfur, carbon and nitrogen) released during normal operation of an electricity generating unit. The risks also include those discussed in the previous section concerning $CO_2$ buildup, acid rain and long-term effects.

b) the health and environmental risk associated with oil spills. Quantification of this effect requires an adequate model of man's food chain as well as other information.

c) the risks associated with the storage of oil near population centers. A major fire accompanied by unfavorable meteorological conditions could lead to catastrophic impacts.

d) the risks associated with extraction (e.g., health effects of water pollution from seepage and spills, and land subsidence). The latter is particularly important in regions of high seismicity, because it is thought that extraction of oil may increase the frequency of earthquakes.

e) the risks associated with oil tanker fires due to collisions in harbors and in coastal shipping lanes.

f) the sociopolitical risks, including war, associated with increasing demand for oil and its limited supply.

Only the health effects associated with the first concern above are addressed in the analyses reviewed in Section 3.

### 2.4.3 Hydroelectric

The utilization of dams for the generation of hydroelectric power involves risks which are characterized by a spectrum of consequences and frequencies. Difficulties in assessing the risks of hydroelectric power generation include:

a) the interpretation and use of actuarial data on dam failure. While historical evidence yields an average failure probability of $2\text{-}7\times10^{-4}$*/ per dam-year, additional assessments of individual dam designs are necessary to determine variance of this average [10,11].

b) the lack of information concerning the consequence of particular dam failures. It has been estimated that the failure of particular dams may have consequences of up to 250,000 deaths [12].

c) analyzing the synergistic effects of other dams or other technologies.

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*/ Based on the period 1940-1972 the actual rate was 7 failures per 10,000 dams per year of height over 45 feet excluding waste impoundment dams; however, the definition of failure is subjective and varies from investigator-to-investigator.

d) analyzing the risks on human health posed by the environmental impact of the dam.

e) analyzing those risks associated with maintenance or utilization of the secondary benefits (e.g., recreational) of the dam.

### 2.4.4 Nuclear

The risks associated with commercial nuclear power have been the subject of extensive analyses. Such studies have identified specific problem areas; however, difficulties remain in fully quantifying the risks from the entire fuel cycle. These difficulties include:

a) the controversy over the biological impact of low level ionizing radiation which includes acute, long-term and genetic effects. Assessments to date have generally relied upon a linear - no threshold biological response to radiation; this model is generally accepted as being conservative for the present generation, has not been replaced by a best estimate model, and does not include genetic effects.

b) the consideration of both occupational (e.g., mining operations) and societal risk from low level radiation. This latter category is complicated by the necessity of modeling radioactive effluent transport, population distribution, plant and animal intake and buildup, and biological response to various chemical species and physical forms.

c) characterizing the contribution of high-consequence low frequency events and verifying the frequency of both high and low probability events.

d) identification of all important accident sequences. A related difficulty involves the identification of common mode and system interaction phenomena, operator error and intervention, and characterization of degraded reactor behavior.

e) assessment of the risks of long term waste disposal. Presently, for example, a narrow consequence model is typically assumed. A related uncertainty involves assessing the risks associated with all possible reprocessing decisions.

f) inability of quantifying the risk of hazardous material being diverted for alternative purposes.

The concerns (a) through (e) are treated to varying degrees of completeness in the analyses reviewed in Section 3; (f) is not addressed.

## 3. SURVEY OF SOME RECENT RISK COMPARISONS

### 3.1 Introduction

Regardless of the difficulties discussed in the previous section, there have been recent attempts to quantify and compare selected risks of various fuel cycles by different investigators. In this section an attempt is made to review several studies which compare selected risks for different energy systems. Before making any judgments on relative risk, it is important to note the following:

a) Each set of risk comparisons does not necessarily represent the risk of the total fuel cycles, but considers only <u>selected</u> contributions to risk. In some instances omissions are significant risk contributions, in others they may not be.

b) Although there may be some degree of self-consistency for each study (base-line data, etc.), there is a lack of consistency from author to author. It is assumed, for example, that for the degree of accuracy desired in this report, a simple scaling correction is appropriate to correct for differing assumed plant capacity factors.

c) Some contributions to risk are determined from actuarial statistics (e.g., mine accidents), while some are based on calculational models (e.g., catastropic nuclear accidents). Hence, there are different degrees of uncertainty associated with the component risks.

