Chapter 3
Technology of Waste Management

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WASTE DISPOSAL

Over the last three decades, the Federal Government has considered disposing of radioactive waste permanently in geologic formations on land, in ice sheets, beneath the ocean floor, and in outer space. Although total containment of radioactive material in any of these environments may be impassible to guarantee, or even expect, these disposal environments are attractive because their remoteness from the Earth's surface minimizes the biological impacts of any potential releases of radioactivity.

Methods of disposal are in various stages of conceptual development. Disposal in mined geologic repositories is the concept most studied, and subseabed disposal is the next. In general, past Federal programs for waste disposal have concentrated almost exclusively on the development of mined geologic repositories. In 1981 this technology was formally selected as the focus of the Federal high-level waste management strategy by the U.S. Department of Energy (DOE), based on its Final Environmental Impact Statement (FEIS) on the Management of Commercially Generated Radioactive Waste, published in 1980.[1] However, very little work has been done on any of the other concepts except subseabed disposal. The uncertainties associated with many of the alternative disposal concepts reflect either the level of conceptual development of the technology or the complexity of the envisioned disposal system. In some cases, uncertainties can be resolved through additional research and development (R&D); in other cases, uncertainties may be unresolvable for all practical purposes.

Mined Geologic Repositories

Technology

The disposal of radioactive waste in mined geologic repositories at depths from 1,000 to several thousand feet below the Earth's surface is the final isolation technology most widely studied and favored by the worldwide scientific community. Three decades of study have revealed no insurmountable technical obstacles to the development of mined geologic repositories, provided suitable sites are found.[2]

The technology of the mined geologic repository is composed of a system of both natural and engineered barriers selected to prevent or limit the escape of waste from the repository so that the radiation exposure to humans from escaped waste is held to very low levels. In addition, geologic disposal also involves a "technology of prediction' '—a set of procedures and techniques for predicting the performance of a repository over the very long time period that the waste remains hazardous. Each element of the technology of geologic repositories will be discussed briefly below.

NATURAL BARRIERS: THE SITE

The site of a mined geologic repository is an integral part of the technology of geologic disposal since it plays a crucial role in isolating the buried waste from the biosphere. For this reason, sites for such repositories must be selected with great care.

[1] U. S. Department of Energy (DOE), *Final Environmental Impact Statement, Management of Commercially Generated Radioactive Waste*, DOE/EIS-0046F (Washington, D. C.: October 1980), hereafter referred to as *FEIS*.

[2] Ibid; American Physical Society (APS), "Report to the American Physical Society by the Study Group on Nuclear Fuel Cycles and Waste Management, " *Reviews of Modern Physics, vol. 50, No.* 1, pt. II, January 1978; Interagency Review Group on Nuclear Waste Management (IRG), *Subgroup Report on Alternative Technology Strategies for the Isolation of Nuclear Waste,* TID-28818 (draft), (Washington, D. C.: October 1978); International Nuclear Fuel Cycle Evaluation (INFCE), Waste Management *and Disposal: Report of INFCE Working Group 7,* International Atomic Energy Agency (Vienna: 1980); U.S. Environmental Protection Agency (EPA), *Draft Environmental Impact Statement on 40 CFR Part 191, Environmental Standards for Management and Disposal of Spent* Nuclear Fuel, *High-*Level and *Transuranic* Wastes, EPA 520/1-82-025, December 1982, hereafter referred to as *DEZS on 40 CFR 191;* National Research Council, A *Review of the Swedish KBS-II Plan for Disposal of Spent Nuclear Fuel* (Washington, D. C,: National Academy of Sciences, 1980); National Research Council, A *Study of the Isolation System for Geologic Disposal of Radioactive Wastes* (Washington, D. C.: National Academy Press, 1983); U.S. Nuclear Regulatory Commission, *Waste Confidence Decision, Federal Register, vol. 49, No.* 171, Aug. 31, 1984, pp. 34658-34688.

The natural features of the site that contribute to isolation are the host rock (which can be selected to prevent or minimize contact between the waste and flowing ground water, the principal potential mechanism for bringing buried waste into contact with human beings),[3] the chemical characteristics of the site and its environment (which can limit the rate at which the waste dissolves in ground water and is transported to the biosphere), and the time required for contaminated ground water to flow from the repository to the biosphere (which, along with the chemical characteristics of the media surrounding the repository, can delay the release of dissolved waste until many of the hazardous radionuclides have decayed). In addition, the location of the site can be selected to reduce the possibility of human intrusion (e. g., by avoiding proximity to valuable natural resources) and to provide for dilution of any contaminated ground water by large quantities of surface water before the ground water is used by human beings.

Until the late 1970's, the natural features of the geologic repository site were seen as the principal means for providing waste isolation. Initially, the emphasis was on a particular host rock, salt, which has features that were felt to provide adequate assurance that the waste would be isolated from contact with flowing ground water.[4] Later studies concluded that the characteristics of the environment surrounding the host rock could provide adequate isolation even if ground water were contaminated by contact with the waste and that there was no clearly superior host rock for mined repositories.[5] Other rocks under consideration include tuff (compacted volcanic ash), basalt (coarse-grained solidified lava), and granite.

