Chapter 2
Radioactive Waste: Its Nature and Management

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Chapter 2
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Various forms of radioactive waste are produced during the preparation, use, and management of reactor fuel for the commercial production of electricity and for defense-related nuclear activities. Radioactive waste is also produced in various industrial and institutional activities, including medical research and treatment. The focus of this assessment is the management of the highly radioactive waste produced during the generation of commercial nuclear power.

In a nuclear powerplant, heat released when atomic nuclei in reactor fuel are made to split (fission) is used to produce steam that powers an electricity-producing generator. This process creates not only the heat needed for generating electricity, but also radioactive byproducts that are present in the "spent" (used) fuel discharged from the reactor. The term ***high-level radioactive waste is*** used in this report to refer to either the high-level waste material produced if the unused radioactive byproducts are separated from the spent fuel for disposal or the spent fuel itself if it is discarded directly as waste. This chapter will describe the nature of radioactive waste; its sources, amounts, and hazards; and the technical and institutional aspects of its management.

NATURE OF RADIOACTIVE WASTE

Nuclear Reactions

Radioactivity

Some atoms, known as radioisotopes, are unstable (radioactive) and undergo a spontaneous decay process, emitting radiation until they reach a stable form. Called ***decay,*** this stabilizing process takes, depending on the type of atom, from a fraction of a second to billions of years. The rate of radioactive decay is measured in half-lives, the time it takes for half the atoms in a sample to decay to another form. After 1 half-life, half the atoms in a sample are unchanged; after 2 half-lives, one-fourth of the original amount remains unchanged. Thus, after several half-lives only a small fraction of the sample's original atoms remain unchanged; yet the sample may still be quite radioactive—either because some atoms have not decayed or because some atoms have decayed to other radioisotopes.

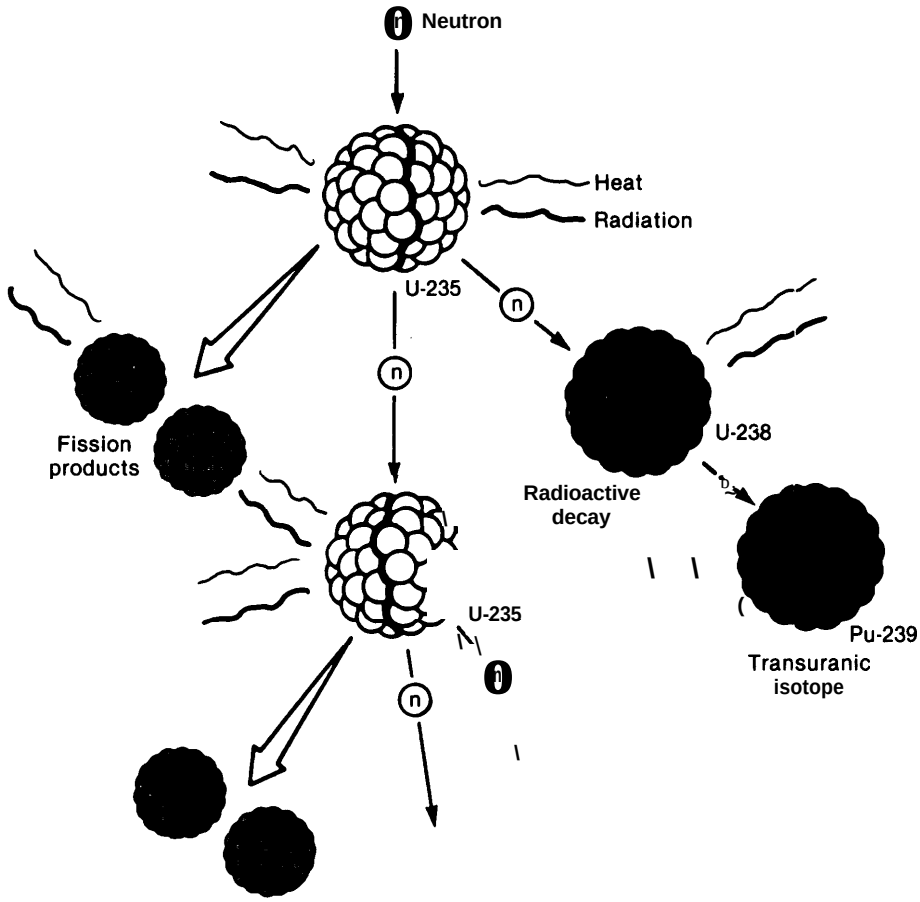
The intensity of radioactivity ***in a*** sample is determined by the number of emissions, or disintegrations, per second and usually is measured in curies (1 curie = 37 billion radioactive disintegrations per second). From this standard, three common measurements are derived: the nanocurie (1 billionth of a curie), the microcurie (1 millionth of a curie), and the megacurie (1 million curies). Elements with shorter half-lives-like thorium-234 at 24.1 days—are more radioactive than those with longer half-lives—like uranium-238 (U^{238}) at 4.5 billion years—because the shorter the half-life, the more atoms in a sample of the element decay and emit radiation each second.

Fission

Some radioisotopes are fissile-i.e., they can split when neutrons are added to their nuclei or, in some circumstances, spontaneously. Only one fissile element, uranium-235 (U^{235}), exists in nature. Others are produced artificially when ' 'fertile' atoms such as U^{238} absorb neutrons and subsequently decay to fissile isotopes, like plutonium-239 (Pu^{239}) (see fig. 2-l).

During fission, the nucleus splits into two smaller nuclei called fission products, releasing neutrons, radiation, and heat in the process. The released

Figure 2-1.- Fission Process



SOURCE: Office of Technology Assessment.

neutrons can cause nearby atoms to split, and, given enough fissionable material, an ongoing chain reaction can begin. Such a chain reaction generates heat, primarily from the fission process itself and secondarily from the subsequent decay of the radioactive fission products. Uncontrolled, a nuclear chain reaction could end in an atomic explosion. In a nuclear reactor, however, the fissile atoms (U^{235}) are diluted with many non-fissile atoms (U^{238} and other atoms that absorb neutrons so that the chain reaction is maintained but cannot produce an explosion.

Produced in great quantities in a reactor are: 1) transuranic (TRU) isotopes—atoms that absorb enough neutrons to become heavier than uranium atoms, and 2) fission products—isotopes lighter than uranium atoms that are formed by the fission of an atom. Generally, fission products are more radioactive and have short half-lives, from seconds to decades. TRU isotopes can have half-lives as long as millions of years.

Effects of Radiation

Highly energetic radiation can penetrate human tissue and other matter, triggering molecular and chemical changes that can result in damage or death to cells, tissue, or even the entire organism. The extent of the damage depends on the type of radiation, the length of exposure, the distance from the radiation source, and the susceptibility of the exposed cells. The principal concern about radioactive waste is that it might be released into the environ-

ment and be taken into the body through drinking water or food supplies, thus placing a source of radiation very close to vulnerable tissues.

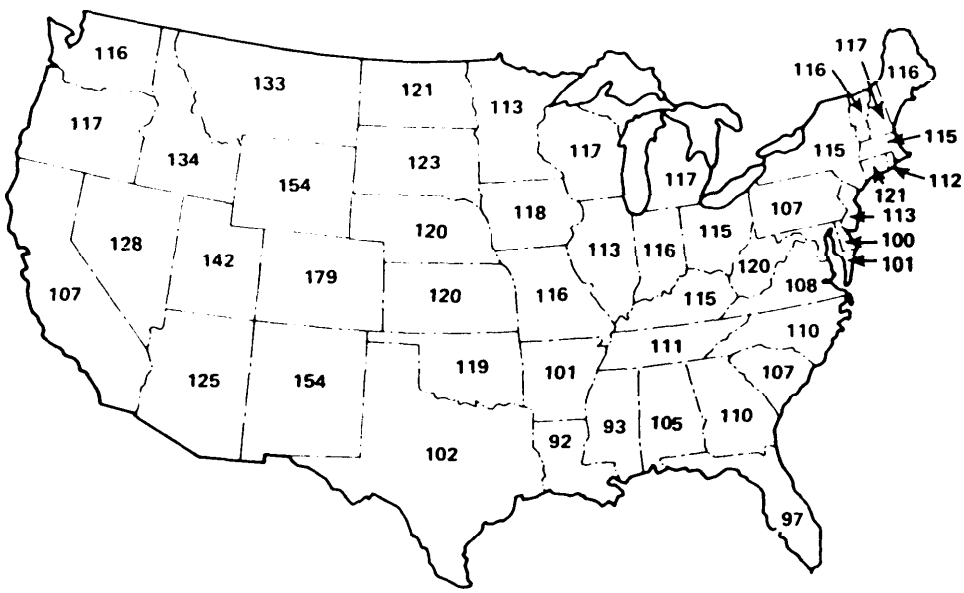
Radiation exposure is measured in reins, a unit that indicates the amount of radiation received and the biological implications of the exposure. In a year's time, the average person in the United States is exposed to approximately 160 millirems (thousandths of a rem) of radiation, two-thirds of which comes from natural background sources such as mineral ores, cosmic radiation from outer space, and the radioactive carbon and potassium found in most living things. Natural background radiation from outer space increases with land elevation and is about twice as high for a person living in Denver, Colo., as for a person living at sea level (see fig. 2-2). Slightly less than one-third of this annual exposure comes from medical irradiation (X-rays).

