NRC TASK FORCE REPORT ON REVIEW OF THE FEDERAL/STATE PROGRAM FOR REGULATION OF COMMERCIAL LOW-LEVEL RADIOACTIVE WASTE BURIAL GROUNDS

Manuscript Completed: January 1977
Date Published: March 1977

Office of Nuclear Material Safety and Safeguards
and
Office of State Programs
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

EXECUTIVE SUMMARY

This is the report of the Nuclear Regulatory Commission (NRC) Task Force which examined the programs of the NRC and Agreement State governments to regulate the disposal of commercial low-level radioactive waste. This report is part of the overall NRC examination of waste management and is responsive to issues raised by the General Accounting Office (GAO), the Joint Committee on Atomic Energy (JCAE) and the House Committee on Government Operations.

The underlying issue explored in this report is that of Federal vs State regulation of commercial radioactive waste burial grounds. The need for research and development, a comprehensive set of standards and criteria, a national plan for low-level waste management, and perpetual care funding are closely related to the central issue and also discussed.

Five of the six commercial burial grounds are regulated by Agreement States; the sixth is regulated solely by the NRC (NRC also regulates Special Nuclear Material at the sites). The sites are operated commercially. The operators contribute to the perpetual care funds for the sites at varying rates. The States have commitments for the perpetual care of the decommissioned sites except for one site, located on Federally owned land.

The States, through their regulatory programs have adequately protected the public health and safety. However, waste disposal is a national problem, and the States have neither the resources nor responsibility to develop and implement a national low-level waste disposal program. The citizens of individual States should not bear the cost of major contingency actions or inadequacies in perpetual care funding for burial sites which serve national rather than State needs.

Federal control over the disposal of low-level waste should be increased by requiring joint Federal/State site approval, NRC licensing, Federal ownership of the land, and a Federally administered perpetual care program.

Standards, criteria, and regulations for site selection, operation, monitoring, decommissioning, post-operational maintenance and funding requirements need to be either developed or, if existing, need to be improved.

The NRC should accelerate the development of its regulatory program for the disposal of low-level waste.

Alternatives to shallow land burial of low level wastes need to be evaluated. Criteria to distinguish between waste to be disposed of by shallow land burial (or alternative commercial methods) or sent to a Federal repository need to be developed. There is not now a planning base for insuring adequate disposal capacity without undisciplined site proliferation. However, it is projected that there is adequate capacity in current sites to the year 1990. There is sufficient time to develop a national low-level waste management plan, a regulatory program, and evaluate alternative methods of disposal before additional disposal sites need to be developed.

The undisciplined proliferation of low-level burial sites must be avoided. NRC should evaluate alternative disposal methods, conduct necessary studies, and develop a comprehensive low-level waste regulatory program (i.e., accomplish the above recommendations) prior to the licensing of new disposal sites.

APPENDIX B

HISTORY OF LOW-LEVEL WASTE MANAGEMENT

Starting with the Manhattan Engineering District Program, the AEC generally used three methods for disposal of radioactive waste: dilution and dispersion, shallow land burial, and sea disposal. Disposal of commercial waste generally conformed to practices utilized by the AEC's national laboratories. Sea disposal was phased out over the past decade. Dilution and dispersion through release of effluents are still permitted under existing regulations but with increasing emphasis on maintaining such releases to the environment as low as reasonably achievable, most wastes are presently disposed of by shallow land burial. The following chronology traces some of the important events in the evolution of the current commercial waste management practices.

Chronology of Commercial Waste Disposal Practices

1940's & 1950's	-	Low-level waste disposal by dilution and dispersion, shallow land burial at AEC facilities, or at sea.
January 1960	-	Commission announces that regional land burial sites for commercial low-level waste shall be established on Federal or State owned land and operated by private contractors.
May 1960	-	AEC announces that AEC land burial sites in Idaho Falls, Idaho and Oak Ridge, Tennessee will accept commercial wastes as an interim measure pending designation of commercial waste sites.
June 1960	-	Commission initiates phase out of sea disposal, by placing a moratorium on issuing new sea disposal licenses. Existing licenses for sea burial were allowed to remain in effect.
February 1961	-	AEC establishes regulations to permit commercial operation of low-level burial grounds on Federal or State owned land. Regulations mainly procedural with little technical criteria for site selection, etc.

February 1962	-	AEC initiates Agreement State program which permits Agreement State regulation of commercial burial grounds.
September 1962	-	Commission licenses first commercial land burial site located at Beatty, Nevada.
1962 - 1971	-	Five additional commercial burial sites were licensed by the AEC and Agreement States.
May 1963	-	AEC withdraws interim commercial disposal at AEC sites.
June 1970	-	Last disposal at sea.
September 1974	-	AEC proposes restrictions on burial of transuranic contaminated waste.*

Table B-1 summarizes the present licensing and operational status of the six existing commercial waste burial grounds. Until the early 1970's, no problems were identified in the regulation and operation of the commercial burial grounds. Problems subsequently arose at four sites: Maxey Flats, Kentucky, West Valley, New York, Beatty, Nevada and Sheffield, Illinois. A discussion of those problems and additional background information about the current status of the sites is contained in Appendix C. None of the problems has created a significant public health and safety problem, but they do illustrate the difficulties facing the regulatory agencies. They have resulted in irregularities in operation of certain sites and have highlighted the lack of adequate regional distribution of capacity for disposal of low-level waste.

*In 1970, the AEC implemented policies limiting the burial of long-lived transuranic radionuclides (Transuranic elements are elements having atomic numbers greater than 92 including plutonium) at AEC operated sites. Such waste containing greater than 10 nanocuries per gram were sent to retrievable storage facilities. The AEC issued a proposed rule on September 12, 1974 which would have limited burial of transuranic wastes at commercial sites also. Following creation of the NRC and ERDA, ERDA withdrew the draft environmental statement needed to fulfill NEPA requirements for the rule. Although the rule has not been implemented, all the commercial burial sites except the Hanford site presently limit the burial of transuranium nuclides as noted in Table B-1.

TABLE B-1

Commercial Waste Burial Grounds

Location	Operator	Originally Licensed by (year)	Currently Licensed by	TRU Accepted	Operational Status
Beatty, Nevada	Nuclear Engineering Co., Inc. (NECO)	AEC (1962)	State & NRC*	<10 nanocuries/ gram	SNM license suspended
Maxey Flats, Kentucky	NECO	Kentucky (1962)	State	<10 nanocuries/ gram	Open
West Valley, New York	Nuclear Fuel Services	New York (1963)	State	0.1 gram Pu/ft^3 other elements, yes	Closed
Hanford, Washington	NECO	AEC (1965)	State & NRC*	Yes	Open
Sheffield, Illinois	NECO	AEC (1967)	NRC	<10 nanocuries/ gram	Open
Barnwell, S. Carolina	Chem-Nuclear Systems, Inc.	South Carolina (1971)	State & NRC*	<10 nanocuries/ gram	Open

*NRC licenses only Special Nuclear Material.

Presently, the West Valley site is temporarily closed due to water management considerations. It was voluntarily closed by the site operator in March 1975, after the release from the north end of the burial ground of low levels of radioactivity to a local stream. The Maxey Flats site is virtually unused, currently, due to economic considerations. A 10 cents per pound excise tax was placed on waste received for burial by the Kentucky Legislature. This tax makes the cubic foot charge at the site about three times the charge at other sites. The present Sheffield site is almost full unless new technology can be applied. Continued use of the remaining portion of the 20 acres depends on technical demonstration of a compact and fill method of trench construction. Expansion of the site boundaries depends on the outcome of local rezoning hearings as well as NRC safety and environmental analyses.

With regard to program management, it is clear that today's waste disposal system did not evolve out of any grand scheme to meet national needs. In 1960 the AEC published an announcement that it "has determined that regional disposal sites for permanent disposal of low-level packaged radioactive waste materials shall be established, as needed, on State or Federal Government-owned land." The only positive action directed toward implementation of this policy was issuance of a regulation requiring that disposal take place on Federal or State land. It exercised no positive control over the "establishment as needed" portion of the statement. It is interesting to note that AEC staff studies in the early 1960's indicated that the first regional need for a site would be in the Northeast. However, sites in Nevada and Kentucky were licensed before the one in New York.

Appendix C

BACKGROUND INFORMATION, NRC AND AGREEMENT STATE INSPECTION PROGRAMS, AND REVIEW OF PROBLEMS AT THREE COMMERCIAL BURIAL GROUNDS

Background Information

Six commercial shallow land burial grounds have been licensed for the disposal of low level radioactive wastes. The locations, operators, licensing considerations, and operational status are summarized in Table B-1, Appendix B.

Five of the six commercial burial grounds are located in and regulated by Agreement States (Beatty, Nevada; Hanford, Washington; Barnwell, South Carolina; Maxey Flats, Kentucky; West Valley, New York). At three of the sites, the NRC licenses special nuclear material because of quantities authorized for possession by the commercial operator. The site located in the non-Agreement State (Sheffield, Illinois) is regulated by the NRC, although the State licenses and controls activities concerning naturally occurring and accelerator-produced radioisotopes that are not subject to NRC control. The sites are all commercially operated. The Nuclear Engineering Company, Inc., operates four of the sites (Hanford, Beatty, Sheffield, and Maxey Flats), Nuclear Fuel Services, Inc., operates the West Valley site and Chem Nuclear Systems, Inc., operates the Barnwell site. All of the burial grounds are on State-owned land except the Hanford site which is on Federal land leased to the State of Washington. The States have assumed responsibility for assuring long-term care and maintenance of all sites although responsibility for the Hanford site will eventually revert to the Federal government.

The principal operations at a commercial land burial ground are the receipt, temporary storage, and burial in trenches of packaged radioactive wastes. The packages are normally buried as received, with no processing or repackaging of package contents. However, in some cases, the primary package containing the waste is shipped in a reusable overpack or secondary container which may be required by Department of Transportation regulations for shipment of the particular materials involved.

An average burial trench at a commercial burial site is about 300 feet long, 40 feet wide, and 25 feet deep and has a volume of about 340,000

cubic feet. The volume is not completely utilized since there are voids between packages, and between packages and the earth-fill. (It is estimated that about 50% of the volume is utilized.)

Currently, about 2.5 million cubic feet of wastes are buried each year. The approximate cumulative totals of wastes buried through the end of 1975 are shown in Table C-1.

Table C-1

CUMULATIVE TOTAL VOLUME AND QUANTITIES OF COMMERCIAL WASTE BURIED THROUGH 1975

Volume (ft^3)	13,100,000
Byproduct Material (curies)	3,300,000
Source Material (kg)	680,000
Special Nuclear Material (kg)	1,056
Plutonium (kg)	113

NRC and Agreement State Inspection Program

NRC and Agreement State licensing and inspection programs address site operation and performance in both routine and special cases. NRC and State staffs conduct routine inspections and independent confirmatory measurement programs to assure that operations are being conducted safely and in accordance with licenses and applicable regulations. After learning of the Maxey Flats problem, NRC staff collected and evaluated environmental samples at the remaining sites during November and December 1974. Additional samples were taken at each of the sites during February 1976. The results of the NRC independent samples agreed with licensee and State analytical results and showed no evidence of significant transport of radioactivity through migration. NRC staff also found that the licensees and States had initiated environmental monitoring programs which considered the major pathways of exposure to the public. In addition, as a precautionary measure following discovery of pilfering at the Nevada site, special inspections and surveys at other sites were conducted to rule out similar occurrences.

Agreement State regulatory programs for burial sites receive annual attention from NRC staff during evaluation of the programs' compatibility with the Commission's regulations and provisions for the protection of public health and safety. Review meetings involve detailed discussions

of each State's regulatory program and procedures. Waste burial ground license and inspection files are reviewed approximately every two years, or more frequently if unusual problems are being experienced in operation of a site. Routine site visits are conducted about every three years; more frequently if problems are experienced. During each review, the environmental surveillance program conducted at the site by the State and the operator, any ongoing special site studies, changes in perpetual care funding, major changes in the license, operational problems, and contingency actions are discussed. During the site visits, the general site operations, the burial procedures being used, and the onsite and offsite environmental surveillance activities are reviewed. During 1976, NRC visited all sites, except the Kentucky site. The Maxey Flats site was visited as part of a special NRC independent study in 1975.