The studies reviewed are discussed below and are summarized in Table 3.1.

3.2 Comar and Sagan (1976)

In 1976, Comar and Sagan [13] presented the results of a study on the health effects of energy production and conversion for 1,000 MWe oil, coal, and nuclear power plants operating for one year (the assumed capacity factor is not given). The health effects considered are given as: premature occupational deaths, premature general public deaths and occupational injuries in terms of accident and disease. The various facets of the fuel cycle considered are extraction, transport, processing and conversion.

Long term effects such as atmospheric buildup of $CO_2$ and high level radioactive waste disposal are not included. For the most part, the results presented were obtained from the available literature and were not determined explicitly for the study.

There are several other points worth noting:

a) genetic effects due to fossil fuel combustion were not included.

b) the fossil fuel data did not discriminate between premature deaths occurring early in life and those due to persons with chronic disease, already at high risk.

c) the data used for fossil fuel were based on epidemiological studies.

d) low-level effects of radiation were based on the BEIR report of 1972 [14].

e) catastropic risks of the nuclear plant were based on the Rasmussen Study (WASH-1400, [5]), as it appeared in draft form.

3.3 Gotchy (1977)

In 1977, Gotchy [15] examined the health effects attributable to coal and nuclear fuel cycle alternatives. Estimates of mortality and morbidity were presented based on "present day" (1977) knowledge of health effects. Emission rates used were based upon fuel cycle facilities expected to go into operation during the period 1975-1985. The results are given as excess deaths per 0.8 gigawatt-year electric (GWye) (i.e., 1,000 MWe power plant operating at 80% of capacity for one year).*/

*/ During a recent (February 1980) Subcommittee meeting of the ACRS, Gotchy indicated that current refinements to the 1977 study do not change the assessed risks appreciably.

For nuclear energy, the health effects due to normal operation were taken from the "Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed-Oxide Fuel in Light Water Reactors" (GESMO) [16] and Table 5-3 of 10 CFR 51 (updated to include the long-term impact of radon-222). The health effects due to accidental releases were obtained from WASH-1400 [5].

Dose-response relationships for fossil fuel combustion were obtained from the epidemiolgical studies of Lave and Seskin [17] and Winkelstein, et al [18]. Other assumptions included:

a) the use of actual population distributions within 80 km of several nuclear plant sites (also used for the coal plants),

b) actual meteorological data,

c) use of 3% sulfur coal, 12% ash for upper bound and 0.4% sulfur coal with 3% ash for lower bound,

d) 99% particulate removal from emissions,

e) 75% plant capacity factor,

f) 10% per hour oxidation rate for conversion of sulfur oxides to sulfates.

3.4 Hamilton and Manne (1978)

In 1978, Hamilton and Manne [19] attempted to estimate the excess morbidity and mortality for various technological and population alternatives due to air pollution from a 1000 MWe fossil fuel power plant within 80 km of the plant. Using these results, they also estimated the excess mortality and morbidity to calculate the health effects associated with the total production of electric power in the USA in 1975.

The results were obtained using the Biomedical and Environmental Assessment Division (BEAD) models developed at Brookhaven National Laboratory. Dose-response functions for fossil fuel were based on the Lave and Winkelstein data and on a linear extrapolation for the radiation dose-response function.

3.5 Hamilton (1979)

In a series of papers, Hamilton [4,20] has reviewed the Brookhaven work using BEAD models for various contributions to risk from coal and nuclear power plants. This work differs from the Hamilton and Manne paper discussed above in that it considers the use of low rather than high sulfur coal in future electricity generation. Furthermore, this work includes other aspects of the coal and nuclear fuel cycles such as processing, waste management, etc.

In examining Hamilton's work, it should be noted that the results for coal neglect the potential risks due to solid wastes (both the carcinogenic components and the radioactive dose due to radon gas and radium). The results for nuclear utilize the WASH-1400 risk estimates for catastrophic accidents.