Because the site plays such a central role in geologic disposal in mined repositories, the final validation of the concept will depend on construction and operation of a repository at an actual site.[6] No site has been approved for such a repository anywhere in the world, although some reviews have concluded that it will not be difficult to find suitable sites.[7] It is generally agreed that identification of specific sites for detailed geologic investigation is necessary to resolve the remaining technical questions about geologic disposal.[8]

In the United States, the process of finding suitable sites involves the screening and progressive elimination of sites in different regions of the country. It is likely that only a small percentage of the sites screened will survive the site selection process. Because of the high degree of variability among sites, each potential site must be evaluated individually through surface exploration and by geological mapping, geophysical (nondestructive) surveying, drilling, and in situ testing within candidate rock formations. The technology for identifying and "characterizing' potential sites is available or under development.[9]

The suitability and total waste capacity of each potential site must be evaluated on a case-by-case basis because of the great variability among sites. In some cases, for example, a fault (a fracture in the Earth's crust, along which there has been relative displacement of adjacent rock formations) may reduce the suitability of a particular site; in other cases, the fault could actually provide an additional natural barrier.

Because all potentially usable rock types have not been evaluated for repository sites, the total number and capacity of potential repository sites in the United States is unknown at this time. However, general knowledge about geologic formations throughout the United States suggests that at least several suitable repositories could be located, although it is probable that suitable sites cannot be found in all States.

ENGINEERED FEATURES

The principal engineered features are the overall design of the repository, the waste form (e. g., solidified high-level waste or unprocessed spent fuel), and the waste package, which may include an overpack (e. g., a titanium container) designed to provide containment for up to 1,000 years and

[3]APS, op. cit.

[4]See discussion of the evolution of the role of the waste form in app. A.

[5]Ibid.; IRG, op. cit. ; National Research Council, *Isolation System.*

[6]NFCE, op. cit., p. 119.

[7]APS, op. cit. The National Research Council review of a Swedish waste disposal plan also concluded that suitable disposal sites could be found in Sweden. National Research Council, *Review of the Swedish KBS-II Plan.*

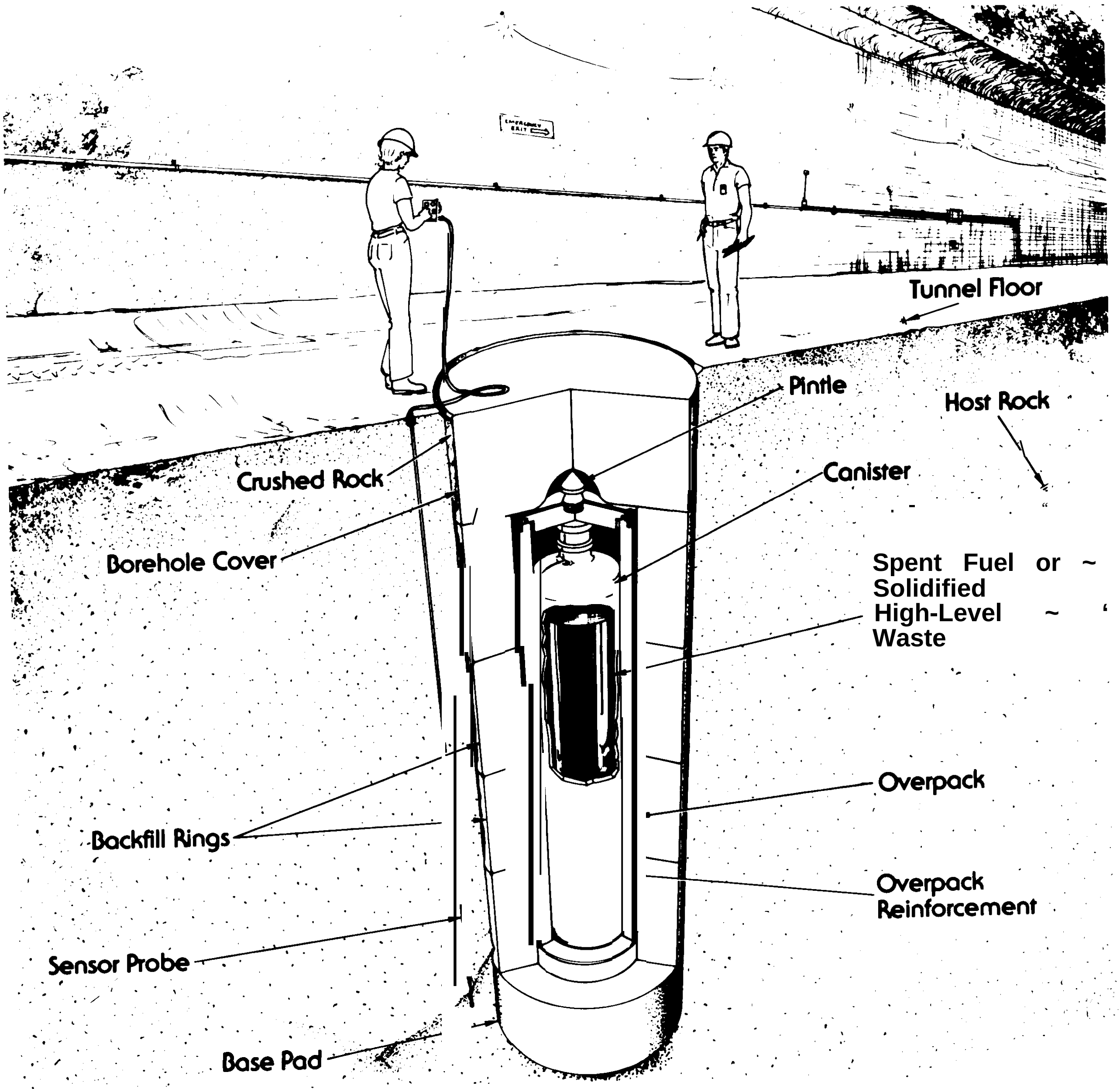
[8]IRG, op. cit.; U.S. Department of Energy and U.S. Geological Survey (USGS), *Earth Science Technical Plan for Disposal of Radioactive Waste in a Mined Repository, Draft*, DOE/TIC-l 1033 (draft), April 1980, p. 1.