An acute radiation dose—50 reins or more over a 24-hour period—results in radiation sickness within 1 hour to several weeks. The chance of death is nearly 100 percent from a dose above 1,000 reins, 90 to 100 percent from 600 to 1,000 reins, and 50 percent from 400 reins. With a dose of 200 reins or less, survival is almost certain. Other consequences range from gastrointestinal and circulatory system disorders to long-term effects like cancer, birth abnormalities, genetic defects, and poor general health. Long-term effects also result from chronic exposure to low-level radiation. In radioactive waste disposal, the concern centers on the possibility of such chronic low-level exposures caused by escaped waste, rather than acute doses.

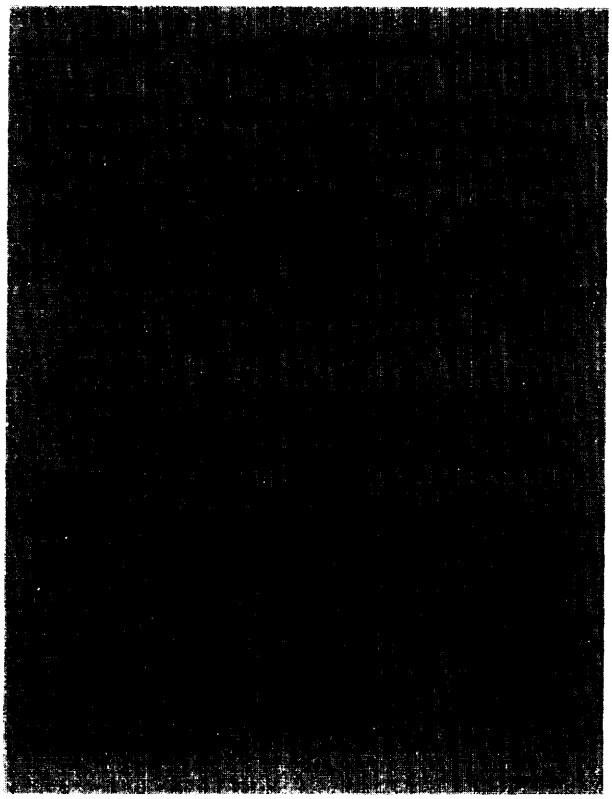
The Nuclear Fuel Cycle

Several kinds of radioactive waste are generated during all stages of the nuclear fuel cycle—from the preparation of reactor fuel (front-end of the cycle), through the operation of the reactor, to the storage and possible reprocessing of spent reactor fuel (back-end of the cycle). The following activities comprise the nuclear fuel cycle for uranium both as originally envisioned and as now in use in the 74 operating commercial nuclear powerplants in the United States.

Figure 2-2.—Natural Background Radiation Varies From State to State (millirem per year)



SOURCE: A. W. Klement, Jr., Estimates of *Ionizing* Radiation Doses *in the* United States, *1960-2000*, Environmental Protection Agency Publication No. ORP/CDS 72-1, 1972.



Front End of the Fuel Cycle: Preparation of Reactor Fuel

MINING

Uranium ore, the raw material of reactor fuel, is extracted from surface and underground mines, producing low-level radioactive dust and releasing radioactive gas.

MILLING

At mills the uranium ore is crushed and ground, then chemically treated to extract uranium oxides and produce yellowcake (USOB). The process generates low-level airborne wastes and a large volume of slightly radioactive mill tailings.

CONVERSION AND ENRICHMENT

Yellowcake is converted to uranium hexafluoride gas (UFG), leaving low-level waste solids. At enrichment facilities the concentration of U^{235} in the gas is increased from the 0.7 percent found naturally in uranium ore to the 3 to 4 percent needed for fuel for the reactors in use in the United States. In the process, low-level airborne and liquid waste are produced.

FUEL FABRICATION

The enriched UFG gas is then converted to solid uranium dioxide (UO_2), shaped into pencil eraser-size pellets, and loaded into 12-ft long metal fuel rods. The rods are then sealed, arrayed in fuel assemblies of 50 to 300 rock, and transported to reactors. Low-level gas, liquid, and solid radioactive waste remain.

Reactor Operation

The light-water reactor (LWR) is the principal reactor type in commercial use in the United States.[1] In the LWR, the fuel assemblies are immersed collectively in a coolant (water), where they form the reactor core. The control rods interspersed among the fuel rods control the number of nuclear reactions in the reactor fuel. Heat from fission and, to a lesser extent, from the decay of fission products is used to heat water to steam. In one type of LWR, the boiling-water reactor (BWR), the steam is produced directly from the cooling water surrounding the reactor core. In the other type, the pressurized-water reactor (PWR), the cooling water is pressurized to prevent boiling and is used instead to transmit heat from the core to boil water in a separate steam generator. In both types the steam causes a turbine to rotate, generating the electric power transmitted to consumers. A typical nuclear powerplant produces about 1 million kilowatts (kW), or 1 gigawatt (GWe), of electricity.

After about 3 years, the buildup of fission products and TRU elements in a fuel assembly impedes the efficiency of the chain reaction. When the concentration of U^{235} in the fuel is less than 1 percent, the assembly, considered "spent" fuel, is removed and replaced with fresh fuel. A typical l-GW_e PWR discharges about 60 assemblies, or a total of

[1] Seventy-three of the seventy-four commercial powerplants are LWRS. The one high-temperature gas reactor at Fort St. Vrain, Colo., operates like an LWR but uses helium gas for its coolant. Another type of reactor under consideration for future use is the breeder reactor, designed to produce more fissile material than it uses by converting nonfissile U^{238} in the fuel into plutonium, which would be extracted through reprocessing and recycled as new fuel.

about 27 metric tons (tonnes)[2] of spent fuel, each year, while a 1-GW, BWR discharges about 175 assemblies, or 31 tonnes, annually.[3] Table 2-1 shows the characteristics of BWR and PWR fuel assemblies before and after irradiation in a reactor.

Because of the decay of the fission products and TRU elements, spent fuel is extremely hot and radioactive when it is initially discharged from the reactor. For this reason it is stored in water basins to provide the cooling and radiation shielding that it requires. For example, freshly discharged spent fuel from a PWR generates up to about 221 megacuries of radioactivity and 2.2 megawatts (MW) of thermal heat per tonne.[4] BWR fuel is slightly less hot and radioactive, since it generally has a lower "burnup'—a measure of the amount of the fissile material in the fuel that has been used before discharge, and thus of the amount of radioactive waste products it contains.

The heat output and radioactivity of spent fuel decay rapidly in the first year after discharge, by factors of 216 and 88, respectively, for PWR fuel. The approximately 10 kW of heat emitted per tonne after one year equates to that of one-hundred 100-watt light bulbs. The heat and radioactivity decay less rapidly after the first year, by additional factors of 8 and 6, respectively, by the end of 10 years after discharge.

[2]Note that only the mass of the initial uranium is considered in the measurement of fuel amounts and not the mass of the rest of the assembly. While this report will use the term "tonnes' for simplicity, other terms in common use are MTU (metric tons of uranium), MTHM (metric tons of heavy metal), and MTIHM (metric tons of initial heavy metal). A metric ton, or tonne, is equivalent to 1,000 kilograms, or about 2,205 pounds.