3.6 CONAES (1979)

One of the more comprehensive attempts to compare the risks of various energy options is the recent study by the Committee on Nuclear and Alternative Energy Sources (CONAES) of the National Research Council [21]. Although the final report is published, the supporting documents concerning risk are still in preliminary form. A detailed description of the models and data used will be described in the final CONAES supporting documents.

3.7 Results

The results of the five studies reviewed above are presented in Table 3.1. All entries in the Table have been linearily scaled to reflect the production of $10^{10}$ Kwh of electric power. (This scaling was considered appropriate for the degree of accuracy desired here). Table 3.2 indicates the range of assessed values for the five studies. The large variance in the nonfatal effects is due in part to interpretation. The studies summarized in Tables 3.1 and 3.2 indicate that the assessed risks of nuclear power are less than or equal to the assessed risks of coal or oil. The omissions in Table 3.1 indicate that those particular facets of risk were not addressed or not differentiated to reflect occupational versus general public effects.

The studies reviewed did not consider to the same degree the risks associated with hydroelectric or natural gas plants. Hamilton and Manne [19] estimated 0.2 deaths and 20 disabilities per $10^{10}$ Kwh of natural gas generated electricity. For an equivalent amount of natural gas generated electricity, the review of the literature by Comar and Sagan [13] estimated occupational fatalities to be 0.065-0.32 and occupational injuries to be 4.5-27. However, its transport as liquified natural gas (LNG) gives it the potential for a series of high consequence events which may not be of low frequency when compared to nuclear fuel cycle risks. This risk has not been included in the assessments.

The environmental risks of a hydroelectric power plant do not lend themselves to quantitative analysis and are difficult to compare to fossil-fuel and nuclear cycle risks. This energy source also has a significant contribution to public risk because of potential high consequences (up to ten or hundreds of thousands of deaths) accompanied by relatively moderate frequency ($10^{-4}$ per dam-year on the average) events.

## TABLE 3.1

HEALTH EFFECTS OF THE USE OF COAL, OIL AND NUCLEAR POWER (normalized to $10^{10}$ Kwh)

fuel
oil

| Consequence | COMAR and SAGAN (1) | GOTCHY (2) | HAMILTON and MANNE (3) | HAMILTON (4) | CONAES (5) |
|---|---|---|---|---|---|
| occupational deaths | 0.16-1.5 | -- | -- | - | -- |
| general public deaths | 1.14-114 | -- | -- | -- | -- |
| total deaths | 1.3-116 | -- | 3-150 | -- | -- |
| occupational disease/accidents | 14.77 | -- | -- | -- | -- |
| general public disease/accidents | -- | -- | -- | -- | -- |
| total disease/accidents | 14.77 | -- | 150-300 | -- | -- |

TABLE 3.1 (con't)

HEALTH EFFECTS OF THE USE OF COAL, OIL AND NUCLEAR POWER (normalized to $10^{10}$ Kwh)

fuel

coal

| Consequence | COMAR and SAGAN (1) | GOTCHY (2) | HAMILTON and MANNE (3) | HAMILTON (4) | CONAES (5) |
|---|---|---|---|---|---|
| occupational deaths | 0.62-5.7 | 0.50 - 10.9 | -- | -- | 4-6 |
| general public deaths | 1.8-127 | 20.3-158 | -- | -- | 3-304 |
| total deaths | 2.4-133 | 21-169 | 10-200 | 13.5-16 | 7-310 |
| occupational disease/accidents | 30-143 | -- | -- | -- | -- |
| general public disease/accidents | -- | -- | -- | -- | -- |
| total disease/accidents | 30-143 | -- | 300-500 | 88 | 61-152 |

TABLE 3.1 (con't)