Review of Occurrences at Kentucky, New York, and Nevada

Kentucky - In the early 1970's, Kentucky became concerned about the accumulation of water in completed trenches at the Maxey Flats Burial Ground and the increase in the volume and quantity of waste being received at the site for burial. Kentucky required the Maxey Flats site operator (the Nuclear Engineering Company, Inc.-NECO) to institute a water management program at the site which included pumping water from trenches to above-ground storage tanks and installing an evaporator to concentrate the pumped liquids for disposal as solids.

In October 1974, Kentucky informed the NRC of the results of their special six month environmental study at Maxey Flats. The study, published in December 1974, concluded that the burial ground was contributing radioactivity to the local environment, but at levels which did not present a public health hazard. They identified tritium, cobalt-60, strontium-89 and 90, cesium-134 and 137 and plutonium-238 and 239 in individual samples in the unrestricted environment. The levels ranged from slightly above background to orders of magnitude above background for certain individual samples. Kentucky recommended further studies at the site to assess the long range health and safety significance of their findings.

Kentucky expanded their Radioactive Waste Disposal Environmental Study Design Committee to include members from other Kentucky and Federal agencies and held a meeting in February 1975. The NRC participated. The Committee recommended a six point program for further studies at the Maxey Flats site. The studies included a deep geology study, a weathered

zone study, and an environmental-biological exposure pathway study. The Committee estimated that the cost for completion of all studies would exceed one million dollars.

On April 30, 1975, The Governor of Kentucky, Julian M. Carroll, requested the NRC to independently assess conditions at the Maxey Flats site and to provide him with findings and recommendations. An NRC review group was appointed and reviewed information about the site, conducted a site visit and met with Kentucky and NECO officials. The NRC concluded, on the basis of their study, that there is no significant public health problem associated with the release of radioactive material from the burial ground and that Kentucky has taken appropriate action to implement the recommendations made in their December 1974 report. The NRC also made several recommendations concerning methods to improve the water management program and to minimize the potential for migration of radioactivity. Governor Carroll was informed of the results of the NRC review in July 1975. He subsequently issued a press release indicating the NRC was responsive to his request and directed the Kentucky Department for Human Resources to carry out the NRC's recommendations. Kentucky has taken action to carry out the NRC's recommendations and has continued an extensive environmental monitoring program. Several USGS research studies are currently under way at the site.

An EPA press release in January 1976 focused a great deal of public attention on shallow land burial grounds. The press release concerned an EPA report which presented environmental data developed during Kentucky's six (6) month study, described various potential migration pathways and drew conclusions from EPA's analysis of the Kentucky data. The EPA report was reviewed by the NRC and comments provided to EPA. NRC commented that the report failed to give adequate attention to the public health and safety significance of the data and that the paper was preliminary in nature since it presented several conclusions concerning pathways for migration of plutonium based on data which the author conceded equally supported other possibilities.

The Kentucky Legislature has imposed a 10 cents per pound excise tax on waste received at the site for burial, effective in June 1976. The tax is intended to assure that adequate funds for any contingency are available. Prices at other sites are determined primarily on a cubic foot basis and range from $\$1.25/ft^3$ to $\$3.25/ft^3$ for most categories of waste. The additional tax in Kentucky results in a disposal cost that is 3 or 4 times higher than the charges at other sites.

Nevada - In March 1976, the Nevada State Department of Human Resources initiated an investigation at the Beatty, Nevada burial ground following a report by the Nuclear Engineering Company, Inc., the Beatty burial ground operator. NECO had reported to the State that a cement mixer used at the burial ground to solidify low-level liquid radioactive waste had been used in the town of Beatty to pour concrete slabs at a local saloon and other private properties. During the course of the State's investigation concerning the use of the cement mixer, the State uncovered evidence that other violations of the company's license had occurred over a period of several years involving removal of contaminated tools, equipment, and supplies from the Beatty site by NECO employees. The State reported its evidence to the NRC and the State suspended NECO's license to operate the burial ground on March 8, 1976, and the NRC suspended NECO's license on March 11, 1976.

A Federal/State investigation which was subsequently conducted at Beatty revealed that the contaminated equipment, tools, and material had been removed from the site to the town of Beatty by NECO employees. No evidence was found that any member of the public received a significant radiation exposure and contaminated material that was identified during the survey was turned in by citizens and returned to the NECO site.

Subsequently, on May 25, 1976, the Nevada Department of Health and Welfare lifted the order suspending NECO's State license authorizing operation of the Beatty burial ground. The order Nevada issued suspending NECO's license was based on emergency conditions existing in the vicinity of the burial ground and permitted immediate action to be taken to eliminate any hazard to the public health and safety due to the removal of potentially contaminated items from the burial ground. The order was lifted by the State on the basis that the emergency conditions had abated and that there was no significant hazard to the public health and safety at and in the vicinity of the disposal site. The NRC has not taken action to reinstate its license to NECO to dispose of special nuclear material at the Beatty site and will not act until completion of the Department of Justice investigation.

New York - In March 1975, the NRC was informed of a water seepage problem at the West Valley, New York burial ground. The State had noted increased levels of tritium in water samples taken from onsite monitoring stations. The source was traced to water seeping out of the caps of two trenches. The flow was estimated to be approximately 1 gallon per day. The seepage resulted from the compaction of waste in the trench and the filling up of the trench with water and subsequent seepage through the low end of the trench. The site operator,

Nuclear Fuel Services, Inc., (NFS) diverted seepage to a holding lagoon. No significant increase in radioactivity in the unrestricted environment was detected.

A meeting of Federal, State and NFS representatives was held at the site on March 11, 1975. Based on discussions between NFS and State representatives, NFS dispatched a letter informing their customers that they were suspending operation until the requirements for operation of the site were known and agreed to by the State.

NFS requested and obtained approval from the State to pump liquids from the trenches to a holding lagoon. The liquids are subsequently processed through the reprocessing plants' low level waste treatment system and released. NFS and State representatives held several meetings since March 1975 to reach agreement on the conditions for reopening and operating the site. Several studies being conducted by the State, EPA and USGS are also under way at the site. As of December 1976, no agreement has been reached and the site remains closed.

DECOMMISSIONED NUCLEAR FACILITIES

Decommissioned fuel cycle facilities or power reactors can become a major waste quantity upon retirement.

Three alternatives for decomissioning contaminated facilities have been identified in NRC's regulations:

1. Protective Storage (Mothballing): the facility is prepared to be left in place safely for an extended period, which might range from decades to two or three centuries. Potentially mobile radioactive materials are removed from the site. All operational systems and support utilities are placed in a nonoperation mode. A continuous surveillance program must be established.

2. Entombment: this involves all the decommissioning steps of mothballing, but in addition provides for sealing all contaminated facility components in a high-integrity structure. Such contaminated components might include the pressure vessels and internals of a LWR or the major processing vessels of a reprocessing facility.

3. Dismantling: all radioactive components and materials which exceed the criteria for unrestricted release are removed from the facility site. Once all the radioactivity is gone, all restrictions on the site are removed. Decommissioning may be undertaken immediately after facility retirement, or following a period of protective storage to allow decay of short-lived radionuclides.

All three of the decommissioning alternatives have been employed:

-- four reactors at Hanford and the Fermi reactor in Michigan have been placed in protective storage and remain mothballed.

-- the Hallam (Nebraska) nuclear power facility has been entombed.

-- the Elk River (Minnesota) reactor was dismantled after shutdown in 1968, and the reactor site returned to unrestricted use.

Other facilities have also been subjected to these decomissioning technologies.

However, the most pressing waste management/decommissioning issue before the NRC at this time is the NFS facility at West Valley, N.Y.

The NFS site presents a dual waste management problem in that the site contains 680,000 gallons of high-level radioactive waste in storage, and the General Accounting Office has recommended that a waste management program for this material be developed and that the site itself be decomissioned.

NRC has had underway for some time a technical assessment of the requirements created by the deactivation of the West Valley facility. The Commission has concluded on the basis of currently available information that the wastes can be stored as they are at present until ERDA and its contractors can develop a set of disposal alternatives and their associated costs and risks.

The NRC staff will work closely with ERDA to identify those alternatives which are realistic from a regulatory viewpoint. The review of alternatives can be used as a focusing mechanism for the concerned parties in negotiation of an agreement for disposing of the waste and in determining attendant financial responsibility.

The GAO has assumed that there is no further use for the West Valley site, and it must be fully decommissioned. NRC agrees that this is a viable option, but further information is needed from the co-licensees at the site (NFS and NYSERDA) as a basis for developing regulatory guidelines (NRC has no regulatory guidelines for decomissioning reprocessing facilities).

The NYSERDA has suggested, in the name of the State of New York, that ownership of the site and responsibility for its contents be transferred from NYSERDA to the Federal Government (ERDA). Negotiations on this question are still in process.

Although NRC does not presently have established criteria for decommissioning of reprocessing plants, we have had Battelle Pacific Northwest Laboratories prepare a draft report on such decommissioning, and it has been made available to the public. Insofar as this report is useful for application to the NFS situation, it will be relied upon by the staff. Specific guidelines, tailored to the future use or disposition of the plant, will be developed as appropriate.

Established 1845 SCIENTIFIC AMERICAN June 1977 Volume 236 Number 6

The Disposal of Radioactive Wastes from Fission Reactors

A substantial body of evidence indicates that the high-level radioactive wastes generated by U.S. nuclear power plants can be stored satisfactorily in deep geological formations

by Bernard L. Cohen

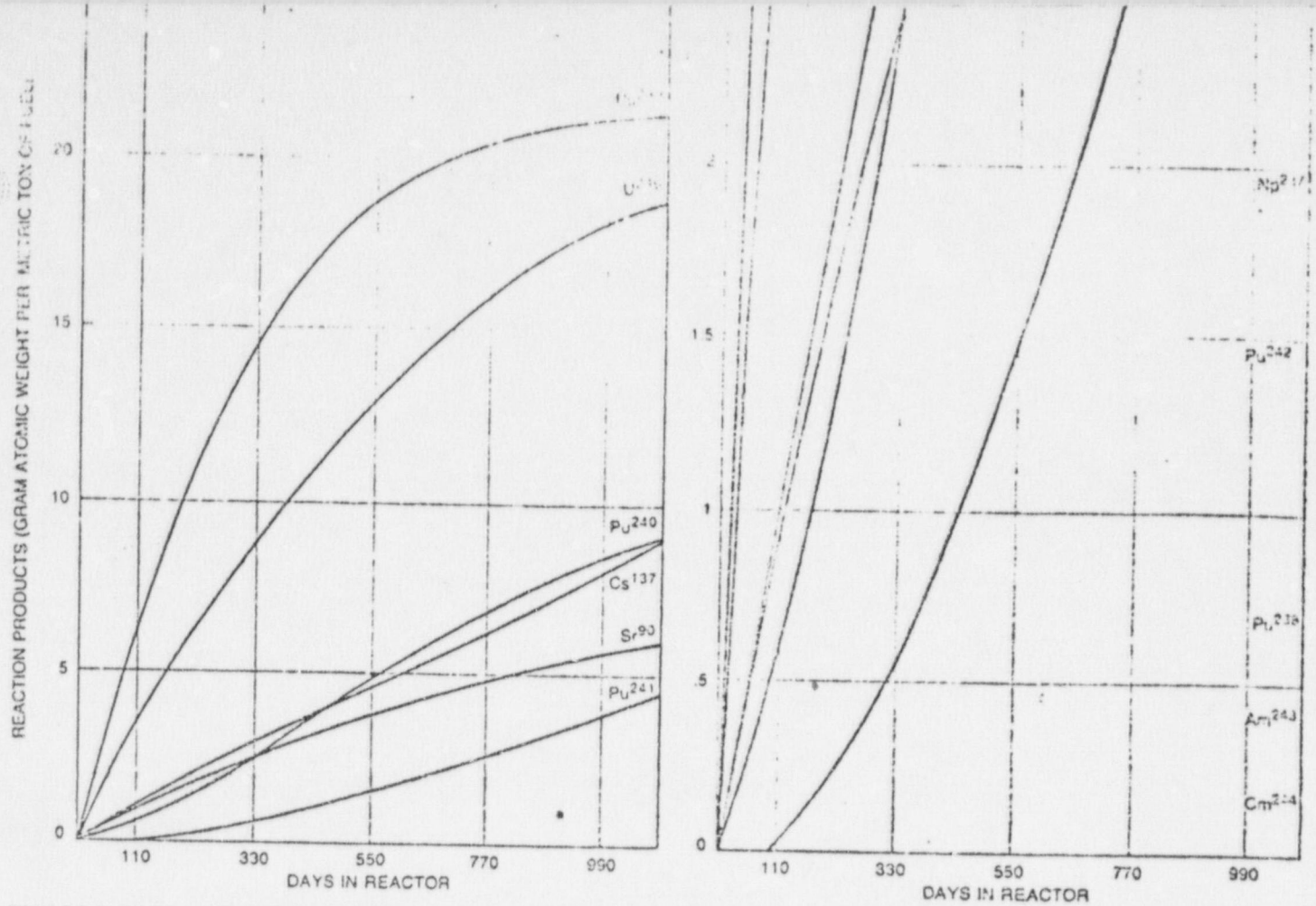
The task of disposing of the radioactive wastes produced by nuclear power plants is often cited as one of the principal drawbacks to the continued expansion of this country's capacity to generate electricity by means of the nuclear-fission process. Actually the task is not nearly as difficult or as uncertain as many people seem to think it is. Since 1957, when a committee of the National Academy of Sciences first proposed the burial of such wastes in deep, geologically stable rock formations, a substantial body of evidence has accumulated pointing to the technical feasibility, economic practicality and comparative safety of this approach. In recent years a number of alternative schemes—some of them involving undersea burial—have also been put forward, but deep underground burial remains the best understood and most widely favored solution to the problem of nuclear-waste disposal.