[3]National Research Council, Waste Isolation Systems Panel, *A Study of the Isolation System for Geologic Disposal of Radioactive Wastes* (Washington, D. C.: National Academy Press, 1983), pp. 28-29. See chapter note 1 for further discussion of the amounts of spent fuel produced by the generation of 1 GW-year of electricity.

Table 2-1 .—Physical Characteristics of LWR Fuel Assemblies

	BWR	PWR
Overall assembly length (m) .	4.470	4.059
Cross section (cm)	13,9 x 13.9	21.4 x 21.4
Fuel pin array	8 x 8	17 x 17
Fuel pins/assembly	63	264
Nominal volume/ assembly (m^3)	0.0864	0.186
Assembly total weight (kg) . .	275.7	657.9
Uranium/assembly (kg)		
Initial.	183.3	461.4
Discharge	176.5	441.2
Enrichment (wt% U^{235})		
Initial.	2.75	3.20
Discharge	0.69	0.84
Plutonium/assembly at discharge (kg)	1.54	4.18
Other TRU elements/assembly at discharge (kg)	0.10	0.43
Fission productslassembly at discharge (kg)	5.2	15.7
Average discharge burnup (MW-d/tonne initial uranium)	27,500	33,000
Average thermal power (kW/assembly)		
Discharge.	278	1,017
1 year after discharge	1.3	4.7
10 years after discharge . .	0.2	0.5
Average radioactivity (megacuries)assembly)		
Discharge. . ., ...	28,3	102.0
1 year after discharge	0.35	1.16
10 years after discharge . .	0.06	0.18

SOURCE: Derived from data presented in A. G. Croff and C. W. Alexander, *Decay Characteristics of Once-Through LWR* and *LMFBR* Spent *Fuels,* High. *Level* Wastes, and *Fuel Assembly* Structural *Material Wastes.* ORNL/ TM-7431 (Oak Ridge, Term.: Oak-Rige National Laboratory, '1980)

Backend of the Fuel Cycle: Spent Fuel Management and Waste Isolation

At present, many of the activities envisioned to treat and manage commercial spent fuel exist in theory, based on extensive experience with defense spent fuel, but not in practice. Thus, deciding what to do with commercial spent fuel and the waste products it contains is often referred to as "closing the back end of the nuclear fuel cycle. The following section provides an overview of the existing and envisioned activities of the back end of the fuel cycle.

REPROCESSING AND RECYCLE

Spent fuel contains much material of no discernible value, as well as uranium and plutonium, over 99 percent of which can be recovered through reprocessing and then recycled for reactor fuel. In the reprocessing operation, spent fuel rods are chopped into pieces and dissolved. From the solution all but 0.5 percent of the uranium and plutonium is extracted. If the recovered uranium were recycled, it would be converted to uranium hexafluoride (UF_6) gas for reuse in producing fresh nu-

[4]A. G. Croff and C. W. Alexander, *Decay Characteristics of Once-Through LWR and LMFBR Spent Fuels, High-Level Wastes, and Fuel-Assembly Structural Material Wastes,* ORNL/TM-7431 (Oak Ridge, Term.: Oak Ridge National Laboratory, November 1980).

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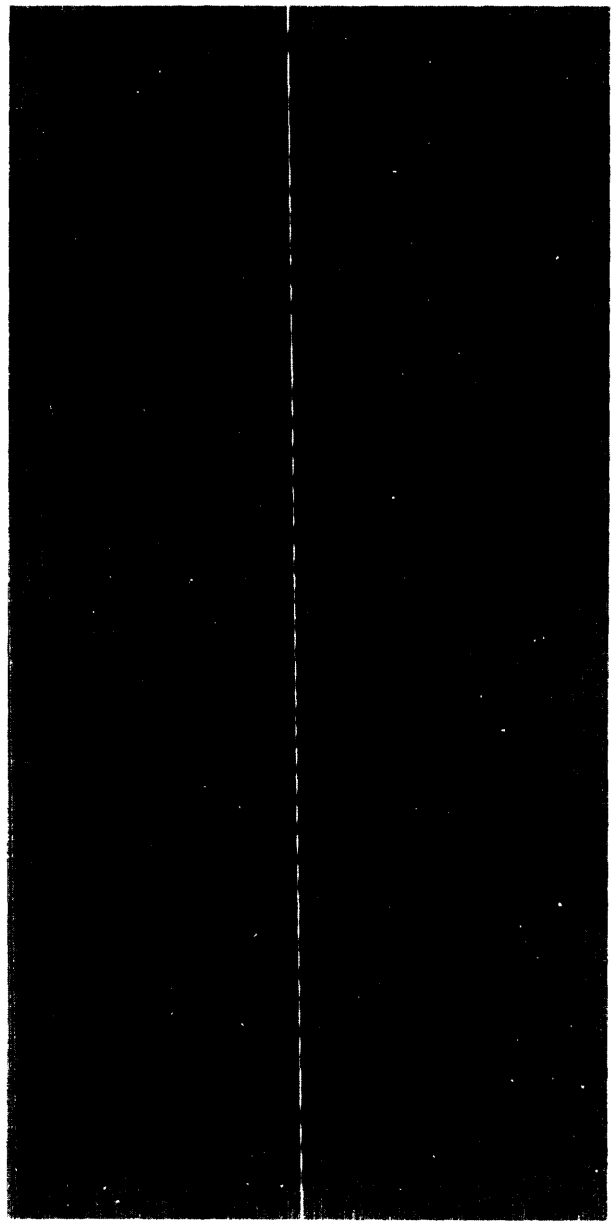
clear fuel. If the recovered plutonium were recycled, it would be converted to plutonium oxide (PuO_2) and combined with uranium to make mixed oxide (MOX) fuel.

The leftover solution from reprocessing, highly radioactive at 10,000 curies per gallon, contains primarily fission products and is defined as high-level waste. It must, by regulation, be solidified before disposal. Any recovered uranium or plutonium that is not recycled must also be disposed of. Both reprocessing and MOX fuel fabrication generate substantial quantities of TRU wastes—materials contaminated with enough long-lived TRU elements to require long-term isolation like high-level waste.

Defense spent fuel—from reactors designed to produce plutonium for weapons and from the powerplants of nuclear naval vessels—routinely is reprocessed to recover plutonium and unused enriched uranium. The nuclear fuel cycle was originally envisioned to include such reprocessing for all commercial spent fuel. However, for economic and political reasons discussed in chapters 3 and 4, no commercial spent fuel is now being reprocessed in the United States. Of the three commercial reprocessing plants originally planned, only the facility at West Valley, N. Y., actually operated (from 1966 to 1972). It closed for modifications and never reopened. The facility at Morris, Ill., had design problems and never opened, and the facility at Barnwell, S. C., has never been completed. Without commercial reprocessing there can be no commercial recycling of uranium or plutonium.

WASTE MANAGEMENT

Nearly all the highly radioactive byproducts produced thus far by commercial nuclear power generation in the United States are contained in the spent fuel that has been discharged by operating reactors. The original expectation that all spent fuel would be reprocessed to recover usable uranium and plutonium, and that the radioactive byproducts would be separated as high-level waste, has not been realized. It now appears possible that at least some spent fuel would be treated as waste and discarded directly without reprocessing, which is often referred to as a "once-through" fuel cycle. Thus, the term high-level ***radioactive waste is*** used in this report to refer to either the high-level waste from reprocessing or the spent fuel itself, if discarded as



waste. Because of the uncertain future of reprocessing, high-level radioactive waste management at present can be seen as including: 1) management of spent fuel until a decision is made about whether to reprocess it, and 2) final isolation of the fission products and unused TRU elements that are now in the spent fuel and that may or may not be separated later.

The high-level radioactive waste management system is a network of facilities for storing spent

fuel and any high-level waste from reprocessing, facilities for final isolation of whichever material is ultimately discarded, and transportation links connecting those facilities with one another and with any reprocessing and recycling activities that ultimately occur. Each of these activities will be described briefly here and discussed at greater length in chapter 3.