HEALTH EFFECTS OF THE USE OF COAL, OIL AND NUCLEAR POWER (normalized to $10^{10}$ Kwh)

fuel

nuclear

| Consequence | COMAR and SAGAN (1) | GOTCHY (2) | HAMILTON and MANNE (3) | HAMILTON (4) | CONAES (5) |
|---|---|---|---|---|---|
| occupational deaths | 0.11-0.98 | 0.51 | -- | -- | 0.3-0.5 |
| general public deaths | 0.01-0.18 | 0.33-1.98 | -- | -- | 1.5 |
| total deaths | 0.13-1.16 | 0.84-2.49 | 1-3 | 1.35 | 1.8-2.0 |
| occupational disease/accidents | 4.6-15 | -- | -- | -- | -- |
| general public disease/accidents | -- | -- | -- | -- | -- |
| total disease/accidents | 4.6-15 | -- | 8-30 | 26.2-30.9 | 15.2-22.8 |

Footnotes:

(1) reflects review of literature (1975 technology)

(2) expected effects of facilities to go into operation during 1975-1985

(3) estimated health effects for electricity production in the U.S. (1975 technology)

(4) update of Hamilton and Manne to reflect use of low sulfur coal

(5) expected effects during 1985-2010

TABLE 3.2

RANGE OF ASSESSED HEALTH EFFECTS
(normalized to $10^{10}$ Kwh)

| | OIL | COAL | NUCLEAR | NATURAL GAS |
|---|---|---|---|---|
| deaths | 1.3-150 | 2.4-310 | 0.13-3 | 0.065-0.32 |
| disease/accidents | 14.77-300 | 30-500 | 4.6-30.9 | 4.5-27 |

# 4. SUMMARY AND CONCLUSIONS

## 4.1 Summary

In this report, an effort has been made to discuss some of the difficulties associated with performing risk analyses and to present in a unified manner results from a selected group of recent risk assessments. The former aspect is discussed in Section 2 proceeding from a presentation of the concerns associated with assessing comparative risks in general, to a sketch of specific areas of uncertainties surrounding the health effects of current technologies capable of providing significant amounts of electricity.

Five recent studies, which primarily compared the health effects of the use of coal and nuclear energy, are summarized in Section 3. In light of the aforementioned difficulties in assessing the risks of any fuel cycle, these studies are recognized as estimating only portions of the total risks. Nevertheless, the estimated health effects were normalized in an approximate manner and tabulated as broad appraisals with minimum critique of the individual assessment methodologies. From the combination of these effects, the assessed risks of the nuclear power cycle, when discussed in terms of expected values, are comparable to or less than its alternatives.

## 4.2 Discussion

In order to assess and compare the health and environmental risks of the available methods for generating electricity, the uncertainties (such as those discussed in Section 2) should be evaluated. Although the results of incorporating these uncertainties into the assessments and comparisons contained in Section 3 would at best be qualitative, they can be considered in a relative sense.

Uncertainties in actuarial as well as health effects data (or models) may increase or decrease assessed risks; uncertainties due to a lack of the ability to quantify effects which lead to the omission of risk components can only increase assessed risks. Furthermore, risk assessments may be more sensitive to unquantifiable effects than to uncertainties in data. Before any conclusions can be stated, some of the more important uncertainties should be discussed.

With respect to fossil fuel combustion, the damage function (dose/response relation) of air transported sulfates is not well known. Morgan, et. al. [22] estimated a mean function value of 3.7 deaths per $10^5$ people/mg of sulfate/ $m^3$ of air which had a low confidence level (95% confidence interval 0-11.5). Atmospheric $CO_2$ buildup and acid rain are real phenomena which have potentially catastrophic consequences; but, the corresponding links between assaults on the ecosphere and human health are poorly understood and unquantified at present. Groundwater contamination from mine water runoff or from coal combustion waste is a serious hazard and also is not quantified. These two unquantified risks may have a more profound effect on fossil fuel assessed risks than the uncertainty in the damage function described above.

With respect to nuclear energy, there are several important uncertainties to consider. Despite the well known controversy, the hazard function of low level radiation is better known than that of airborne sulfates. The identification of all important accident sequences, and the characterization and verification of the contribution to risk of specific sequences, is a common concern to all risk analyses. The 1977 Ford/MITRE study [23] concluded that the frequency of core melt with breach of containment as predicted in WASH-1400 may be low by as much as a factor of 500; however, that report goes on to say:

> It is significant that even under such extremely pessimistic assumptions, the fatalities [expected value] are less than the high end of the range of estimated deaths associated with [the normal operation of] coal-fired power plants.