In what follows I shall describe the nature of the wastes produced by nuclear power reactors, evaluate their potential impact on public health and the environment and outline current plans to dispose of them in secure underground repositories.

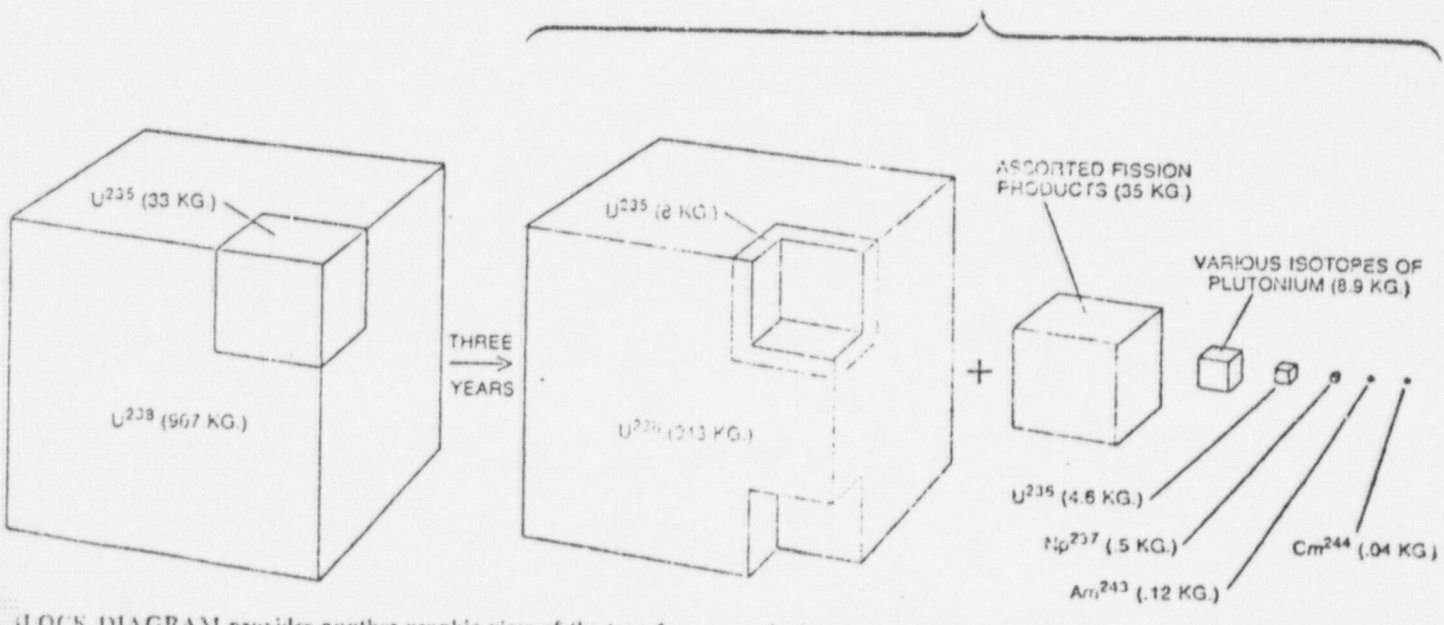
What are the special characteristics of nuclear-plant wastes, and how do they differ from the wastes produced by the combustion of other fuels to generate electricity? For the sake of comparison it might be helpful to consider first the wastes resulting from the operation of a large (1,000-megawatt) coal-burning power plant. Here the principal waste is carbon dioxide, which is emitted from the plant's exhaust stacks at a rate of about 600 pounds per second. Carbon dioxide is not in itself a dangerous gas, but there is growing concern that the vast amounts of it being released into the atmosphere by the combustion of fossil fuels may have deleterious long-term effects on the world's climate. The most harmful pollutant released by a coal-burning power plant is sulfur dioxide, which is typically emitted at a rate of about 10 pounds per second. According to a recent study conducted under the auspices of the National Academy of Sciences, sulfur dioxide in the stack effluents of a single coal-fired plant causes annually about 25 fatalities, 60,000 cases of respiratory disease and $12 million in property damage. Among the other poisonous gases discharged by coal-burning power plants are nitrogen oxides, the principal pollutants in automobile exhausts (a large coal-fired plant releases as much of these as 200,000 automobiles do), and benzpyrene, the main cancer-causing agent in cigarettes. Solid wastes are also produced, partly in the form of tiny particles. In the U.S. today such "fine particulate" material is considered second in importance only to sulfur dioxide as an air-pollution hazard; approximately a sixth of all man-made fine-particulate pollution comes from coal-burning power plants. Finally there is the residue of ashes, which for a 1,000-megawatt coal-fired plant accumulates at a rate of about 30 pounds per second.

The wastes from a nuclear power plant of equivalent size differ from the by-products of coal combustion in two important ways. First, their total quantity is millions of times smaller when the wastes are prepared for disposal: the total volume produced annually by a 1,000-megawatt nuclear reactor is about two cubic meters, an amount that would fit comfortably under a dining-room table. The comparatively small quantities of radioactive materials involved here make it practical to use highly sophisticated waste-management procedures, whose cost must be viewed in relation to the price of the electricity generated. For a 1,000-megawatt plant that price is roughly $200 million per year.

The second distinguishing characteristic of nuclear wastes is that their potential as a health hazard arises not from their chemical properties but from the radiation they emit. There appears to be a widespread misapprehension that this factor introduces a considerable degree of uncertainty into the evaluation of the potential health hazards associated with nuclear wastes, but the truth is quite the opposite. The effects of radiation on the human body are far better understood than the effects of chemicals such as air pollutants, food additives and pesticides. Radiation is easy to measure accurately with inexpensive but highly sensitive instruments; indeed, that is why radioactive isotopes are used so widely in biomedical research. Moreover, a large body of information has been compiled over the years from human exposure to intense radiation, including the atomic-bomb attacks on Japan, medical treatment with different forms of radiation and the inhalation of radon gas by miners. The available data have been analyzed intensively by national and international groups, including the National Academy of Sciences Committee on the Biological Effects of



BUILDUP OF REACTION PRODUCTS per metric ton (1,000 kilograms) of uranium fuel in the active core of a typical U.S. power reactor of the light-water type is plotted here on two different vertical scales as a function of time over the three-year period the fuel customarily resides in the core. The hundreds of products resulting from the fission of uranium-235 nuclei in the fuel are represented by two characteristic fission fragments, strontium 90 and cesium 137, which together constitute about 5 percent of the total. All the other isotopes shown result from nuclear reactions in which uranium nuclei in the initial fuel are transmuted by neutron-capture reactions, followed in some cases by radioactive decay. Leveling off of the curve for fissionable plutonium 239 means that near the end of the effective life of the fuel this isotope is being consumed by fission reactions and neutron-capture reactions almost as fast as it is being created.



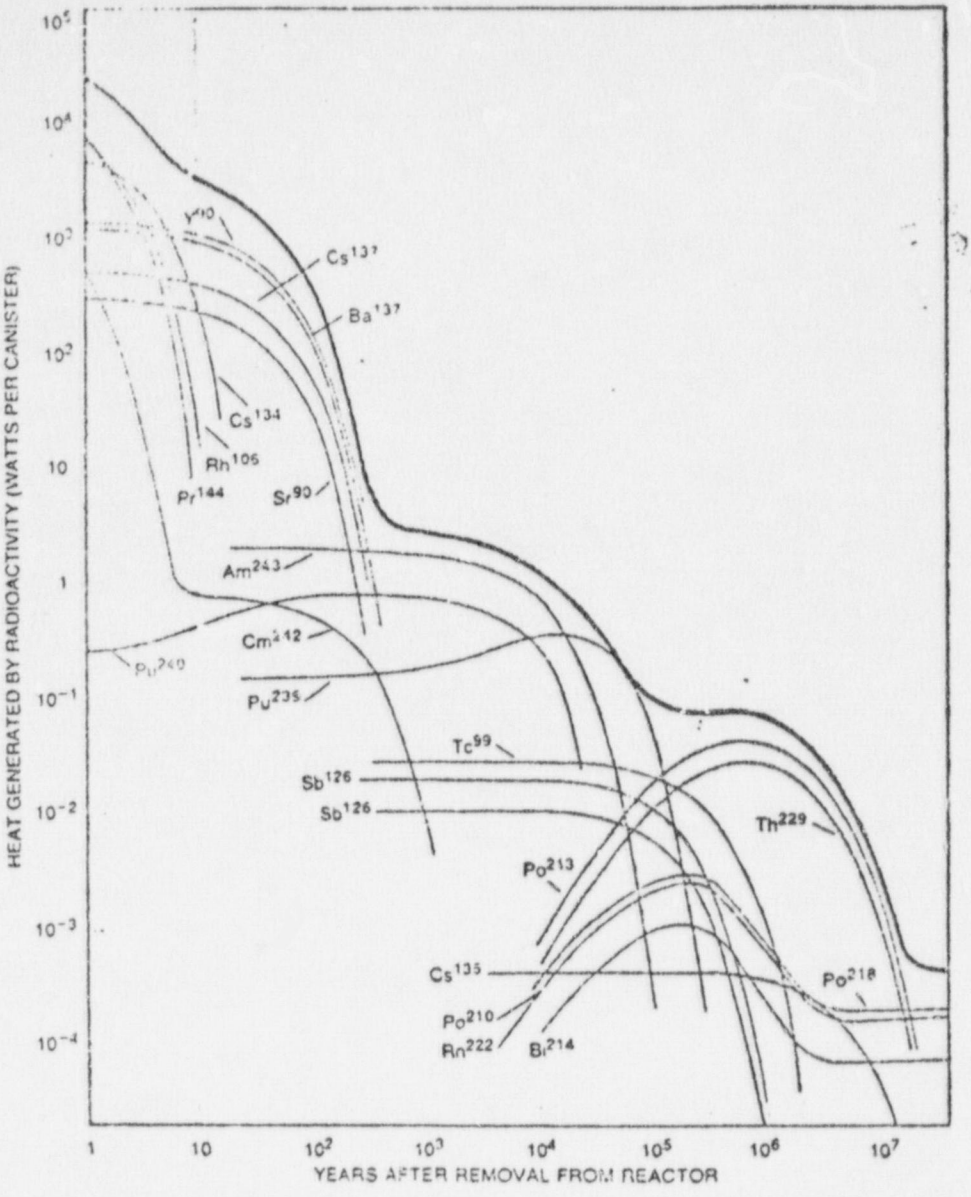
BLOCK DIAGRAM provides another graphic view of the transformation that takes place in the composition of the nuclear fuel in a light-water reactor over a three-year period. For every 1,000 kilograms of uranium in the initial fuel load (*left*) 24 kilograms of uranium 238 and 25 kilograms of uranium 235 are consumed (*center*), reducing the "enrichment" of uranium 235 from 3.3 percent to .8 percent. Uranium that is consumed is converted into 35 kilograms of assorted fission products, 8.9 kilograms of various isotopes of plutonium, 4.6 kilograms of uranium 236, .5 kilogram of neptunium 237, .12 kilogram of americium 243 and .04 kilogram of curium 244 (*right*).