[9]Ibid.; Cyrus Klingsberg and James Duguid, *Status of Technology for Isolating High-Level Radioactive Wastes in Mined Repositories*, DOE/TIC 11'207 (draft) (U.S. Department of Energy: October 1980).

a packing material (e. g., bentonite) designed to prevent water from reaching the overpack and to limit the escape of any water that does come into contact with the waste (see fig. 3-l).

As noted above, until the late 1970's, it was generally assumed that the natural geologic features of a salt repository alone would provide an adequate degree of isolation. The solid waste form (required

Figure 3-1.—Emplaced Waste Package



by Federal regulation) and waste package were intended only to prevent accidental release of waste during transportation and handling until retrieval of the waste from the repository was no longer contemplated. They were not seen as playing a crucial role in ensuring long-term isolation of the waste within the repository after it was sealed.[10]

In the mid-1970's to late 1970's, recognition of the uncertainties associated with the prediction of the behavior of the repository and surrounding geology over a period of many thousands of years led to a growing interest in a "multiple barrier" approach in which a combination of manmade and natural barriers would act together to provide confidence in long-term isolation, despite uncertainties about each barrier separately. The result has been a growing emphasis on the role of the waste form and the waste package,[11] which is reflected in Nuclear Regulatory Commission (NRC) regulations for geologic disposal.[12]

The current reference waste form for solidified high-level waste from reprocessing is borosilicate glass, which was selected when a solid waste form was seen as being needed primarily for safe transportation and handling. When the waste form took on an important role in long-term isolation, questions arose about how well borosilicate glass could perform this more demanding task under the conditions anticipated in a repository after closure. Of particular concern was the question of the rate at which waste might dissolve from the glass into ground water at the high temperatures that could be produced by the heat emitted by the waste.[13] Several technical reviews have concluded, however, that borosilicate glass could be an adequate waste form (although perhaps not the best one possible) if the repository were designed so that the temperature of the glass remained relatively low (around 100° C).[14] Recent studies have also concluded: 1) that development of a waste form that would release waste into ground water much more slowly than forms that are currently available could reduce substantially the expected long-term effects of geologic disposal, and 2) that improvements in the waste form would be much more effective than improvements in the rest of the waste package in achieving that result.[15] Further discussion of the value of continued R&D on alternative waste forms is found in chapter 6.

If reprocessing to recover plutonium and uranium does not occur, it is assumed currently that spent fuel would be disposed of directly, so that the waste form would be the uranium dioxide fuel pellets (still in the fuel assemblies) that contain the waste products. Recent analyses have concluded that adequate isolation can be achieved in this way, although the fuel pellets would be more soluble than borosilicate glass.[16] If necessary the spent fuel could be dissolved and resolidified in a better waste form.[17] However, a careful systems analysis would be necessary to determine if the increase in worker exposures and accident risks resulting from more complex waste-processin{: operations would offset the possible decrease in long-term risks from the waste after disposal.[18]

Some have argued that use of sophisticated engineered barriers, 'such as a [ow-volubility waste form or long-lived package, could decrease the reliance on natural barriers to the extent that many more sites would be usable for repositories.[19] (The role of long-lived waste packages in a conservative re-

[10] See app. A.

[11] See, for example, the proposed Swedish KBS waste disposal system in which major reliance is placed on a long-lived waste package, analyzed in National Research Council, *Review of the Swedish KBS-II Plan,* and in National Research Council, *A Review of the Swedish KBS-3 Plan for Final Storage of Spent Nuclear Fuel* (Washington, D. C.: National Academy Press, 1984).

[12] 10 CFR 60.

[13] See, for example, G. J. McCarthy et al., "Interactions Between Nuclear Waste and Surrounding Rock," *Nature,* vol. 273, May 18, 1978, pp. 216-217.

[14] National Research Council, *Isolation System,* p. 7; U.S. Department of Energy, *The Evaluation and Review of Alternative Waste Forms for* Immobilization *of High-Level* Radioactive Wastes, Report No. 3 by the Alternative Waste Form Peer Review Panel, DOE/TIC-11472, July 1, 1981.