Interim Storage.—When the reactors that now are operating or under construction were designed, it was assumed that spent fuel discharged from the reactor would first be stored in water-filled storage basins at the reactor for about 6 months to dissipate the thermal heat and allow the decay of some of the short-lived fission products. It was expected that the spent fuel then would be reprocessed and the resultant high-level liquid waste solidified and shipped to a Federal repository for final isolation. Since no commercial reprocessing is being done, and no final waste repository exists that could allow spent fuel to be discarded directly, practically all spent fuel remains in storage basins at reactor sites. Modifications are being made where possible to increase the amount of spent fuel that can be stored in these basins, which originally were designed with a capacity for only 3 to 5 annual discharges of spent fuel. Transshipment (shipping spent fuel from one reactor site for storage in a basin at another site) and new storage technologies now under development promise additional relief (see ch. 3).

Because of the delays that have already occurred in the availability of both reprocessing and final repositories, it appears likely that most (more than 90 percent) of the spent fuel generated in this century will still be in temporary storage facilities at the end of the century—even if reprocessing or direct final isolation of spent fuel begins in the 1990's.[5] Thus, for the next several decades, waste management will consist primarily of interim spent fuel storage. Any reprocessing that occurs would simply convert some of the stored spent fuel into separated uranium and plutonium and waste of various types, all of which would require interim storage until final isolation of the waste and recycling (or perhaps direct final isolation) of the plutonium and uranium.

Final Isolation.—Final isolation, the last step in radioactive waste management, is intended to limit or prevent the release of highly radioactive byproducts of nuclear fission into the environment for the thousands of years it takes for these byproducts to decay to low levels. There is no licensed final isolation facility for high-level radioactive waste in the world.

There are two conceptually distinct technological approaches to waste isolation that could be used for final isolation: ***storage*** and ***disposal.*** Briefly, disposal is isolation that relies primarily on natural (environmental) and manmade barriers, does not permit easy human access to the waste after its final emplacement, and does not require continued human control and maintenance. Storage is isolation that permits easy access to the waste after emplacement and requires continued human control and maintenance to guarantee isolation. Thus, disposal is always designed to provide final isolation, while storage may be intended for either interim or final isolation.[6]

Although some have viewed long-term storage as a viable final measure for managing high-level radioactive waste,[7] Federal Government policy since the 1950's has been directed primarily toward the development of disposal facilities for final isolation. However, storage will of necessity be the only form of waste management until the capacity for disposal is available and may continue to be a major part thereafter—either because it is desirable to defer disposal even after facilities are available (e.g., to maintain easy access to spent fuel for possible reprocessing) or simply because an extended period would be required to eliminate the backlogs of waste built up in storage by the time disposal operations begin.

In the United States, Government efforts are focused on the development of mined, geologic re-

[5] U. S. Department of Energy, *Spent* Fuel *and* Radioactive Waste *Inventories, Projections, and Characteristics, DOE/RW-0006,* September 1984, *fig. C .2,* p, *284,* and *fig. C .3,* p. *285.*

[6] Much of the debate about radioactive waste management has been clouded by blurred and shifting distinctions between storage and disposal. In particular, storage is often defined as emplacement with the intent to recover the material, while disposal is defined as emplacement with no intent to recover, a distinction which is based on a subjective criterion—the intention of the person emplacing *the waste*—that cannot be directly observed from inspection of the facility receiving the waste. In contrast, the definitions used in this report are based on the observable design characteristics of the system under consideration.

[7] *See app. A, p. 206.*

positories for disposal, although other disposal alternatives, such as emplacement in the seabed, have been and probably will continue to be considered. The Nuclear Waste Policy Act of 1982 (NWPA) commits the Federal Government to begin operation of a geologic repository by the beginning of 1998. Until the mid-1990's, the activities associated with disposal will involve locating and evaluating suitable repository sites and developing disposal technology (see ch. 3).

Transportation.—Linking the stages of the nuclear fuel cycle are transportation activities that also generate wastes, primarily from the contamination of transport containers by the transported materials. Because most commercial spent fuel is now stored at reactor sites, very little transportation of commercial spent fuel occurs in this country at this time, although some transshipment does take place.

Amounts of Radioactive Waste

High-Level Waste From Reprocessing

The principal source of high-level waste at present is the reprocessing of spent fuel from defense nuclear activities. Such waste is stored as liquid, salt cake, and sludge in near-surface tanks or as calcined solids in underground bins at Federal installations at the Hanford Reservation (Washington), the Savannah River Plant (South Carolina), and the Idaho National Engineering Laboratory. A small amount of high-level waste, from reprocessing about 234 tonnes of commercial spent fuel, is stored at the Nuclear Fuel Services facility in West Valley, N.Y. Table 2-2 shows the existing and projected amounts of high-level radioactive waste, in terms of volume, radioactivity, and thermal power (the rate of heat output). Note that if reprocessing of spent fuel from commercial power reactors is undertaken, it could rapidly become the dominant source of high-level waste.

Spent Fuel

By the end of 1983, about 10,000 tonnes of spent fuel was in storage in water basins at nuclear power reactors in the United States. Commercial spent fuel was being generated at a rate of about 1,400 tonnes/yr in 1983, and the Department of Energy (DOE) estimates the rate will reach about 2,300 tonnes/yr by 2000. This increase would result in a total of about 21,000 tonnes by the end of 1990 and 43,000 tonnes by the end of 2000.[8] The currently operating reactors can be expected to produce about 55,000 tonnes of spent fuel, or about 196,000 fuel assemblies, over their operating lifetimes. [8]

*U. S. Department of Energy, op. cit.
'Projections supplied by the U.S. Department of Energy. See app. F.

Table 2.2.-Current and Projected Inventories of Defense and Commercial High. Level Radioactive Waste

	End of calendar year 1983			End of calendar year 2000		
Material	Volume[a] (cubic meters)	Radioactivity (megacuries)	Thermal power (kilowatts)	Volume[a] (cubic meters)	Radioactivity (megacuries)	Thermal power (kilowatts)
High-Level waste:						
Defense:						
Savannah River.	111,000	776	2,280	83,000	699	2,040
Idaho	10,000	65	190	14,000	241	726
Hanford	203,000	474	1,380	217,000	430	1,256
Defense total	324,000	1,315	3,850	314,000	1,370	4,022
Commercial:						
West Valley	2,000	35	104	—	23	68
. . . . .	0	0	0	300	324	1,106
Spent fuel:						
Cumulative	4,600 (10,000 tonnes)	12,900	48,000	19,400 (42,800 tonnes)	35,700	131,000
Annual	620 (1,400 tonnes)	7,400	29,400	1,050 (2,320 tonnes)	13,700	55,300

[a]Spent fuel volumes calculated Using a nominal volume of 0.0864 m³ for a BWR assembly and 0.186 m³ for a PWR assembly. (DOE/NE-0017/2, table 1.9, p. 32)
[b]Assumes a first reprocessing plant starts operation in 1995 at 500 tonne/yr through 2004.

SOURCE U S Department of Energy, *Spent Fuel and Radioactive Waste /inventories, Projections, and Characteristics*, DOE/RW-0006, Washington, D.C., 1984.

The total volume of existing and projected commercial spent fuel discharges is shown in table 2-2. Because most of the high-level defense waste is relatively dilute, and has not been concentrated and solidified, the current inventory of commercial spent fuel represents only about 1 percent of the volume of such defense waste. However, the current inventory of spent fuel already has a considerably higher level of radioactivity and heat output than the defense waste, and the annual discharge from the currently operating reactors exceeds the total defense waste inventory in those two measures. This is very significant for waste management, since the heat output is a more important factor than the physical volume of the waste in determining the amount of repository space needed for disposal.