Ionizing Radiation and the United Nations Scientific Committee on the Effects of Atomic Radiation. The result is a fairly reliable set of estimates of the maximum effects of various levels of radiation on the human body.

What are the radioactive substances in the waste products of a nuclear reactor, and how are they formed? In a light-water reactor (the type of nuclear plant now in general service for generating electricity in this country) the fuel consists initially of a mixture of two isotopes of uranium: the rare, readily fissionable isotope uranium 235 ("enriched" to 3.3 percent) and the abundant, ordinarily nonfissionable isotope uranium 238 (96.7 percent). The fuel mixture is fabricated in the form of ceramic pellets of uranium dioxide (UO_2), which are sealed inside tubes of stainless steel or a zirconium alloy. In the course of the reactor's operation neutrons produced initially by the fission of some of the uranium-235 nuclei strike other uranium nuclei, either splitting them in two (and thereby continuing the chain reaction) or being absorbed (and thereby increasing the atomic weight of the struck nucleus by one unit). These two types of reaction result in a variety of nuclear products, which can be plotted as a function of the time the fuel is in the reactor, usually about three years [*see illustration on opposite page*].

The most important reaction in a light-water reactor is the fission of uranium 235, which creates hundreds of different products, of which strontium 90 and cesium 137, two characteristic fission fragments, constitute about 5 percent of the total. Another important reaction is the capture of neutrons by uranium-238 nuclei, which gives rise to plutonium 239. (Actually the neutron-capture reaction first yields uranium 239, which then decays radioactively in two steps to plutonium 239.) The plutonium 239 does not continue to build up linearly with time, because it may also participate in nuclear reactions. For example, a nucleus of plutonium 239 may fission when it is struck by a neutron, or it may absorb the neutron to become a nucleus of plutonium 240. The leveling off of the plutonium-239 curve means that near the end of the effective life of the fuel load this isotope is being destroyed by such processes at nearly the same rate as the rate at which it is being created.

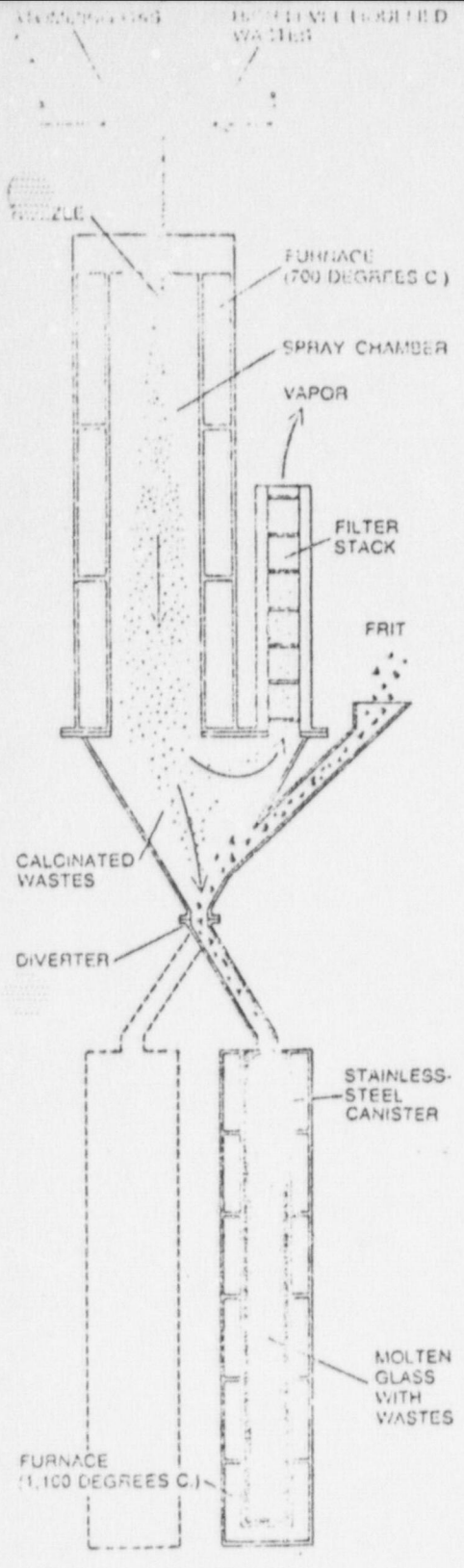
Plutonium 240 can also capture a neutron and become plutonium 241, which can in turn either fission or capture another neutron and become plutonium 242. Plutonium 242 can be converted by the capture of still another neutron into curium 243 (after an intervening radioactive decay from [illegible] and there is even an appreciable buildup of curium 244 created



HEAT GENERATED by the various radioactive isotopes in the spent fuel from a nuclear power plant must be allowed to dissipate safely, which means that in any long-term storage plan the canisters containing the high-level wastes must be spread out over a fairly large area. The problem can be substantially alleviated by resorting to an interim-storage period of about 10 years (*colored panel at left*), after which the heat generated by each canister will have fallen off to about 3.4 kilowatts. The gray curves trace the contributions of the more important radioactive isotopes to the overall heating effect, which in turn is indicated by the black curve.

lowed by a radioactive decay. By the same token successive neutron captures beginning with uranium 235 can respectively give rise to uranium 236, neptunium 237 and plutonium 238.

For every metric ton (1,000 kilograms) of uranium in the initial fuel load 24 kilograms of uranium 238 and 25 kilograms of uranium 235 are consumed in the three-year period, reducing the enrichment of the uranium 235 from 3.3 percent to .8 percent. In the process 800 million kilowatt hours of electrical energy can be produced and the uranium that is consumed is converted into roughly [illegible] kilograms of various fission products, [illegible] kilograms of plutonium, [illegible] kilograms of neptunium 237, [illegible] kilograms of uranium 236, [illegible] kilograms of curium 244 and [illegible] kilograms of other transuranic elements. Since only 25 kilograms of uranium 235 are consumed and a fifth of that amount is converted into uranium 236 and neptunium 237, one can easily calculate that only 60 percent of the energy-releasing fission reactions actually take place in uranium 235. Thirty-one percent occur in plutonium 239, 4 percent occur in plutonium 241 and 5 percent are induced by high-energy neutrons in uranium 238. (These figures are averages over the three years the fuel customarily is in the reactor. Near the end of that period only 36 percent of the fission reactions take place in uranium 235, with 54 percent occurring in plutonium 239, 10 percent in plutonium 241 and 5 percent in uranium 238. In view of the current public controversy over the projected future recycling of



CURRENT PLAN for handling high-level radioactive wastes calls for their incorporation into glass cylinders about 300 centimeters long and 30 centimeters in diameter. In the single-step solidification process depicted here the liquid high-level waste is first converted into a fine powder inside a calcining chamber (*top*), then mixed with glassmaking frit (*middle*) and finally melted into a block of glass within the thick stainless-steel canister in which it will eventually be stored (*bottom*). When canister is full, flow is switched by a diverter valve into a new canister (*broken outline*); hence the process is continuous.

esting to note that plutonium is already in intensive use as a nuclear fuel.)

After the spent fuel is removed from the reactor it is stored for several months in order to allow the isotopes with a short radioactive half-life to decay. (This temporary storage is particularly important with respect to an isotope such as iodine 131, one of the most dangerous fission products, which has a half-life of only eight days.) Thereafter one of the options would be to send the spent fuel to a chemical-reprocessing plant, where the fuel pins would be cut into short lengths, dissolved in acid and put through a series of chemical-separation processes to remove the uranium and plutonium, which would then be available to make new fuel. Everything else (except for certain gases, which would be discharged separately, and the pieces of the metal fuel pins that do not dissolve in the acid) is referred to as "high level" waste. In addition to all the fission products, which are responsible for the bulk of the radioactivity, the high-level wastes would in this case include the isotopes of neptunium, americium and curium, along with the small amounts of uranium and plutonium that would not be removed in reprocessing, owing to inefficiencies in the chemical separations.

The simplest and most obvious way to dispose of the remaining high-level wastes (once an economically sufficient quantity of them began to accumulate) would be to bury them permanently deep underground. On the face of it such an approach appears to be reasonably safe, since all rocks contain traces of naturally radioactive substances such as uranium, thorium, potassium and rubidium, and the total amount of this natural radioactivity in the ground under the U.S. down to the proposed nuclear-waste burial depth of 600 meters is enormously greater than the radioactivity in the wastes that would be produced if the country were to generate all its electric power by means of nuclear fission. Of course, the radioactivity of the nuclear wastes is more concentrated, but in principle that does not make any difference; the biological effects of radiation are generally assumed to have a linear relation to dosage, so that distributing a given total dosage among more people would not change the number of adverse health effects. (If this "linearity hypothesis" were to be abandoned, current estimates of the potential health hazards from nuclear wastes and all other aspects of the nuclear power industry would have to be drastically reduced.)

The detailed procedures for handling the high-level wastes are not yet definite, but present indications are that the wastes will be incorporated into a borosilicate glass (similar to Pyrex), which will be fabricated in the form of cylinders about 300 centimeters long and 30 centimeters in diameter. Each glass cylinder will in turn be sealed inside a thick stainless-steel casing. These waste canisters will then be shipped to a Federally operated repository for burial. One year's wastes from a single 1,000-megawatt nuclear power plant will go into 10 such canisters, and the canisters will be buried about 10 meters apart; hence each canister will occupy an area of 100 square meters, and all 10 canisters will take up 1,000 square meters. It has been estimated that an all-nuclear U.S. electric-power system would require roughly 400 1,000-megawatt plants, capable of generating 400,000 megawatts at full capacity, compared with the present average electric-power usage of about 230,000 megawatts. Accordingly the total high-level wastes generated annually by an all-nuclear U.S. electric-power system would occupy an area of less than half a square kilometer.

The main reason for spreading the canisters over such a large area is to dissipate the heat generated by their radioactivity. The problem of dealing with this heat can be substantially alleviated by waiting for 10 years after the reprocessing operation, at which time the heat generated by each canister will have fallen off to about 3.4 kilowatts. The advantage of delayed burial is seen more clearly when the heating effect is translated into the estimated rise in temperature that would result at the surface of a canister buried alone in rock of average thermal conductivity [*see top illustration on page 26*]. It is evident that burial after a wait of a year would lead to a temperature rise of 1,900 degrees Celsius, whereas waiting for 10 years would reduce the rise to 250 degrees C. The difference is critical, since glass devitrifies (crystallizes and becomes brittle) at temperatures higher than 700 degrees. In rock of average thermal conductivity the maximum average temperature of the rock just above and below the burial depth would be reached 40 years after burial, when the average temperature at the burial depth would be increased by 140 degrees [*see bottom illustration on page 26*]. If the canister were to be buried in salt, which has a much greater thermal conductivity, the rise in temperature at the burial depth after 40 years would be less: 85 degrees.