[15] National Research Council, *Isolation System,* p. 280; EPA, *DEIS on 40 CFR 191,* p. 208.

[16] National Research Council, *Isolation System;* INFCE, op. cit.; IRG, op. cit.; EPA, *DEIS on 40 CFR 191,*

[17] DOE, *FEIS,* pp. 4.20-4.22.

[18] National Research Council, *Isolation System,* p. 14.

[19] See, for example, National Research Council, *Isolation System,* p. 45. However, this and other recent studies have concluded that it is very important to select a site with chemical characteristics that will limit the rate at which particularly toxic and long-lived radionuclides such as Np^{237} can dissolve into ground water. EPA, *DEIS on 40 CFR 191, p. 109.*

pository system design is discussed further in ch. 6.) While there is no consensus about the degree to which engineered barriers might substitute for natural ones, there is growing agreement that they may usefully complement natural ones to provide a high degree of isolation through a multiple-barrier system in which each barrier helps compensate for the uncertainties about the others .20

TECHNOLOGY OF PREDICTION

Development and operation of mined geologic repositories will require not only location of specific sites and design of engineered facilities appropriate for those sites but also decisions by the licensing authority, NRC, that those combinations of sites and engineered features can be expected to provide the required degree of waste isolation for a required period of time. In addition to the physical technology, therefore, a "technology of prediction' is needed to show in a formal licensing process that a proposed repository is likely to meet established standards.

The repository development and licensing process is uncharted territory. The ability of a geologic repository to isolate radioactive waste for millenia cannot be demonstrated directly in the same sense that a new aircraft can be demonstrated to perform according to its design specifications. For this reason, there must be heavy reliance on predictions of the long-term isolation provided by the repository based on the use of mathematical models that embody scientific understanding of the behavior of the repository and its environment .21 Techniques for predicting repository performance are needed as a basis for detailed design of a repository, as well as for the licensing process .22 Such long-term prediction has never been done in a formal regulatory process, and no widely reviewed and generally accepted method for predicting repository performance exists. Many analytic procedures to be used in the licensing process must be developed, including data collection and validation techniques, methods for verifying and validating scientific models, and the formal procedures for using such models to predict repository performance .23 The importance of an explicit program to develop the technology of prediction is discussed in chapter 6.

OVERALL STATE OF TECHNOLOGY

No licensed mined repository for high-level radioactive waste exists in the United States or elsewhere in the world. The failure to develop and license mined repositories in the United States stems to a large extent from nontechnical factors such as inadequate and intermittent Federal support and reluctance to address major institutional problems. The main areas of technical disagreement concern not the ultimate feasibility of developing mined repositories, but the degree of conservatism in design (e. g., temperature limits and the design requirements for engineered barriers) and the pace and scope of the R&D program needed to develop a repository safely.[24] Technical reviews have concluded that the major remaining technical uncertainties about geologic disposal could be sufficiently resolved in time to allow the first repository to be constructed and licensed for operation by the late 1990's, if no unforeseen technical or institutional problems arise .25

[20] Both proposed EPA criteria for geologic disposal, and final NRC regulations place emphasis on use of a multiple-barrier approach. See proposed EPA standards in the *Federal Register, vol. 47, No. 250,* Dec. 29, 1982, pp. 58196-58206. Final NRC technical criteria, 10 CFR, pt. 60, are found in *Federal Register, vol. 48, No. 120,* June 21, 1983, pp. 28194-28229, and are summarized in app. D.

21 IRG, op. cit. ; APS, op. cit.; Klingsberg and Duguid, op. cit.; National Research Council, *Isolation System;* EPA, *DEIS on 40 CFR 191.*

22 Thomas H. pigford, "The National Research Council Study of the Isolation System for Geologic Disposal of Radioactive Wastes, presented at the meeting of the Materials Research Society, Boston MA, November 1983.

[23] See National Research Council, *Implementation Of Long-Term Environment/ Radiation Standards: The Issue of Verification* (Washington, D. C.: National Academy of Sciences, 1979), for detailed discussion of steps needed in demonstrating compliance with criteria

[24] For example, the authors of a USGS report that is cited sometimes as raising fundamental questions about the overall concept of geologic disposal believe that acceptable geologic repositories can be constructed. J. D. Bredehoeft et al., "Geologic Disposal of High- Level Radioactive Wastes—Earth Science Perspectives, *Geological Survey Circular 779,* U.S. Geological Survey, undated, p. 111. Also, as noted above, the questions about the suitability of borosil icate glass as a waste form relate to its performance at very high temperatures and can be dealt with by keeping the temperature in the repository low. The extensive debates about waste management policy during the Carter administration dealt not with whether to develop geologic repositories, but instead with how many sites and geologic media should be examined before selecting a site. IRG, op. cit.

[25] DOE and USGS, Op. cit, , p. 1, concludes that 10 years (from 1980) should be needed to resolve the major technical uncertainties.