Hazards of Radioactive Waste

Comparison of Nuclear Waste to Uranium

While the original uranium in reactor fuel is itself a low-level health hazard, many of the radioisotopes produced by the fission of uranium or the conversion of uranium into transuranic elements are more toxic. First, most of these radioisotopes have shorter half-lives than that of uranium. Some of the fission products are so short-lived that about 80 percent are gone by the time the spent fuel is removed from the reactor.[10] This means that they undergo more radiation-producing decays per second than the original ore; hence, their radioactivity per gram of material is much higher. Second, some of the waste products are more biologically dangerous than the original uranium because of the intensity of radiation emitted and because they stay in the body longer, once ingested, or concentrate in particularly vulnerable organs. For example, 1 curie of the transuranic isotope americium-241 (Am^{241}) is estimated to be about 10 times as hazardous as 1 curie of U*38.“

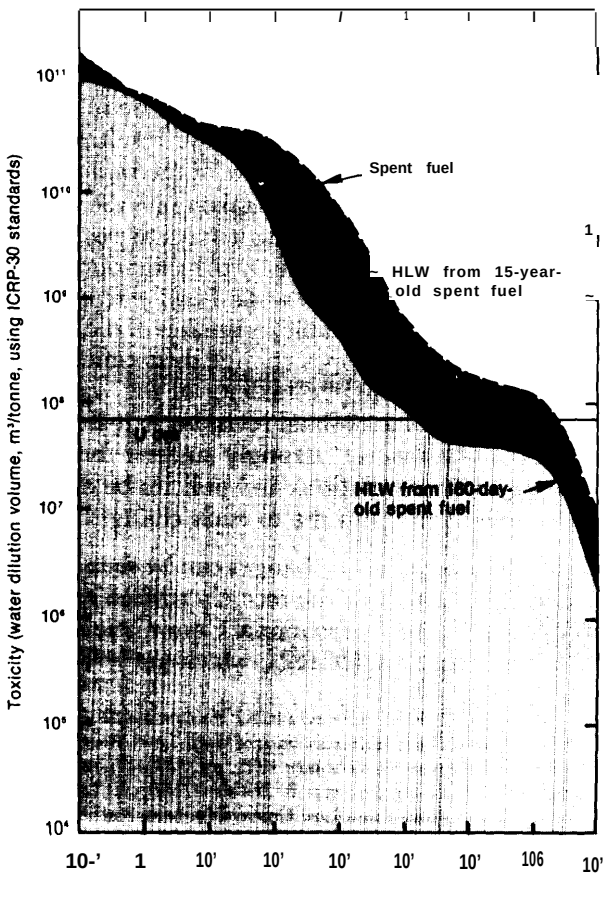
The hazard posed by radioactive waste is often discussed in terms of an overall measure, or index, of the toxicity of the waste. A commonly used measure of toxicity is the water dilution volume (WDV), defined as the volume of water (usually measured in cubic meters) that would be required to dilute the waste to acceptable drinking standards. Figure 2-3 shows the WDV for 1 tonne of spent fuel, for the high-level waste that would result if the spent fuel were reprocessed both 160 days and 15 years after discharge from the reactor, and for the uranium ore needed to produce 1 tonne of fuel. Those WDVS are calculated using standards based on recent data for toxicity of various radioisotopes. Figure 2-2 shows that it would take about 1 million years for high-level waste from reprocessing 15-year-old spent fuel to fall below the toxicity of the

[10] Bernard L. Cohen, “High-Level Radioactive Waste From Light-Water Reactors, ” Reviews *of Modern Physics, vol. 49, No.* 1, January 1977, pp. 1-19.

[11] International Commission on Radiation Protection, *Limits for Intakes of Radionuclides by Workers,* ICRP-30 *(New* York: Pergamon Press, 1979).

[12] 1bid.

Figure 2-3.-Toxicity of Spent Fuel, High-Level Waste, and its Parent Uranium Ore



SOURCE: Data supplied by Oak Ridge National Laboratory.

original ore. The toxicity of the unreprocessed spent fuel would fall below that of the original ore after about 3 million years. The figure also shows that following the decay of most of the fission products in the first few hundred years, the toxicity of spent fuel would exceed that of the waste from reprocessing 15-year-old fuel by a factor of from 2 to 5.

Such comparisons of spent fuel and high-level waste with each other and with uranium ore in terms of a simple toxicity index should be used only with great caution, for several important reasons. First, these comparisons may be somewhat misleading since a toxicity index such as the WDV is only a crude measure of the ***potential*** hazard to humans. It will greatly overestimate the actual hazard posed by the waste, which must take into account how likely it is that the waste will be released into the biosphere and eventually be ingested by humans. A discussion of the hazard from radioactive waste that considers the barriers between the waste and human beings is contained in chapter 3.

Second, there are substantial uncertainties in the estimates of the risk of cancer per curie of any radioisotope ingested into the body, resulting from uncertainties about: 1) the fate of the radioisotope in the body (what fraction is taken into the system, where it goes, and how long it stays there), and 2) how much damage is done by the radiation the radioisotope emits.[13] As new data and extrapolation methods become available, estimates of the toxicity of various radioisotopes change over time. These uncertainties about the toxicity of the waste and the likelihood of additional revisions in toxicity estimates in the future[14] strongly suggest that waste management regulations and policies be designed to be relatively immune to such changes.

The impact of such changes can be seen by considering the effects of the recently revised estimates published by the International Commission on Radiation Protection (ICRP), which are reflected in figure 2-2. Except for a few recent studies,[15] most published analyses use older estimates such as those underlying Nuclear Regulatory Commission (NRC) standards for protection of the general public, contained in the Cede of Federal Regulations (CFR).[16] The effect of the recent changes is shown in figures 2-4 and 2-5, which display the toxicities of spent fuel and high-level waste from reprocessing that spent fuel 160 days after discharge from the reactor, calculated using both the ICRP and the CFR standards. These figures show that the

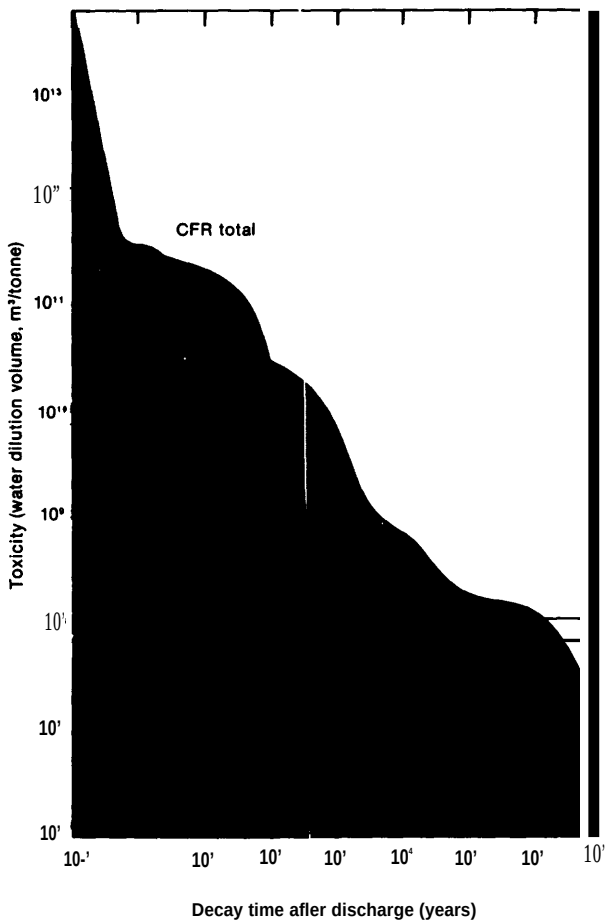
[13] Bernard L. Cohen, "Effects of ICRP Publication 30 and the 1980 BEIR Report on Hazard Assessments of High-Level Waste," *Health Physics, vol.* 42, No. 2, February 1982, pp. 133-143; and National Research Council, op. cit., app. B. See also Charles E. Land, "Estimating Cancer Risks From Low Doses of Ionizing Radiation, *Science, vol.* 209, September 12, 1980, pp. 1197-1203.

[14] A discussion of the possible need for further revisions of the ICRp-30 estimates of the toxicity of Np^{237} is found in Bernard Cohen, "Effects of Recent Neptunium Studies on High-Level Waste Hazard Assessments," *Health Physics, vol. 44, No. 5,* May 1983, pp. 567-569.

[15] Cohen, "Effects of ICRP 30;" National Research Council, op. cit.; A. G. Croff, "Potential Impact of ICRP-30 on the Calculated Risk From Waste Repositories, *Transactions of the American Nuclear Society, vol.* 39 (1981), pp. 74-75.