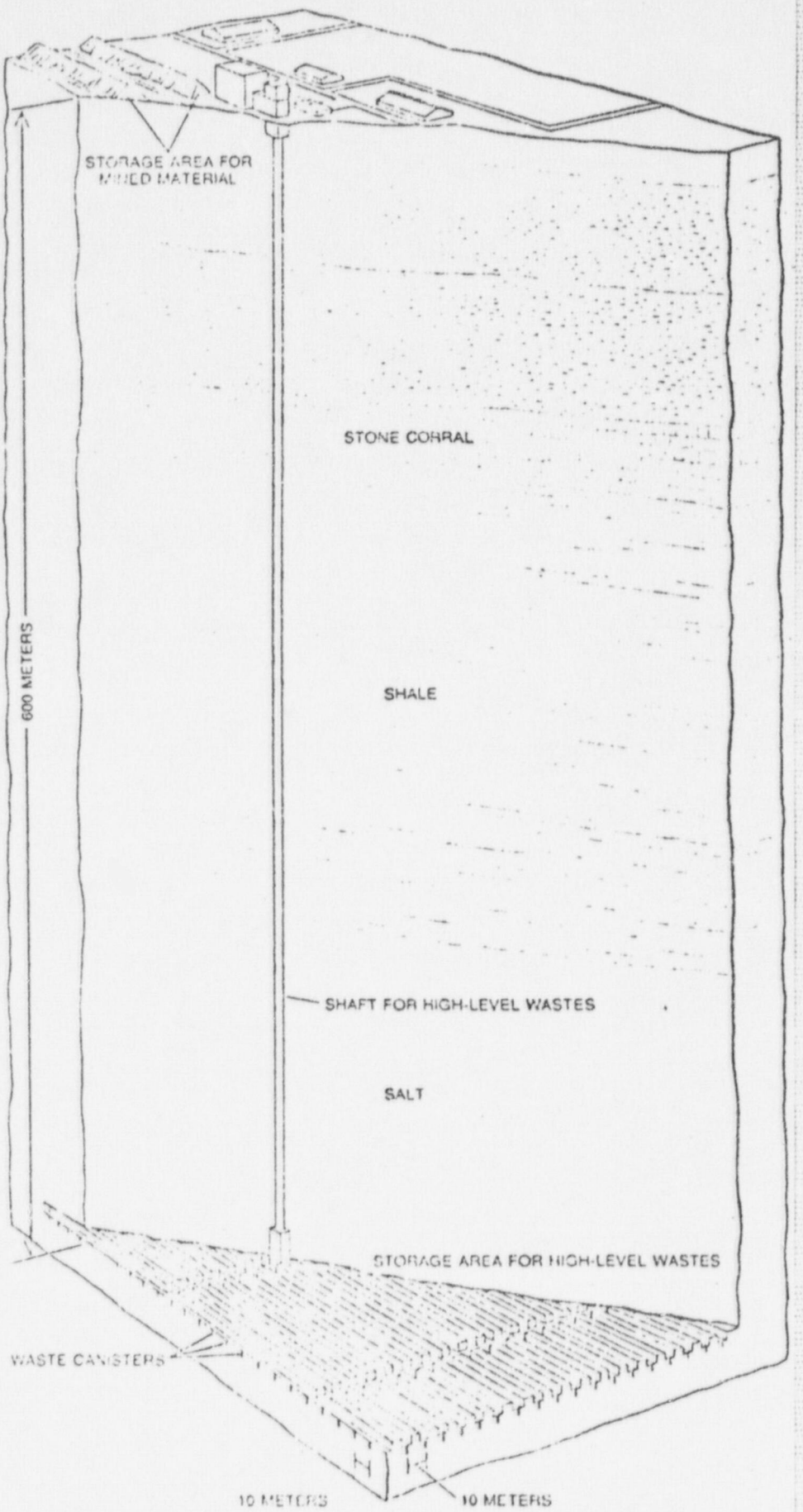
In salt an additional effect must be taken into account, since the heat will cause the migration of water toward the waste canister. Typical salt formations contain about .5 percent water trapped in tiny pockets. The solubility of salt in water increases with temperature, so that if the temperature on one side of the pocket is raised, more salt will go into solution on that side. This raises the salt content of the water above the saturation point for the temperature on the opposite side of the pocket, however, causing the salt to precipitate out of solution on that side. The net effect is a

migration of the water pocket in the direction of the higher temperature, which is of course the direction of the buried waste canister. The rate of the migration depends on how rapidly the temperature increases with distance, and on how rapidly the temperature gradient, as I have explained, falls off with time.

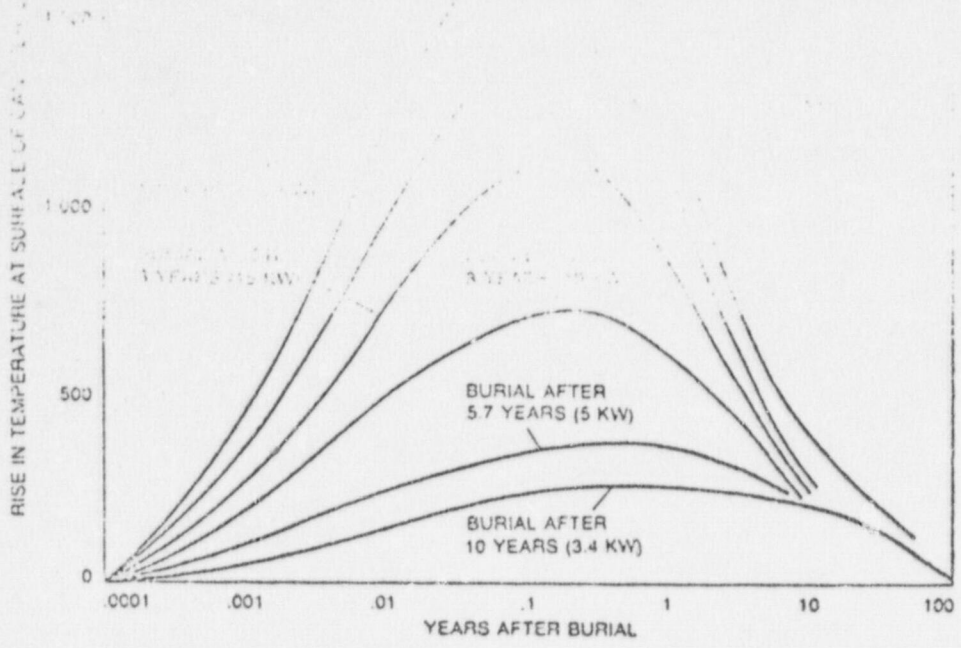
This process is expected to lead to the collection of water around each canister at an initial rate of two or three liters per year; within 25 years a total of 25 liters will have collected, with very little further collection expected thereafter. Since the temperature at the surface of the canister would be higher than the boiling point of water, the water arriving at the canister would be converted into steam and would be drawn off by the ventilation system (assuming that the repository is not sealed). Small amounts of water would continue to migrate toward the canisters after 25 years, carrying corrosive substances such as hydrochloric acid arising from chemical reactions induced in the salt by the radiation from the canister. It is therefore usually assumed that the stainless-steel casings will corrode away, leaving the waste-containing glass cylinders in contact with the salt.

How can one evaluate the health hazards presented by such radioactive waste materials? The most direct hazard is from the gamma radiation emitted by the decaying nuclei. Gamma rays behave much like X rays except that they are even more penetrating. The effect of gamma rays (or any other form of ionizing radiation) on the human body is measured in the units called rem, each of which is equal to the amount of radiation that is required to produce the same biological effect as one roentgen of X radiation. ("Rem" stands for "roentgen equivalent man.") In analyzing the impact of radioactive wastes on public health the only significant radiation effects that need to be considered are those that cause cancer and those that induce genetic defects in progeny. According to the best available estimates, for whole-body radiation such as would be delivered by a source of gamma rays outside the body the risk of incurring a radiation-induced fatal cancer is approximately 1.8 chances in 10,000 per rem of radiation exposure. The estimated risk for total eventual genetic defects in progeny is about 1.5 chances in 10,000 per rem of radiation delivered to the gonads (with the effects spread out over about five generations). In the discussion that follows I shall be referring only to cancers, but it should be kept in mind that there are in addition a comparable (or perhaps somewhat smaller) number of genetic defects caused by exposure to gamma radiation.

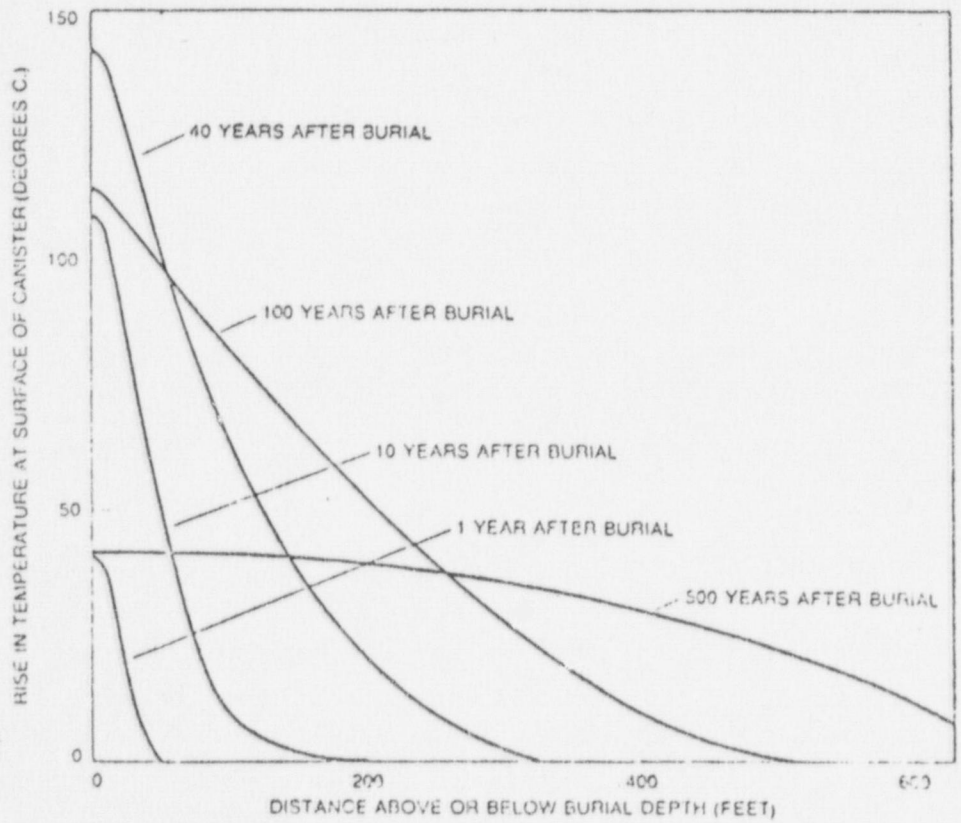
The biological damage done by a



DEEP UNDERGROUND BURIAL is at present the method favored by most nuclear power experts in the U.S. for the long-term storage of high-level radioactive wastes. In this idealized diagram of a proposed Federally operated repository in southeastern New Mexico the waste canisters are shown emplaced at a depth of 600 meters in a geologically stable salt formation. In order to dissipate the heat from the canisters they would be buried about 10 meters apart; thus each canister would occupy an area of about 100 square meters. On this basis the total



ADVANTAGE OF DELAYED BURIAL is evident in this graph, in which the heating effect of a single waste canister is translated into the estimated rise in temperature that would result at the surface of the canister if it were buried alone in rock of average thermal conductivity. The numbers labeling each curve indicate the heat generated by the canister (in kilowatts) after a given interim-storage period (in years). Thus burial after one year (*top curve*) would cause a temperature rise of 1,900 degrees Celsius, whereas waiting for 10 years (*bottom curve*) would reduce the increment to 250 degrees C. Colored area at top symbolizes critical fact that glass devitrifies (crystallizes and becomes brittle) at temperatures higher than 700 degrees C.



MAXIMUM AVERAGE TEMPERATURE of the rock just above and below the burial depth of the waste canister would be reached 40 years after burial, when the average temperature at the burial depth would be increased by about 140 degrees C. If the waste canister were to be buried in salt, the corresponding temperature increments would be considerably reduced.

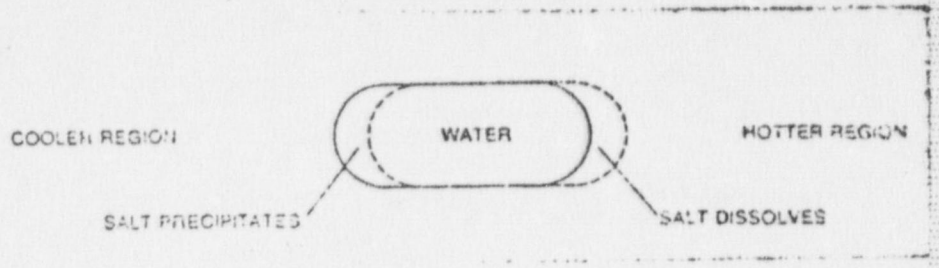
one first plots the gamma-ray energy emitted per second (in watts) by the wastes resulting from one full year of a U.S. energy budget based on all nuclear generation of electric power [*see bottom illustration on opposite page*]. From such a graph one can see that for the period between eight and 400 years after reprocessing the dominant contribution to the total gamma-ray emission is made by cesium 137 and its immediate decay product barium 137. During this four-century period the total gamma-ray hazard falls by more than four orders of magnitude.