TECHNOLOGY DEPLOYMENT

Disposal in mined geologic repositories will involve the following activities (as well as others listed in ch. 2):

Disposal Technology Development and Siting. —DOE'S present R&D efforts are focused on spent fuel transportation and storage; data collection on geohydrologic environments and waste/rock interactions; the development and evaluation of waste forms, canisters, and other engineered barriers; the development of equipment and facility designs for waste handling, processing, and disposal; and the development of predictive mathematical models for evaluating the suitability of potential repository sites. Information from in situ testing and impact evaluation activities at potential sites will be used by DOE to develop full-scale repository designs to be submitted to NRC for approval. According to current regulatory procedures,[26] if a potential repository site and design met appropriate NRC requirements, NRC would authorize construction. After some or all of the repository and supporting surface facilities were constructed, NRC would thoroughly evaluate the suitability of the site and determine whether to approve emplacement of waste in the repository.

Repository Development and Operation.—Repository development would involve excavating rock from the repository, preparing (canning) the waste in surface facilities at the repository site, lowering the canisters of waste into the repository, and emplacing the canisters of waste and the surrounding overpack material into holes drilled in the rock formation (see fig. 3-2). Each repository would remain in operation from 10 to 40 years, depending on its size and the rate of waste emplacement. During this operational phase, additional information on the behavior of the repository would be collected and used to refine further the predictions of the long-term behavior of the repository. Individual rooms or modules of the repository could be backfilled or kept open for a certain period of time to permit further cooling of the waste or to maintain ready access to the waste.

After the repository is filled, DOE could request that its license be amended to permit decommissioning or closure of the facility. NRC would make a decision about the request after considering the plan and the public comments about it in light of NRC requirements. The tunnels connecting individual rooms or modules of the repository would then be backfilled and the vertical access shafts to the repository, permanently sealed. After closure, monitoring could be used to detect unexpected releases from the repository.

Safety

The expected efficacy of geologic disposal is not based on the conclusion that the waste can be contained completely until it decays to harmlessness. Instead, ***it is assumed that some releases may occur and that engineered and natural barriers can limit the size of such releases to very low levels.*** The two principal modes of possible release of radioactivity from a well-designed and well-sited mined repository would be small, concentrated releases from human intrusion (e. g., from digging a well near or into a repository), which could expose a few individuals to relatively large doses of radiation, or the gradual release of radioactivity from the repository into ground water (and, ultimately, into drinking water or food supplies), exposing a potentially large population to very small doses (compared to background radiation).[27] The release of a large fraction of the waste in a repository would be extremely unlikely, and the chance that any individual would receive a very high dose of radiation would be small.[28]

The U.S. Environmental Protection Agency (EPA) has calculated that releases from a geologic repository containing 100,000 metric tons (tonnes) of spent fuel (the lifetime output of about 100 one-gigawatt [GWe] reactors) could be expected to produce fewer than an average of one fatal cancer every 10 years over a 10,000-year period. Table 3-1 shows that this level of health effects is smaller than the health effects that could result from other sources of ionizing radiation. For example, it is much less than 1 percent of the fatal cancers that would be produced in the same exposed population from normal levels of background radiation.[29] The results

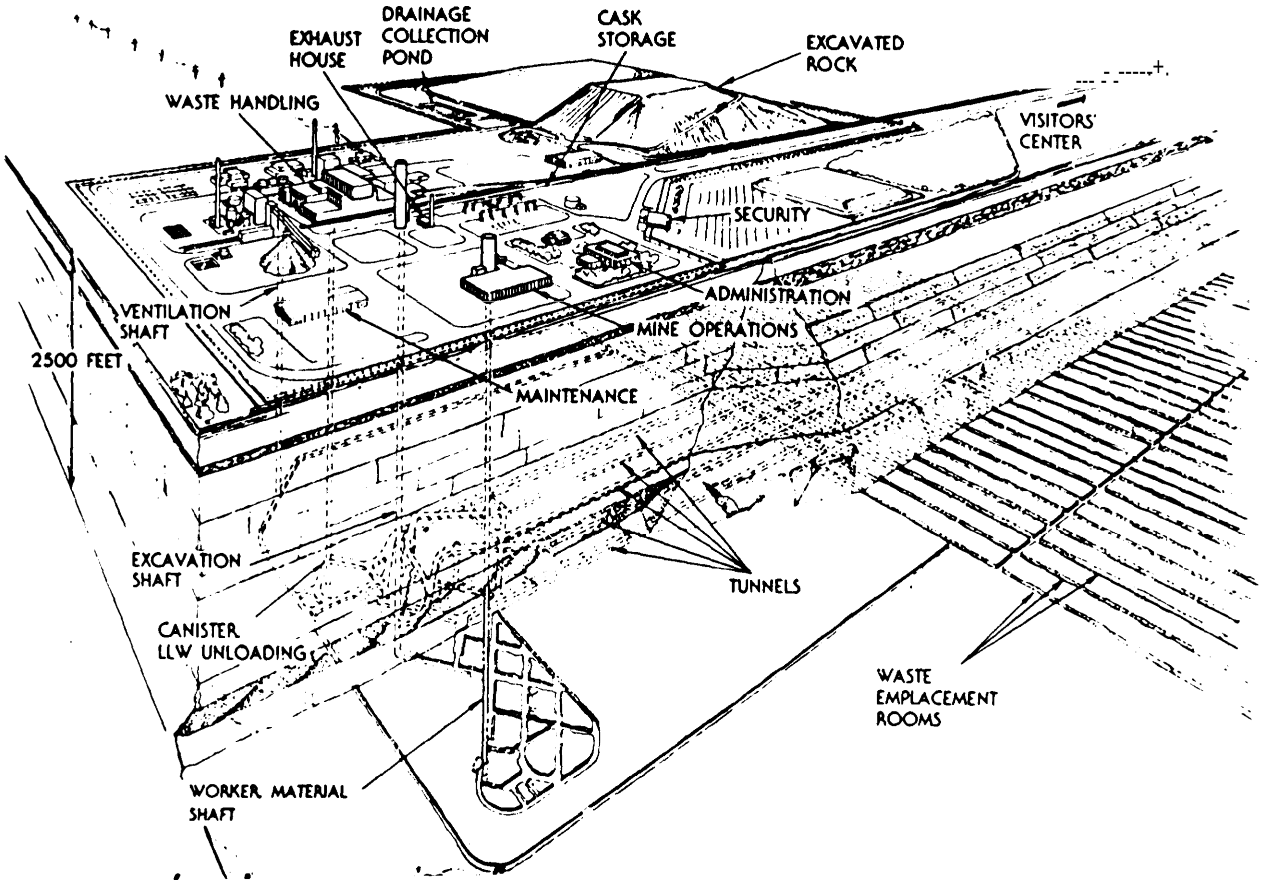
[26] 10 CFR 60, Subparts B and C, published in 46 FR 13971, Feb. 25, 1981.