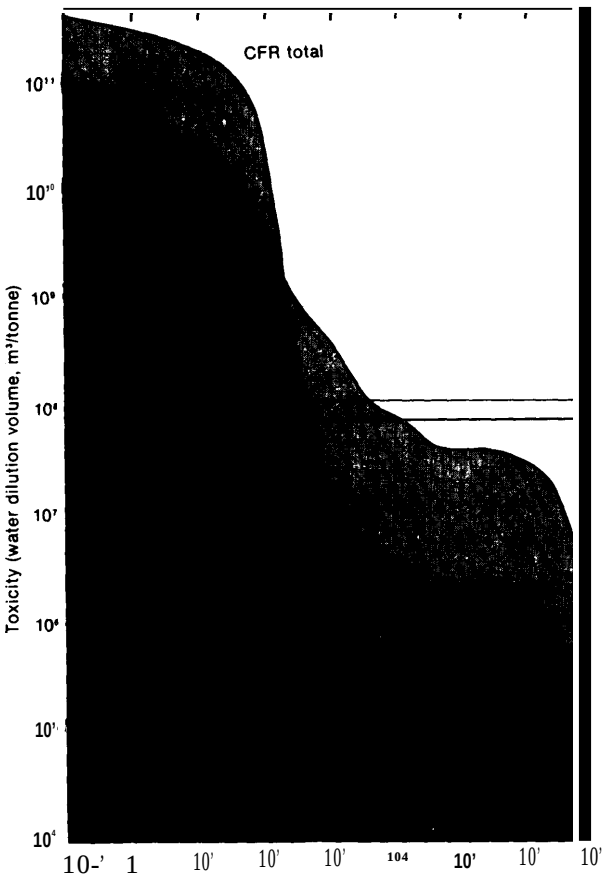
[16] 10 CFR 20, app. B, table II.

Figure 2-4.—Toxicities of PWR Spent Fuel and Its Parent Uranium Ore



SOURCE: National Research Council, A *Study of the Isolation System* for Geologic *Disposal of Radioactive Wastes,* 1983.

Figure 2=5.-Toxicities of PWR High-Levei Waste and its Parent Uranium-Ore



SOURCE: National Research Council, *A Study of the* Isolation *System for Geologic Disposal of Radioactive Wastes,* 1983.

ICRP estimates decrease the toxicity of both spent fuel and high-level waste for the first few hundred years, but increase it in the long-run, with a greater increase for high-level waste than for spent fuel. For example, the amount of time it takes for each to decay to the toxicity of uranium ore is increased—from about 7,000 years to about 3 million years for spent fuel, and from about 400 years to about 20,000 years for high-level waste.

Third, comparisons between the toxicity of spent fuel and high-level waste from reprocessing are also sensitive to the underlying assumptions regarding reprocessing and recycle of the separated plutonium that affect the actual radionuclide content of the high-level waste. For example, the toxicity of high-level waste is highly dependent on the assumed delay in reprocessing spent fuel after it is discharged from the reactor. The longer the delay, the less the difference between the toxicity of the resulting high-level waste and the original spent fuel. Delay allows 14-year-half-life plutonium-241 (Pu^{241}) in the spent fuel to decay into Am^{241}, which will be separated into the high-level waste. Am^{241} and its decay product neptunium-237 (Np^{237}) are the principal contributors to the long-term toxicity of both spent fuel and high-level waste.

This effect can be seen by comparing the two curves for high-level waste shown in figure 2-3. These figures show that increasing the delay before reprocessing from 160 days to 15 years increases the time required for the toxicity of the high-level waste to decrease to that of the original ore from about 20,000 years to about 1,000,000 years. Most published comparisons of the toxicity of spent fuel and high-level waste assume that reprocessing occurs a short time (from 150 days to about 1.5 years) after discharge from the reactor, which was originally expected to be the normal case for operation of commercial reactors with recycle. This tends to maximize the difference in toxicity between the spent fuel and the resulting high-level waste. However, the delays that have already occurred in the initiation of large-scale commercial reprocessing make it unlikely that fuel younger than 15 years old would be routinely reprocessed in the United States for decades after reprocessing began. Thus, the curve for high-level waste from 15-year-old spent fuel in figure 2-3 represents a more realistic estimate of the toxicity of the high-level waste that might actually be produced by reprocessing commercial spent fuel in the United States during this century.

Finally, the radionuclide content, and thus the toxicity, of high-level waste will depend heavily on the extent to which the plutonium that is separated from the spent fuel during reprocessing is recycled in MOX fuel. The reason that high-level waste is

[17] Earlier repressing alone, unaccompanied by early recycle of the plutonium, would not avoid this effect, since the plutonium-241 in the separated plutonium would continue to decay into americium-241 which would have to be disposed of in high-level waste sooner or later. While rapid recycle of the plutonium could fission the plutonium-241 before it could decay, recycle itself complicates the waste disposal task in ways that could offset this advantage. This is discussed further in chapter 3.

[18] National Research Council, op. cit., p. 34.

less toxic than the spent fuel from which it is derived is that reprocessing removes practically all of the plutonium, which not only is highly toxic itself, but also decays to form other toxic radioisotopes. However, unless that plutonium is recycled and destroyed by fission in a reactor, it would eventually have to be disposed of in addition to the high-level waste. In other words, reprocessing by itself simply separates the plutonium from the fission products and other TRU elements in the spent fuel, but does not eliminate it. The additional step of recycling the plutonium would be required to reduce the amount of plutonium that must ultimately be disposed of. However, plutonium recycle increases the toxicity of the resulting high-level waste compared to that produced from reprocessing fuel containing only uranium, since it increases the amounts of important transuranic elements in the waste. [19] As a result, the net reduction in waste toxicity that will result from reprocessing and recycling will be less than that implied by comparisons (e. g., those shown in fig. 2-3) which consider only the high-level waste resulting from fuel that contains only uranium.

Comparison of Radioactive and Other Toxic Waste

Comparing radioactive waste to other hazardous industrial waste provides some perspective on the problem of radioactive waste management. [20] Hazardous wastes include organic materials (e. g., chlorinated hydrocarbons) and inorganic chemical components—almost all of which, like radioactive waste, are manmade and do not exist in the natural environment—and metals, such as barium and arsenic, which occur naturally, but usually in chemically bound forms. Both radioactive and other toxic wastes can cause cancer, birth defects, and genetic mutations, although the causal relationships for such effects may be better understood in the case of radioactive materials [21]

Unlike many toxic organic and inorganic compounds, radioactive waste cannot readily be detoxified or destroyed .22 As a result, it must be isolated from the environment until it decays spontaneously to low levels of radioactivity. Because radioactive waste eventually decays, it is unlike some organic and inorganic compounds, which persist indefinitely unless some treatment is applied to them, and unlike the toxic metals, 'which persist forever, although they too can be stabilized or immobilized to render them relatively harmless. This spontaneous decay, however, produces the radiation that makes the material toxic and releases heat. Both the radiation and the heat complicate the task of disposal (see ch. 3).

The amount of high-level radioactive waste generated each year is much less than the amount of other hazardous wastes. In 1983 about 1,400 tonnes of spent fuel were generated compared to 255 million to 275 million tonnes annually of other hazardous wastes .23 On the other hand, the cost of disposing of the small amount of radioactive waste is much higher than for other hazardous waste, because of the differences in disposal techniques that must be used. The current cost estimate for disposal of spent fuel or equivalent reprocessed waste in a deep geologic repository is about $125,000 per tonne [24] compared to estimates of up to $240 Per tonne for shallow landfill disposal of other hazardous wastes and up to $791 per tonne for treatment of such wastes .25 Considering that the generation

19 For example, Am, which is a major contributor to long-term toxicity both directly and through daughter Np^{237}, would be increased about threefold by plutonium recycle in light-water reactors. See National Research Council, op. cit., pp. 289-290. See the analysis of reprocessing in ch. 3, for further discussion of the effects of reprocessing time and plutonium recycle on the overall high-level waste management problem.

20 For a detailed analysis of the problems of hazardous waste management, see *Technologies and Strategies for Hazardous Waste Control* (Washington, DC.: U.S. Congress, Office of Technology Assessment, OTA-M - 196, March 1983). For a more extensive comparison between nuclear and nonnuclear hazardous wastes, see James P. Murray, Joseph J. Barrington, and Richard Wilson, "Risks of Hazardous Chemical and Nuclear Waste: A Comparison, Discussion Paper E-82- 11, Energy and Environmental Policy Center, Harvard University, November 1982.

21 Land, op. cit.; and Thomas H. Maugh, 11, "Chemical carcinogens: How Dangerous Are Low Doses?" *Science, vol.* 202, Oct. 6, 1978, pp. 37-41.