One way to grasp the potential hazard presented by this amount of gamma radiation is to consider what would happen if the source of radiation were to be distributed over the entire land surface of the U.S. The number of fatal cancers per year induced in that case could be as high as many millions. Clearly the material that gives rise to the radiation must be confined and handled with great care. On the other hand, gamma rays are attenuated by about a factor of 10 per foot in passing through rock or soil, so that there would be no danger of this type from wastes that remain buried deep underground.

A measure of the care that must be taken in handling the waste canisters is indicated by the fact that a dose of 500 rem (which has a 50 percent chance of being fatal) would be received in 10 minutes by a human being standing 10 meters away from an unshielded new waste canister. There is no great technical difficulty, however, in providing shielding adequate for safe and effective remote handling of the waste canisters.

If any of the radioactive wastes were to enter the human body, their biological effects would be enhanced, since the radiation they would emit would strike human tissue in all directions and since the exposure would continue for some time. Accordingly one must consider the two major possible entry routes: ingestion and inhalation. The ingestion hazard can be evaluated in terms of the number of cancer-causing doses in the wastes produced by one year of all-nuclear electric power in the U.S. [*see illustration on page 28*]. In this graph the value of 10^8 at 10^4 years, for example, means that if all the wastes, after aging for 10,000 years, were to be converted into digestible form and fed to people, one could expect a million fatal cancers to ensue. This "worst case" scenario assumes, of course, that many millions of people are involved, but in view of the linear relation between dose and effect generally assumed for calculating such radiation risks it does not matter how many millions there are. The derivation of such a graph is rather complex, involving for each radioactive species the probability of transfer across the intestinal wall into the bloodstream; the probability of transfer from the blood into

each body organ; the time the radioactive substance spends in each organ; the energy of the radiation emitted by the substance and the fraction of the energy absorbed by the organ; the mass of the organ; the relative biological effects of the different kinds of radiation emitted, and finally the cancer risk per unit of radiation absorbed (in rem).



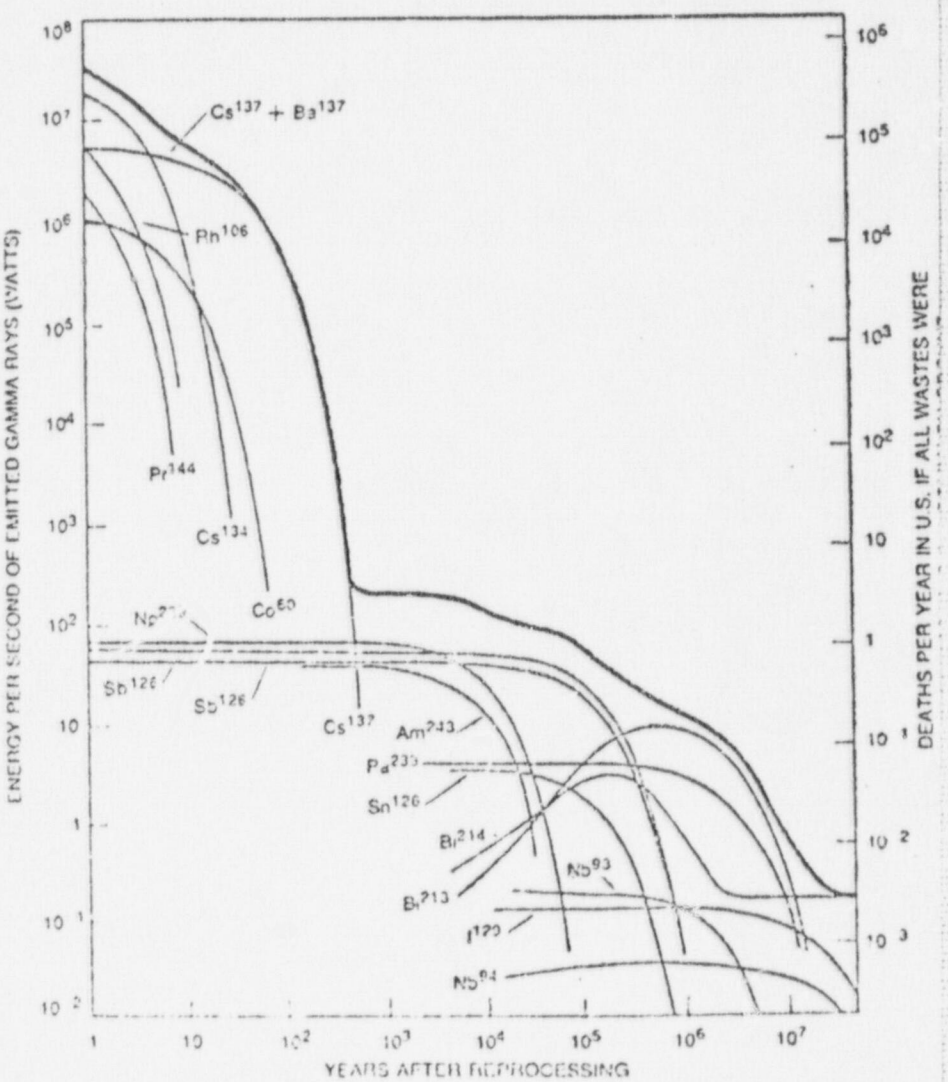
IN SALT the heat from the waste canister would cause the migration of tiny pockets of water in the direction of the higher temperature, since the salt would tend to go into solution on the hotter side of the pocket (*right*) and to precipitate out of solution on the cooler side (*left*).

Feeding all this radioactive material to people is hardly a realistic scenario, however, so that one might consider instead the consequences if the wastes were to be dumped in soluble form at random into rivers throughout the U.S. For this scenario, which comes close to assuming the most careless credible handling of the disposal problem, the graph shows that a million fatalities could result. It is unlikely anyone would suggest such dumping, but in any event it is clearly not an acceptable method of disposal.

In evaluating the inhalation hazard by far the most important effect that must be taken into account is the induction of lung cancers [*see illustration on page 29*]. Here again the graph shows the consequences of a situation approximating the most careless credible handling of the wastes: spreading them as a fine powder randomly over the ground throughout the U.S. and allowing them to be blown about by the wind.

Much attention is given in public statements to the potential hazards represented by the scales in such graphs that show the number of cancers expected if all the radioactive materials involved were to be ingested or inhaled by people. One often hears, for example, that there is enough radioactivity in nuclear wastes to kill billions of people. To put such statements in perspective it is helpful to compare the known hazards of nuclear wastes with those of other poisonous substances used in large quantities in the U.S. [*see illustration on page 30*]. Such a comparison shows that there is nothing uniquely dangerous about nuclear wastes. Nevertheless, it is often emphasized that radioactive wastes remain hazardous for a long time. Nonradioactive barium and arsenic, on the other hand, remain poisonous forever. It might also be argued that the other hazardous substances are already in existence, whereas nuclear wastes are a newly created hazard. Roughly half of the U.S. supply of barium and arsenic, however, is currently imported, and hence these hazards are also being introduced artificially into our national environment. One other important difference often goes unnoted, and that is that the chemical poisons are not carefully buried deep underground as is the plan for the nuclear wastes; indeed, much of the arsenic is used as a herbicide and is routinely sprayed on [illegible]

Actually such quantitative representations of potential hazards are virtually meaningless unless one also takes into account the possible pathways the hazardous agents can take to reach man. Therefore I shall now turn to that subject. It is generally agreed the most important health hazard presented by nuclear wastes arises from the possibility that ground water will come in contact with the buried wastes, leach them into solution, carry them through the overlying rock and soil and ultimately into food and water supplies. Human exposure would then be through ingestion. From the analysis of the ingestion route outlined above one can deduce that the hazard from ingested radioactive mate-



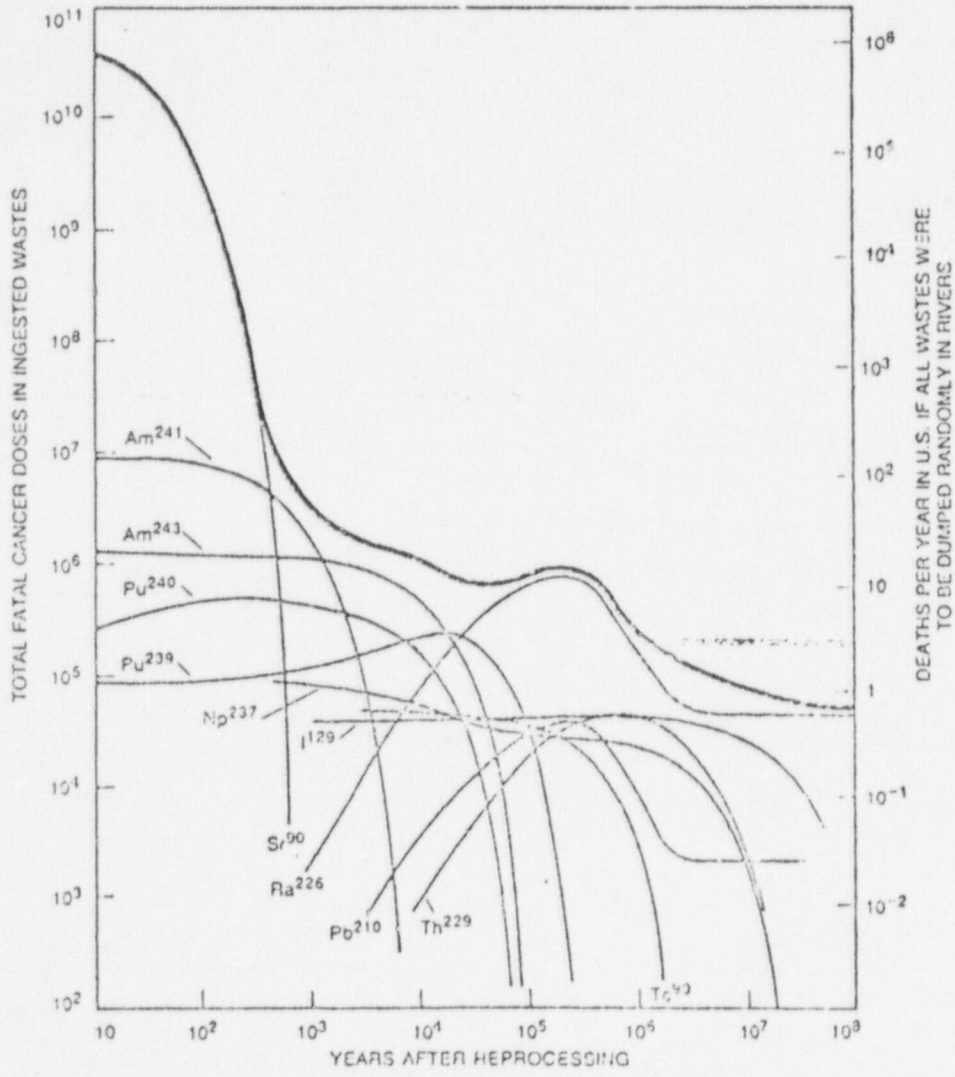
MOST DIRECT HEALTH HAZARD presented by radioactive wastes arises from the gamma radiation emitted by the decaying nuclei. The biological damage done by a gamma ray is assumed [illegible]

few hundred years. In fact, one can calculate that after 600 years a person would have to ingest approximately half a pound of the buried waste to incur a 50 percent chance of suffering a lethal cancer. It is reasonable to conclude that it is very important the wastes be isolated from human contact for the initial few hundred years. I shall first take up that problem but shall return to the longer-term one.

When people first learn that nuclear wastes must be isolated for hundreds of years, their immediate response is often to say this is virtually impossible: man's social institutions and political systems and the structures he builds rarely last that long. This response, however, is based on experience in the environment encountered on the surface of the earth. What one is actually dealing with are rock formations 600 meters below the surface. In this quite different environment the characteristic time intervals re-

the order of millions of years.