[27] EPA, *DEIS on 40 CFR 191; National Research Council, Isolation System.*

[28] EPA, *DEIS on 40 CFR 191,* pp. 107-108.

[29] Ibid., p. 43.

Figure 3-2.-Artist's Conception of the Surface Support Buildings and Underground Facilities of a Radioactive Waste Repository



SOURCE: U.S. Department of Energy.

of EPA's calculations for various geologic media are shown in table 3-2. More recent analysis, which takes into account the revised estimates of radionuclide toxicity discussed in chapter 2, supports EPA's conclusions that the expected effects from a well-designed and well-sited repository would be small compared to the effects from background radiation.[30]

Figures 3-3 and 3-4 show recent estimates of the possible performance of a repository in basalt containing 100,000 tonnes of spent fuel or equivalent high-level waste (solidified in borosilicate glass). Performance is measured in terms of the maximum radiation doses, in millirems per year, that would be received by an individual from water contaminated by waste that has escaped from the repository. The calculations reflect the recent International Commission on Radiation Protection revisions of the estimated toxicity of critical radionuclides that were discussed in chapter 2. Both figures show that the longer it takes for water to travel from the repository to the environment where it can be ingested by humans, the lower the predicted dose, because of radioactive decay during that time. They also show that the dose from spent fuel is expected to be higher than that from high-level waste. However, even for spent fuel, the predicted dose from using contaminated surface water is at most around 10 millirems per year, compared to a normal dose of around 110 millirems per year from normal back-

[30] National Research Council, *Isolation System*, ch. 9.

Table 3-1.—Number of Possible Cancer Cases Due to ionizing Radiation'

Origin	Number of cases per year[b]	Number of cases per 10,000 years[b]
High-level radioactive waste disposal[c] (Proposed EPA standards)	up to 0.1	up to 1,000
Uranium mill tailings[d]:		
Unprotected*	3	30,000'
Protected (covered, etc.)	0.03	300*
Indoor air pollution:		
Residential exposure[e]	1,000 to 20,000	'10,000,000 to 200,000,000*
Residential weatherization (added cases)[e] (Nero estimate)	250t05,000	2,500,000 to 50,000,000*
Residential weatherization (added cases)[f]	10,000 to 20,000	100,000,000 to 2oo,~,ooo'
Background radiating	3,000 to 4,000	30,000,000 to 40,000,000
Cancer deaths (U.S.)[h] (all causes)	430,000	NA

a These numbers are all calculated on the Same basis using a linear non-threshold dose response model. The linear non-threshold model involves a high degree of speculation, and the resulting values have little merit as absolute indicators of the numbers of biological effects that may occur. It has been used here to provide a framework within which relativ risks from various radiation exposure situations can be compared.
b Assuming constant U.S. population and culture—numbers with (*) are extrapolated from annual values.
C EPA proposed rule 413 CFR Part 191 (December 1982) number per 100,IXXI tonne high-level radioactive waste repository.
d NRC, October 1980. "Uranium Mill Licensing Requirements: Final Rules," *Federal Register*, 45, No. 194, 135521%5538. Radon inhalation exposures.
e Nero, A, v., "Indoor Radiation Exposures From ²²²Rn and Its Daughters: A View of the Issue, " *Health Physics*, 45, No. 2 (August 1983), 277-288.
f EPA Report EPA 520/4-78-013 (revised printing, July 1979).
9 NAS/NRC, The Effects on populations of Exposure to Low Level of ionizing Radiation, November 1972 1972 BEIR Report.
h American Cancer Society, Cancer Facts and Figures—1982, 1981.
• Does not include health effects from water pathways.