22 By bombarding radioactive waste with neutrons, some of the long-lived, highly toxic transuranic elements can be split, leaving fission products with short half-lives that decay much more rapidly. However, this docs not now appear to be a practical method for reducing the long-term toxicity of radioactive waste. See discussion of "transmutation" in ch. 3. See also, A. G. Croff, J. O. Blomeke, and B. C. Finney, *Actinide Partitioning Transmutation Program Final Report, I: Overall Assessment,* ORN .-5566 (Oak Ridge, Term.: Oak Ridge National Laboratory, June 1'180),

23 Office of Technology Assessment, op. cit., p. 3.

24 U. s. Department of Energy, *Report on Financing the Disposal of Commercial Spent Nuclear Fuel and Processed High -Level Radioactive Waste,* DOE/S-0020, June 1983, p. 14.

25 Office of Technology Assessment, op. cit., table 34, p. 196.

of about $10 million worth of electricity produces only 1 tonne of spent fuel,[26] it is possible to spend such a large amount per tonne to dispose safely of spent fuel, or high-level waste from that spent fuel, without materially affecting the overall cost of nuclear electricity.

Because radioactive waste is more tightly controlled and regulated than other hazardous wastes, the location and characteristics of virtually all radioactive waste are known,[27] and there is little chance of illegal or uncontrolled dumping of significant quantities, as sometimes occurs with other toxic waste, Radioactive materials are also relatively easy to detect in small concentrations using readily available instruments such as the Geiger counter; thus, the potential threat of any escaped waste can be checked more easily. In contrast, detection of the many more diverse nonradioactive hazardous materials is more difficult; no universal method analogous to a Geiger counter exists to detect easily and economically the many potentially toxic chemicals that might be released, or that have already been released, by hazardous wastes.

[26] The Department of Energy estimates that generation of about 28 trillion kilowatt-hours (kWh) of electricity by nuclear reactors will produce 144,000 tonnes of spent fuel, or an average of about 194 million kWh/tonne. DOE, *Report on Financing the Disposal*, p. 10. With an average charge for residential customers of electricity of 54 mills/kWh in calendar year 1980 (Congressional Budget Office, *Financing Radioactive Waste Disposal*, September 1982, p. xviii), this comes to total revenues of $10,480,000 per tonne of spent fuel generated.

[27] See DOE *Spent Fuel and Radioactive Waste Inventories*, for a complete inventory of radioactive waste in the United States.

INSTITUTIONAL ASPECTS OF WASTE MANAGEMENT

Waste management includes not only the technical activities for treating and isolating nuclear waste but also a range of institutional activities required to guide and support them .28 These are described briefly below and are discussed at greater length in chapters 7 and 8.

Federal Activities

Policymaking

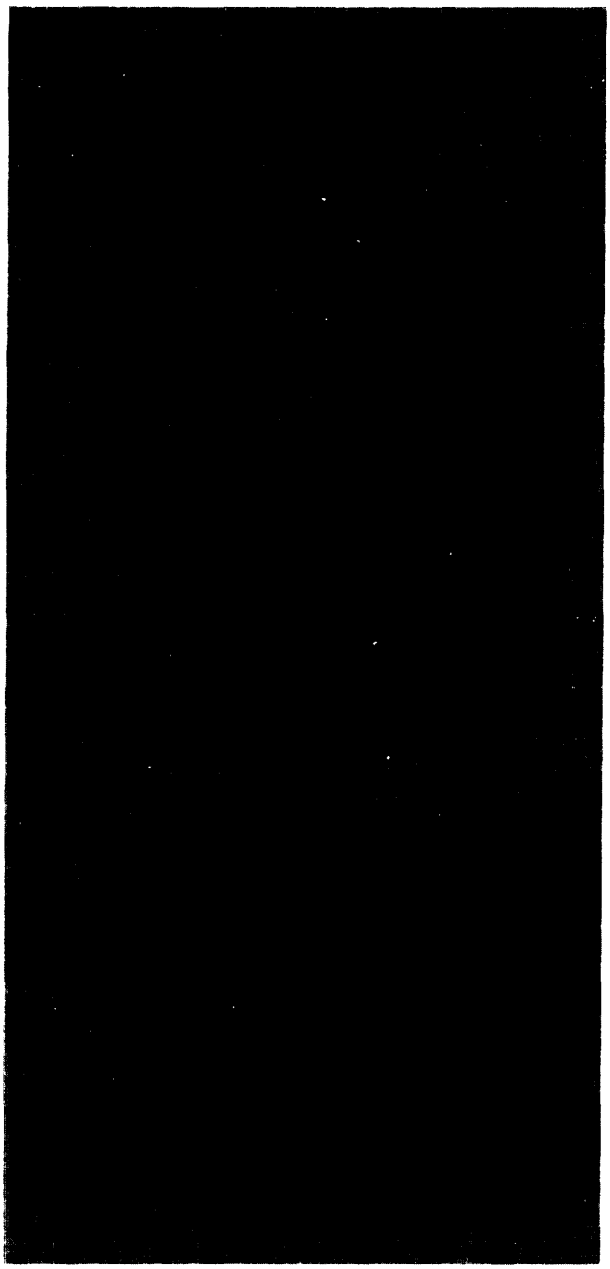
Policymaking or decisionmaking activities at various administrative levels control the overall structure and goals of the system, the integration of the activities, and, to a certain extent, the degree to which the activities are accomplished successfully. Because final isolation of high-level radioactive waste is a Federal responsibility, policymaking in this area is principally a Federal activity, although there is much involvement by non-Federal actors. Even waste management activities under private control, such as interim spent fuel storage, are subject to Federal regulation. The Federal Government's authority for commercial radioactive waste management rests with Congress and the executive branch. Congress establishes general policy through legislation and controls program implementation by reviewing, authorizing, and appropriating resources. The laws passed by Congress authorize Federal agencies to carry out their responsibilities, clarify Federal and State roles in making decisions and implementing programs, and give States legal authority over certain waste management activities. The President and the executive branch further develop and implement the waste management programs.

Regulation

ESTABLISHMENT OF SAFETY REQUIREMENTS

The Environmental Protection Agency (EPA) is responsible for developing generally applicable standards that set limits on the allowable release of radioactivity from the disposal of radioactive waste. Proposed numerical standards for high-level waste disposal in geologic repositories were published for comment in December 1982, and final criteria are expected to be promulgated in 1985. NRC is responsible for developing regulations based on EPA standards for managing high-level radioactive waste. Final NRC regulations for disposal in geologic repositories were issued in 1983.

[28] A more detailed description of the institutional aspects of the Federal radioactive waste management program is found in *information Base for Commercial Radioactive Waste Management*, U.S. Department of Energy, DOE/ET/40110-1, July 1982.



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licensed activities and defense programs. NRC has already developed procedures and regulations (based on anticipated EPA standards) that must be satisfied before a mined geologic repository can be licensed. During the various steps of repository development, NRC may conduct hearings so that other interested parties may participate in licensing activities.

During the development of a repository, NRC will formally evaluate the suitability of potential sites at three stages. If the site appears suitable after in situ testing, NRC will issue a construction authorization for repository development. If the initial phases of repository construction pass NRC requirements, NRC will issue an operating license, and waste emplacement in the repository will commence. If the final predictions of repository performance after waste emplacement meet NRC requirements, NRC will authorize closure of the repository.