In addition to the general security of the deep underground environment a great deal of extra protection is provided for the critical first few hundred years by the various time delays intrinsic to any conceivable release process. The most important of these additional safeguards has to do with the selection of a storage site, which is determined by geological study to be not only free of circulating ground water now but also likely to remain free of it for a very long time to come. In geological terms a few hundred years is a short time, so that predictions of this kind can be highly reliable. Since the patterns in which groundwater flows can be changed by earthquakes, only tectonically stable areas would be chosen. Salt formations offer additional security in this regard, because when salt is subjected to pressure, it flows plastically. Thus it is capable of sealing cracks that develop from tecton-



IF ALL WASTES WERE TO BE INGESTED, the biological effects on the human population of the U.S. would be considerable. As this graph shows, the number of cancer-causing doses in the wastes produced by one year of all-nuclear electric power in the U.S. is such that if all the wastes, after aging for 10,000 years, were to be converted into digestible form and fed to people, one would expect a million fatal cancers to ensue (*scale at left*). If instead the wastes were to be converted into soluble form and immediately after reprocessing dumped at random into rivers throughout the U.S., the result could again be a million fatalities (*scale at right*).

mosses the scars of the burial operations, leaving the canisters sealed deep inside a gigantic crystalline mass.

Suppose, however, water does somehow manage to get into cracks in the rock formation in which the waste is buried. What happens then? The rock would of course be chosen to be impervious to water, so that there would be a second delay while the rock was being leached away before the waste glass was exposed to water. It would seem that there would not be much delay in salt because it is so soluble in water, but in fact the quantities of water deep underground are not large and the mass of salt is huge. For example, if all the ground water now flowing in the region of the proposed Federal waste-repository site in New Mexico were somehow diverted to flow through the salt, it would take 50,000 years for the salt enclosing one year's deposit of nuclear wastes to be dissolved away.

A third delay arises from the time it would take to leach away the waste glass itself. There is some uncertainty on this point, and the matter is complicated by the fact that leaching rates increase rapidly with temperature, but it seems fairly certain that the low rate at which the glass can be leached away will offer considerable protection for at least a few hundred years. If new leaching-rate studies indicate otherwise, it would not be too difficult or expensive to switch to ceramics or other more resistant materials for incorporating the wastes.

A fourth delay arises from the length of time it ordinarily takes water to reach the surface. Typical flow rates are less than 30 centimeters per day, and typical distances that must be covered are tens or hundreds of kilometers. For anything to travel 100 kilometers at 30 centimeters per day takes about 1,000 years.

The radioactive wastes would not, however, move with the velocity of the ground water even if they went into solution. They would tend to be filtered out by ion-exchange processes. For example, an ion of radioactive strontium in the wastes would often exchange with an ion of calcium in the rock, with the result that the strontium ion would remain fixed while the calcium ion would move on with the water. The strontium ion would eventually get back into solution, but because of continual holdups of this type the radioactive strontium would move 100 times slower than the water, thus taking perhaps 100,000 years to reach the surface. For the other important waste components the holdup is even longer.

As a result of all these delays there is an extremely high assurance that very little of the wastes will escape through the ground-water route during the first few hundred years when they are most dangerous. Indeed, the time delays offer

substantial protection for hundreds of thousands of years. I shall give no credit for this factor, however, in the following discussion of the potential longer-term hazard.

As we have seen, the "50 percent lethal" dose of nuclear wastes ingested after 600 years would be half a pound. This is hardly a potent poison, and its dangers seem particularly remote when one considers that the material is carefully buried in low-leachability form isolated from ground water a third of a mile below the earth's surface. Many more potent poisons are routinely kept in the home. It is true, however, that nuclear wastes remain poisonous for a very long time, so that they could conceivably present a hazard.

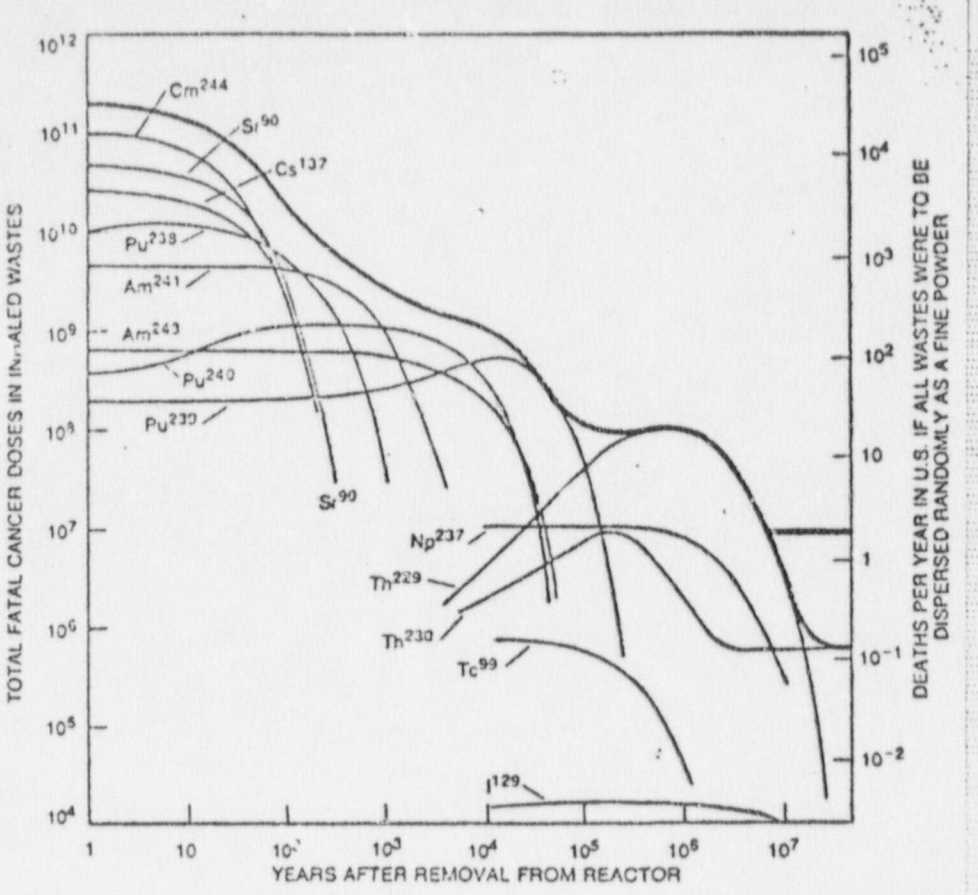
To evaluate this long-term risk one must develop an estimate of the probability that the wastes will escape into the environment. How can this be done? One way is to make a comparison between an atom of nuclear waste buried at a depth of 600 meters and a typical atom of radium somewhere in the rock or soil above the waste canister, assuming that the waste atom is no more likely than the radium atom to escape and find its way into a human being. This would seem to be a conservative assumption, since "the rock or soil above the waste canister" includes the material near the surface, where the erosive forces of wind, surface runoff, freeze-thaw cycles, vegetation and so on are active.

It is difficult to calculate the escape probability for an atom of radium in a particular area, but the average escape probability over the entire continental U.S. can be estimated. To make such a comparison meaningful one can assume that the wastes are buried in a uniform distribution over the entire country, but for calculating averages it is equivalent to assume that they are buried at random locations across the country and always at the same depth. When the assumption is stated this way, it is clearly conservative; one would think that by making use of all the information available from geology, hydrology and lithology one could choose a burial site that would be much securer than a randomly chosen one.

Having made these two basic assumptions—random burial and an equal escape probability for atoms of waste and radium—one need only estimate the average probability that an atom of radium in the top 600 meters of the U.S. will escape. One approach has two steps: calculating the probability that a radium atom will escape from the soil into rivers and multiplying this number by the probability that a given sample of water will be ingested by a human being. The average concentration of radium in rivers (two grams per 10 trillion liters) and the total annual water flow in U.S. rivers (6 quadrillion liters) are known quantities, the annual transfer of radium from the soil into rivers is the product of these two numbers, or 300 grams. Since radium is a product of the radioactive decay of uranium, from the average concentration of uranium in rock (2.7 parts per million) one can readily estimate the amount of radium in the top 600 meters of the U.S. as being 12 billion grams. The annual transfer probability is the ratio of the annual transfer to the total quantity, or .000000025 per year. The inverse of this number, 40 million years, is then the average lifetime of rock in the top 600 meters of the U.S. Therefore the assumption is that each atom of buried nuclear waste has less than one chance in 40 million of escaping each year. About one part in 10,000 of river flow in the U.S. is ingested by human beings, but owing to various purification processes the fraction of the radium in river flow that is ingested is closer to 1.5 part in 100,000. Multiplying this number by the annual probability for escape into rivers (.000000025), one finally obtains the total annual transfer probability of a radium atom from the rock into a human being. It is roughly four chances in 10 trillion.

There are at least two flaws in this calculation. It ignores transfer through food, a factor that reduces the transfer probability, and it assumes that all the radium ingested is taken up by the body, a factor that increases the transfer probability. These problems can be avoided and the calculation can be simplified by estimating the number of human cancers induced annually by ingested radium (12) and dividing that number by the number of cancer-causing doses of radium in the top 600 meters of the U.S. (30 trillion). The first quantity is obtained from actual measurements of the amount of radium in cadavers combined with generally accepted estimates of the risk of a person's getting cancer from the radium. The result for the annual transfer probability obtained by this method is in close agreement with the figure derived by the preceding method. It therefore is reasonable to multiply the dosage scale in the ingestion graph on the opposite page by .0000000000004 (four chances in 10 trillion) to obtain the number of fatalities expected annually from the nuclear wastes produced annually by an all-nuclear U.S. electric-power system.

What all of this means is that after the first few hundred years of storage, during which we would be protected by the time delays discussed above, one could expect about .000001 fatality per year



IF ALL WASTES WERE TO BE INHALED, the most important health hazard would be the induction of lung cancers. In this graph again the scale at left shows the total number of cancer-causing doses in the wastes produced by one year of all-nuclear electric power in the U.S. The scale at right shows the number of deaths expected by the inhalation route if all these wastes were to be spread as a fine powder randomly over the ground throughout the U.S. In both this graph and the one on the opposite page the short colored line at the lower right indicates the corresponding long-term health hazard represented by the natural radioactivity in the uranium ore that would be consumed by such an all-nuclear electric-power system in the U.S.

or less attributable to the buried waste. When this toll is added up, it comes to .4 fatality for the first million years plus an additional four fatalities over the next 100 million years.

If one is to consider the public-health effects of radioactivity over such long periods, one should also take into account the fact that nuclear power burns up uranium, the principal source of radiation exposure for human beings today. For example, the uranium in the ground under the U.S. is the source of the radium that causes 12 fatal cancers in the U.S. per year. If it is assumed that the original uranium was buried as securely as the waste would presumably be, its eventual health effects would be greater than those of the buried wastes. In other words, after a million years or so more lives would be saved by uranium consumption per year than would be lost to radioactive waste per year.

The fact is, however, that the uranium now being mined comes not from an average depth of 600 meters but from quite near the surface. There it is a source of radon, a highly radioactive gaseous product of the decay of radium that can escape into the atmosphere. Radon gas is the most serious source of radiation in the environment, claiming thousands of lives in the U.S. per year according to the methods of calculation used here. When this additional factor is taken into account, burning up uranium in reactors turns out to save about 50 lives per million years for each year of all-nuclear electric power in the U.S., more than 100 times more than the .4 life that might be lost to buried radioactive wastes.