SOURCE: High-Level Radioactive Waste Disposal Subcommittee, Science Advisory Board, U.S. Environmental Protection Agency, "Report on the Review of Proposed Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes (40 CFR 191)," January 1984, table A, pp. 12-13.

Table 3=2.—Projected Population Risks From High= Level Waste Disposal EPA Reference Cases

Repository type	Projected health effects over 10,000 years: Routine release	Faulting	Drilling number (No hit)	Drilling number (Hit)	Breccia pipe	Volcano; meteorite	Total
Granite	10	+	750	+	—	+	760
Bedded salt	o		160	8	+	+	190
Basalt	1,400	:	3,000	2		+	4,400

Number = "No hit" means the drill does not hit solid waste but only repository water, while "hit" indicates the drill does hit solid waste.
+ . Less than 1 projected fatal cancer.
— . Not applicable.

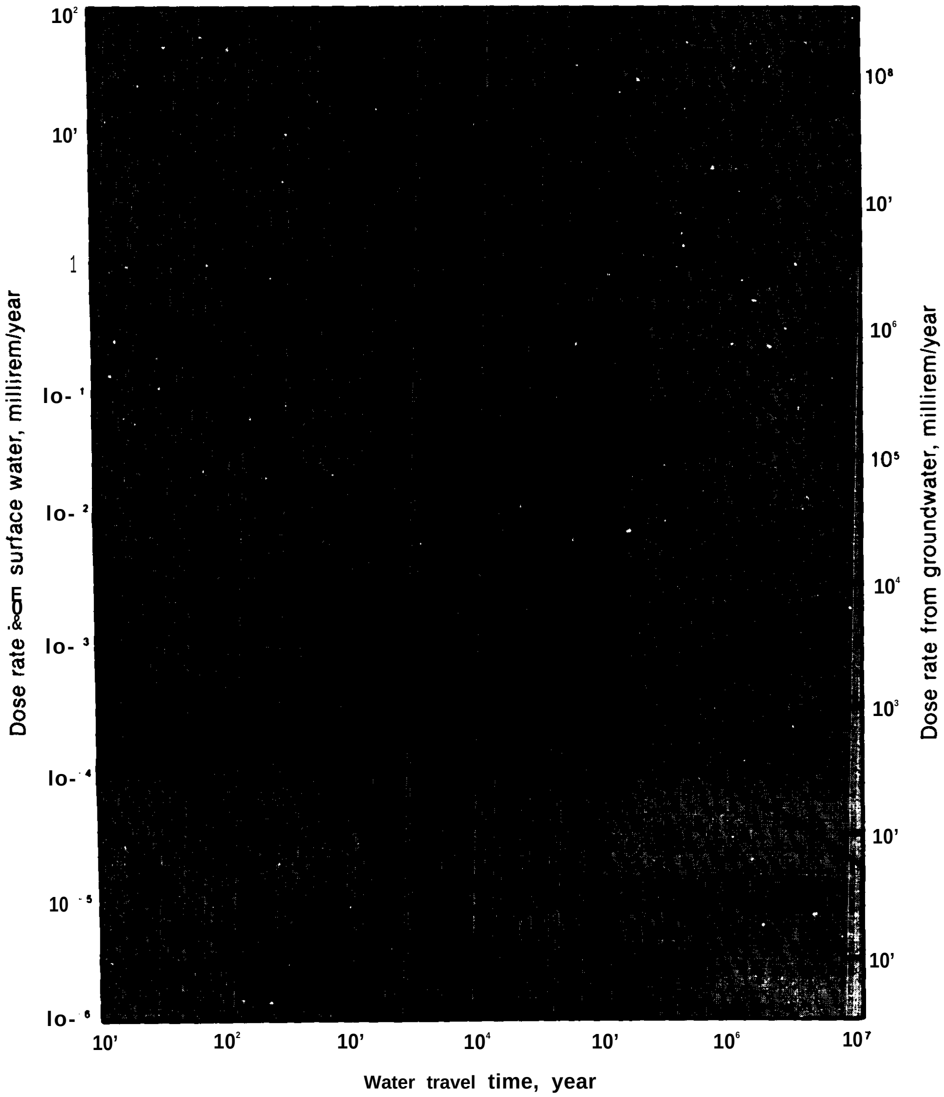
SOURCE: U.S. Environmental Protection Agency, *Draft Environmental Impact Statement for 40 CFR 191: Environmental* Standards *for* Management *arrd Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Waste,* EPA 52011-824125, December 1982, p. 205.

ground radiation. (Further analysis of the difference between high-level waste and spent fuel is found in the discussion of reprocessing below.) It should be noted, however, that these figures show that direct use of contaminated ground water that has not been diluted in a large volume of surface water could lead to doses to some individuals that are well above background levels .31

The acceptability of such expected effects is a value judgment, rather than a technical determination, and is the responsibility of the Environmental Protection Agency. EPA has proposed that the amounts of certain critical radionuclides that can be released from a repository in the first 10,000 years after emplacement be limited to specified levels that are calculated to produce no more than about 1,000 deaths (for a 1OO,OOO-tonne repository) during that period. The proposed limits are shown