More recently, the 1979 Resources for the Future Report [6] stated:

> If all the electricity generated in 1975 had come from coal, the total number of associated fatalities (including coal miners and members of the general public) would have ranged between about 200 and 4,000. . . . If, however, the electricity had been generated from nuclear sources, total fatalities which might have resulted have been calculated at between 60 and 900 (... this includes an evaluation of accident probabilities which is 100 times higher than the controversial Rasmussen Report - partly because of subsequent criticisms of the margin of error assumed originally in that report and partly because of the accident in early 1979 at the Three Mile Island nuclear plant, which involved at least some problems that had not been anticipated). Even without continued improvements in nuclear technology and operating practices, which might be expected in the wake of the Three Mile Island accident, the range of estimates for health threats is substantially lower for nuclear than it is for coal - although the two overlap.

It is also important to discuss the relative uncertainty between fuel cycles. A recent report by the Environmental Protection Agency [24,25] using an upper bound technique, identified the routine operation of coal-fired power plants in urban areas as a potentially significant source of added radiological risk to society, possibly greater than existing nuclear plants. Note that for the nuclear fuel cycle the largest occupational radiological risk exists for uranium mining and milling.

The risks due to the long term storage of nuclear waste have not been adequately quantified; however, this same statement can be applied to the wastes from the coal cycle. A major risk which has not been quantified for coal is the potential contamination of groundwater due to the large projected volume involved, its chemical properties and the lack of an acceptable disposal plan. A second risk contributor for coal ash is the release of radioactive materials. Pigford [26] compared the potential hazard from radioactive trace elements in stored coal ash with the ingestion toxicity of nuclear power waste; he estimated that for a given amount of delivered electricity, the radiotoxicity of the high-level reprocessing waste from a PWR becomes less than the radiotoxicity of coal ash initially containing 24 ppm uranium after 500 years, and less than that of coal ash initially containing 1 ppm uranium after 30,000 years. Unreprocessed spent nuclear fuel retains a toxicity higher than that of ash from the former class of coal until 100,000 years have passed.

A recent concern is the risk of nuclear weapons proliferation and the effect on world peace and stability. Although the benefit of a secure energy supply may offset this risk to some degree, both effects are unquantifiable at this time. The dominant factors determining these risks are sociopolitical in nature, so that any attempt to compare them with direct public health and environmental risks at this point is beyond speculation. A similar statement can be made concerning the risks involved with the growing competition for a diminishing supply of oil on a global scale. As world demand and dependence on any resource that is unequally distributed geographically grows, be it coal, oil or uranium, such risks will necessarily develop. Therefore, the conclusion drawn in this report will necessarily reflect only direct health and environmental risks.

The risks arising from the use of hydroelectric power and the burning of oil have received a lesser amount of attention. Only site specific studies will reduce the uncertainties in assessing the risks of dam failure. These risks appear at present to have catastrophic potential but are unquantified.

The oil fuel cycle shares many common hazards with the coal cycle. The inclusion of potential catastrophic events can only increase the assessed risks.

4.3 Conclusion

It appears that the actual risks of the nuclear fuel cycle are less than or equal to those of its major alternatives: coal and oil. This conclusion is based upon the following considerations:

a) the assessed risks (expected values) of the nuclear fuel cycle are less than or equal to those of coal and oil,

b) the effect of uncertainties (with respect to both data and unquantified risk components) on these assessed values appears to be smaller for the nuclear fuel cycle, and

c) the analysis, while far from complete, of the risks of the nuclear fuel cycle relative to analyses of alternative cycles are more comprehensive.

Uncertainties appear to be largest for hydroelectric energy production, which exhibits both large scale ecological impact and the potential for high consequence - moderate frequency events at specific sites.

The conclusion stated above excludes sociopolitical derived risks, such as nuclear proliferation or war over liquid fuel supplies, which are at present unquantifiable and at best speculative.

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