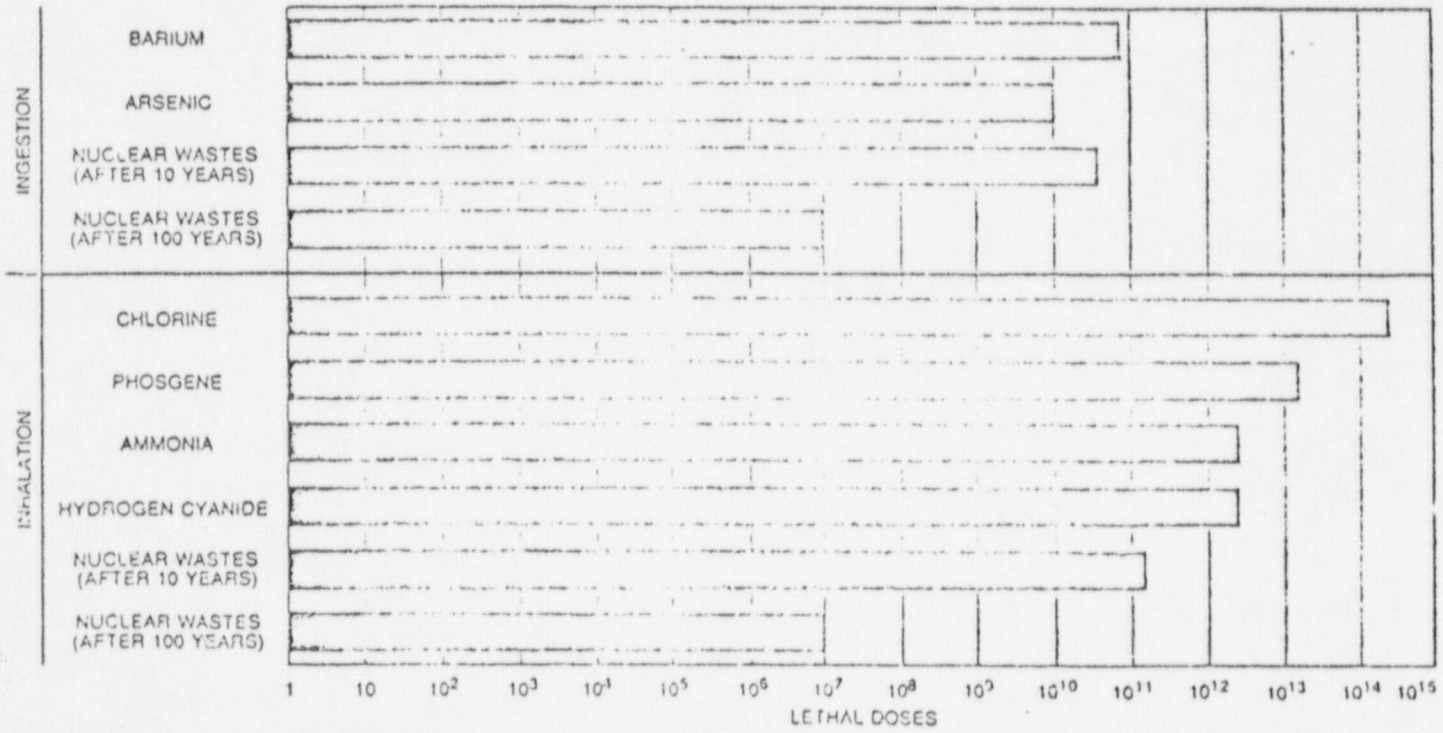
Thus on any long time scale nuclear power must be viewed as a means of cleansing the earth of radioactivity. This fact becomes intuitively clear when one considers that every atom of uranium is destined eventually to decay with the emission of eight alpha particles (helium nuclei), four of them rapidly following the formation of radon gas. Through the breathing process nature has provided an easy pathway for radon to gain entry into the human body. In nuclear reactors the uranium atom is converted into two fission-product atoms, which decay only by the emission of a beta ray (an electron) and in some cases a gamma ray. Roughly 87 percent of these emission processes take place before the material even leaves the reactor; moreover, beta rays and gamma rays are typically 100 times less damaging than alpha-particle emissions, because their energies are lower (typically by a factor of 10) and they deposit their energy in tissue in less concentrated form, making their biological effectiveness 10 times lower. The long-term effect of burning uranium in reactors is hence a reduction in the health hazards attributable to radioactivity.

In this connection it is interesting to note that coal contains an average of about 1.5 parts per million of uranium, which is released into the environment when the coal is burned. The radon gas from the uranium released by one year of an all-coal-powered U.S. electric-generating system would cause about 1,000 fatalities per million years, a rate three orders of magnitude greater than the result obtained above for the wastes from an all-nuclear-powered system.

If the risk of ingesting radioactive waste materials with food or water is so low, what about the risk of inhaling them as airborne particulate matter? The potential hazards from inhaling such materials are much greater and longer-lasting than the hazards from ingesting them. It is difficult, however, to imagine how buried nuclear wastes could be released as airborne particulates. The largest nuclear bombs yet considered would not disturb material at a depth of 600 meters. Meteorites of sufficient size to do so are extremely rare, so that their average expected effect would be a million times lower than that from ingestion. Volcanic eruptions in tectonically quiet regions are also extremely rare; moreover, they disturb comparatively small areas, so that their effects would be still smaller.

Release through ground water could lead to a small fraction of the radioactivity being dispersed at the surface in suspendable form, but calculation indicates that for this pathway to be as hazardous as ingestion all the wastes would have to be dispersed through it. Wastes dispersed at the surface would also constitute an external-radiation hazard through their emission of gamma rays, but another calculation demonstrates that this hazard too is less than that of ingestion.

None of the estimates I have given so far takes into account the possible release of nuclear wastes through human intrusion. Let us therefore consider that

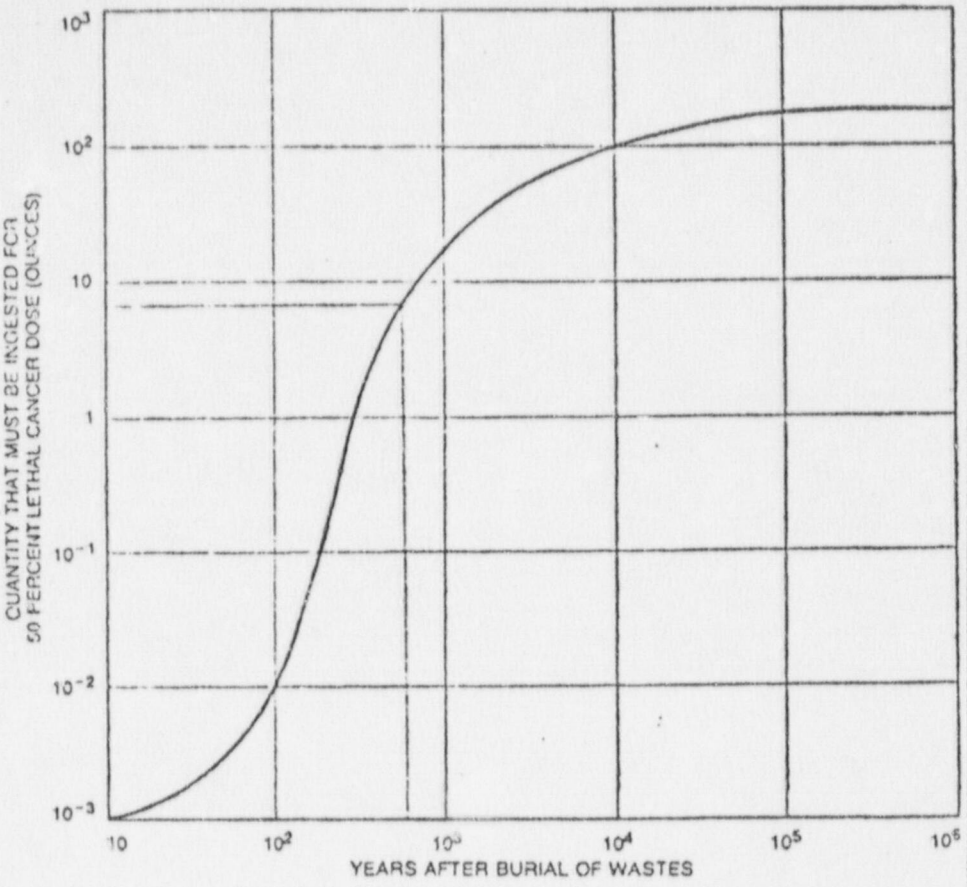


COMPARISON OF HEALTH HAZARDS presented by high-level radioactive wastes from nuclear reactors with those of other poisonous substances routinely used in large quantities in the U.S. demonstrates that there is nothing uniquely dangerous about the nuclear wastes. Moreover, the author notes, "chemical poisons are not carefully buried deep underground as is the plan for the nuclear wastes; indeed, much of the arsenic is used as a herbicide and hence is routinely scattered around on the ground in regions where food is grown."

possibility. Buried waste would not be an attractive target for saboteurs because of the great amount of time, effort, equipment and personal danger that would be needed to remove it. Only release through inadvertent human intrusion, such as drilling or mining, needs to be considered. The current plan is to retain Government ownership of repository sites and to maintain surveillance and long-lasting warning signs, so that this problem would exist only if there were a total collapse of civilization. One of the criteria for the choice of a repository site is that there be a lack of valuable minerals and the prospect of discovering them. (Indeed, the principal factor delaying the development of the proposed New Mexico site is the possibility that it may hold potash deposits.) Nevertheless, if there were random exploratory drilling in the area at the rate of the current average "wildcat" drilling for oil in the U.S., the effects would still be much less than those of release in ground water. If there were mining in the area (presumably for minerals not now regarded as valuable), the operations would have to be on a scale approaching that of the entire current U.S. coal-mining enterprise before their effects would equal those of ground-water release.

Wastes buried in salt might seem to be a poor risk against the possibility of intrusion by mining, since salt is widely mined. The quantity of salt underground, however, is so huge that on a random basis any given area would not be mined for tens of millions of years. Again the probability of release through this pathway is comparable to that through ground water, except that here the wastes are in insoluble form and, if ingested, much less likely to be taken up by the body. A pathway would seem to exist through the use of salt in food, but only 1 percent of the salt mined in the U.S. is so used, and it is purified by allowing insoluble components to settle out. Thus exposure through this pathway would be reduced roughly to that through the use of salt in industrial processes. All in all, then, the probability of the release of stored nuclear wastes through human intrusion is less than that of their release through ground water.

It is often said that by producing radioactive wastes our generation places an unjustifiable burden on future generations in requiring them to guard against their release. Here it should first be recognized that the estimate of the health effects of nuclear wastes I have given—an eventual 1 fatality for each year of all nuclear power—was based on no protection at all. The estimate was derived from a comparison with radium, which is with us in this country's [illegible] deposits to prevent them from



DANGER FROM INGESTED WASTES can be shown to be very great at first but much less after a few hundred years. As this graph shows, after 600 years a person would have to ingest approximately half a pound of the buried wastes to incur a 50 percent chance of contracting a fatal cancer. Such a calculation suggests that although it is obviously very important to isolate such wastes from human contact for a few hundred years, it is less imperative thereafter.

moving operations. Therefore guarding buried nuclear wastes would only serve to reduce that already small toll.

Even if guarding should be considered advisable, it would not be very expensive or difficult. Once the repository is sealed the guarding would consist only in making periodic inspections of the surface area—about 10 miles square for the wastes from 1,000 years of all-nuclear power—to make sure that the warning signs are in good order and to see that no one has unexpectedly undertaken mining or deep drilling. In addition occasional water samples might be drawn from nearby rivers and wells to check for increased radioactivity. Hence keeping watch on the wastes accumulated over 1,000 years of all-nuclear electric power in the U.S. would provide a job for only one person at a time.

Perhaps the best way to put into perspective the burden we are placing on our descendants by storing nuclear wastes is to compare that burden with others we are placing on them. Probably the worst will be the burden resulting from our consumption of the earth's high-grade mineral resources. Within a few generations we shall have used up all the world's economically recoverable copper, [illegible], lead and [illegible]

options for our descendants to exploit for materials. Moreover, we are burning hydrocarbons—coal, oil and gas—at the rate of millions of tons each per day, depriving our descendants not only of fuels but also of feedstocks for making plastics, organic chemicals, pharmaceuticals and other useful products. These burdens are surely far heavier than any conceivable burden resulting from the appropriate burial of nuclear wastes.

What makes this comparison particularly pertinent is that the only way we can compensate our descendants for the materials we are denying them is to leave them with a technology that will enable them to live in reasonable comfort without these materials. The key to such a technology must be cheap and abundant energy. With cheap and abundant energy and a reasonable degree of inventiveness man can find substitutes for nearly anything: virtually unlimited quantities of iron and aluminum for metals, hydrogen for fuels and so on. Without cheap and abundant energy the options are much narrower and must surely lead back to a quite primitive existence. It seems clear that we who are alive today owe our descendants a source of cheap and abundant energy. The only such source we can now guar-

[illegible] controlled fusion.