Development and Operation of Repositories

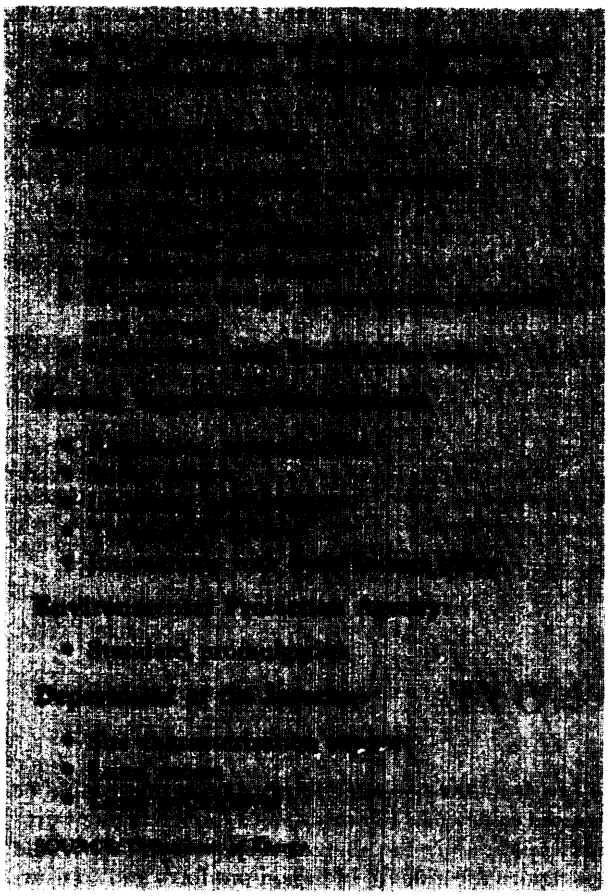
DOE is the Federal agency with lead responsibility for carrying out the high-level radioactive waste management policies adopted by Congress and the administration. The principal activity of DOE and its predecessors (the Atomic Energy Commission and the Energy Research and Development Administration) in this area has been research directed toward siting and constructing one or more geologic repositories for waste disposal. Other Federal agencies, in particular the Department of the Interior, also have some responsibilities in developing repositories.

Funding

Until 1983, funds for developing final isolation facilities came from annual Federal appropriations, with the assumption that the utilities using those facilities would ultimately repay the costs when they delivered waste to a Federal repository. Legislation enacted by Congress at the end of 1982 provides funds through user fees paid by utilities at the time the waste is generated.

Coordination and Management

Although DOE is the lead agency for waste management and Federal interagency cooperation on some waste management activities does exist, there



is no single Federal agency with overall responsibility for coordinating and managing the activities of all the Federal agencies involved in waste management. Interagency coordination is discussed further in chapter 7.

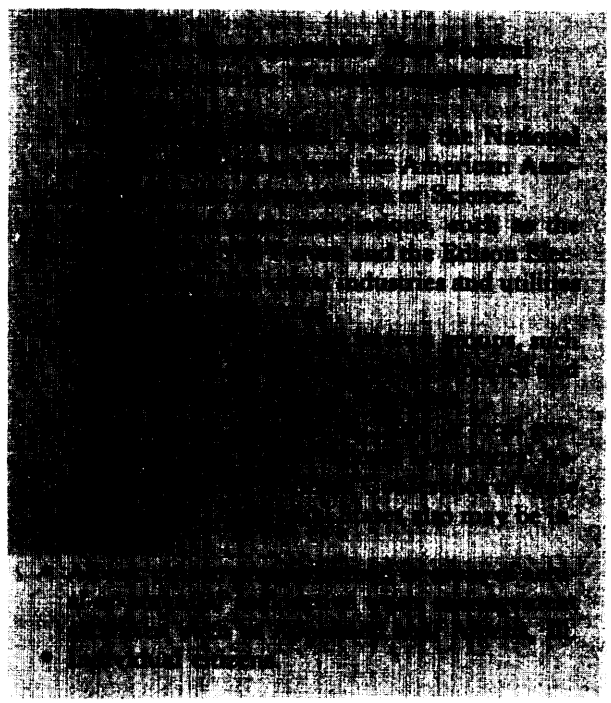
Non-Federal Involvement

Intergovernmental Interaction

Among the most important non-Federal actors in waste management are the governments of the States, Indian tribes, and localities that may be affected by waste management activities. State, local, and Indian tribal governments informally review policy and programs and express concerns by direct appeal to Federal officials, by intervention in site selection processes, and, in the case of States, by passing legislation restricting waste management activities. Twenty-six States, in accordance with formal agreements with the Federal Government, can license uranium milling operations, decommissioned facilities, or commercial burial sites for low-level waste within their State boundaries. State officials have had a major impact on repository siting activities in the past, and the Nuclear Waste Policy Act of 1982 gives a major formal role to States and affected Indian tribes in those activities in the future. The role of State and tribal governments is discussed in chapter 8.

Public Involvement

Interest groups and the general public participate in waste management activities in many ways, including attendance at public hearings sponsored by Federal agencies, direct appeal to Members of Congress and other Federal and State officials, participation on citizen advisory panels and quasi-oversight panels, litigation, and submission of written comments on proposed activities as part of the National Environmental Policy Act process. Technical groups conduct independent studies and reviews and provide advice, either formally as contractors or informally through independent publications, Although there is much controversy over the role of the public in the decisionmaking process, some funds are available to State and local organizations



(from the Federal Government) and to intervener groups (from private sources) to facilitate non-Federal participation in waste management. Public involvement is discussed further in chapter 8.

International Activities

There are approximately 290 commercial nuclear powerplants in operation worldwide and another 215 plants under construction in 31 countries, including the United States. *g Five countries have operating facilities for reprocessing spent fuel from LWRs. Major commercial waste management R&D is being undertaken by the United States, France, West Germany, Great Britain, Sweden, Canada, and Japan.[30] In the United States, DOE is primarily responsible for conducting cooperative R&D efforts with foreign countries. The Department of State is involved in waste management activities that involve U.S. nonproliferation policies or cooperative activities with other countries.[31] The Nuclear Waste Policy Act of 1982 includes provisions (sec. 223) to promote additional cooperation with nonnuclear weapon states in the field of spent fuel storage and disposal.

[29] These figures were valid at the end of 1982. *International Atomic Energy Agency Bulletin,* vol. *25, No.* 1, March 1983, p. 38.

[30] See K. M. Harmon, "Survey of Foreign Terminal Radioactive Waste Storage Programs," in U.S. Department of Energy, *Proceedings of the 1983 Civilian Radioactive Waste Management Information Meeting, CONF-831217,* February 1984, pp. 199-205.

[31] For a single subject of nonproliferation in general, see Office of Technology Assessment, *Nuclear Proliferation and Safeguards* (New York: Praeger Publishers, 1977). Detailed analysis of the relation between nuclear nonproliferation and spent fuel management is found in Frederick C. Williams and David A. Deese, *Nuclear Nonproliferation: The Spent Fuel Problem* (New York: Pergamon Press, 1979).

CHAPTER NOTE

The precise amount of spent fuel discharged by a reactor each year will depend primarily on two factors: the total amount of electricity generated by the reactor that year and the burnup of the fuel (measured in megawatt-days per tonne [MWd/t]), which is a measure of the amount of electricity obtained from each tonne of fuel (and thus of the amount of fissile material in the fuel that is used before the fuel is discharged from the reactor). The higher the burnup, the more complete the utilization of U*[35] and the less the discharge of spent fuel per gigawatt-year (GW-yr) of electricity generated. Since BWRs use lower burnups than PWRs, they discharge more spent fuel per GW-yr of generated electricity.

The 1984 DOE spent fuel projections shown in table 2-2 assume that spent fuel burnup will increase at an annual rate of 2.5 percent from 1985 to 1996, and will be 42,000 MWd/t for PWRs and 37,000 MWd/t for BWRs from 1996 on.[32] It is possible that burnups will increase even further in the future, perhaps up to 50,000 MWd/t, if the price of uranium, and thus of fresh fuel, goes up.[33] In this case, the amounts Of spent fuel resulting from the projected levels of generation could be reduced somewhat. However, even though higher burnups would reduce the amount of spent fuel, they would not reduce the amount of fission products and transuranic elements contained in the spent fuel, since the amount of those isotopes created is approximately proportional to the amount of electricity generated. Use of higher burnups simply means that there will be more fission products and transuranics in each of the smaller number of fuel assemblies discharged for each gigawatt-year of electricity produced. In other words, the waste produced by generation of a given amount of electricity would be concentrated in a smaller amount of spent fuel if a higher burnup were used. Thus, the total heat output from the waste produced in generating a gigawatt-year of electricity, and the total repository space needed for disposal, would be relatively unaffected by increasing the burnup. However, handling and packaging at the repository might be simplified somewhat by the smaller number of spent fuel assemblies involved if they were disposed of directly without reprocessing. For this reason, there may be waste management incentives for increasing burnups beyond the levels that would be justified by the increased efficiency of fuel use alone.

[32] U.S. Department of Energy, *Spent Fuel and Radioactive Waste Inventories,* p. 11.

[33] U.S. Department of Energy, *Nuclear Proliferation and Civilian Nuclear Power, vol. 9,* June 1980, pp. 24-27.