91 EPA cites similar conclusions. EPA, *DEIS on 40 CFR 191*, p. 106.

Figure 3-3.—Individual Radiation Dose as a Function of Water Travel Time From a Repository in Basalt Containing 100,000 Tonnes of Unreprocessed Spent Uranium Fuel



Assumptions:

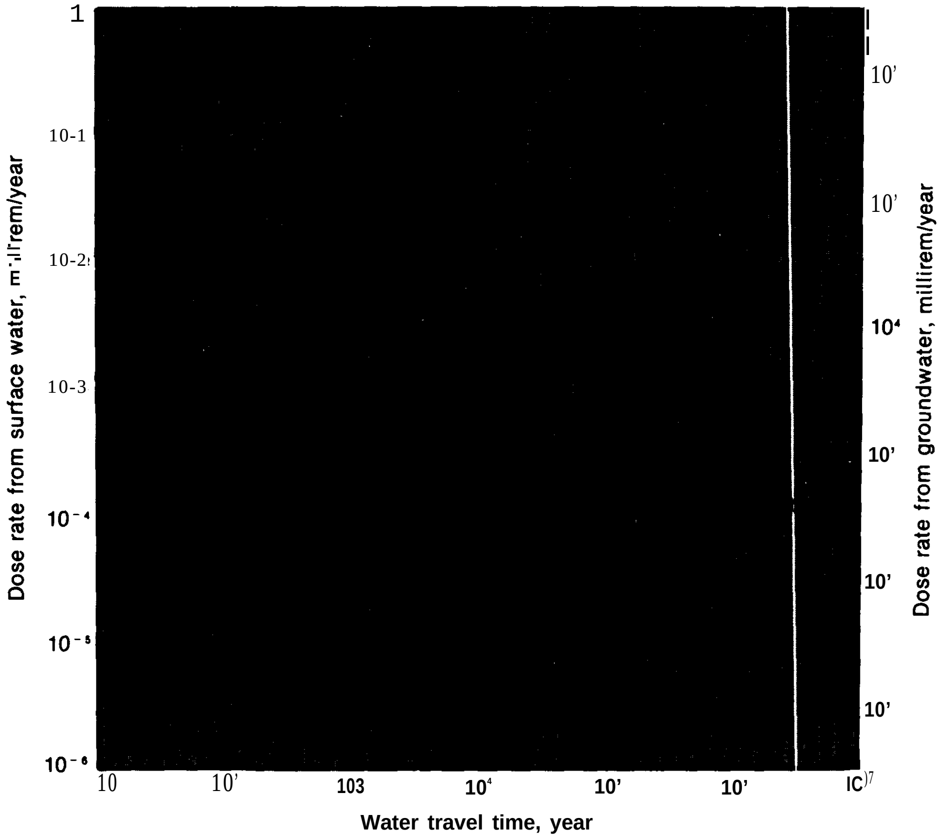
Dissolution rates = 10^{-4}/yr for C, Cs, and 1. All other radionuclides dissolve at a rate determined by their own volubility rather than the rate of dissolution of the waste form.

River flow = 1.1 x 10^{11} m^3/yr

Groundwater flow = 3.2 x 10^4 m^3/yr

SOURCE: Adapted from National Research Council, A *Study of the/so/at/on System for Geologic Disposal of Radioactive Wastes* (Washington, DC: National Academy Press, 19S3).

Figure 3-4.—Individual Radiation Dose as a Function of Water Travel Time From a Repository in Basalt Containing Reprocessing Waste From 100,000 Tonnes of Spent Uranium Fuel



Assumptions:
Dissolution rates = 10^{-4}/yr for Cs. All other radionuclides dissolve at a rate determined by their own volubility rather than the rate of dissolution of the waste form.
River flow = 1.1 x 10^{11} m³/yr
Groundwater flow = 3.2 x 10^{4} m³/yr

SOURCE: Adapted from National Research Council, *A Study ofttre Isolation System for Geologic Disposal of Radioactive Wastes* (Washington, DC: National Academy Press, 19S3).

in table 3-3. The NRC performance requirements for geologic repositories-are summarized in appendix D.

It should be noted that there are disagreements in the technical community about the philosophical approaches reflected in both EPA's proposed standards and NRC final regulations. The issues in dispute include whether to base the safety standards on what is theoretically achievable by a well engineered and sited repository, or on an independently determined standard of acceptable risk; whether to state the standard in the form of limits for the amounts of radionuclides that can be released by a repository over a fixed period, or in terms of acceptable levels of radiation exposure to, or health effects in, exposed population; or individuals; and whether to set performance standards for individual components of a repository system (such as the waste package), or only for the system as a whole .32

[32] A discussion and critique of the NRC regulations and proposed EPA standards is found in National Research Council, *Isolation System*, ch. 8. Suggestions for revisions of the proposed EPA standards are found in the "Report on the Review of Proposed Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes (40 CFR191)" by the High-Level Radioactive Waste Disposal Subcommittee of the Science Advisory Board of the U.S. Environmental Protection Agency, January 1984. This group suggested that the release limits be ten times higher than proposed by EPA.

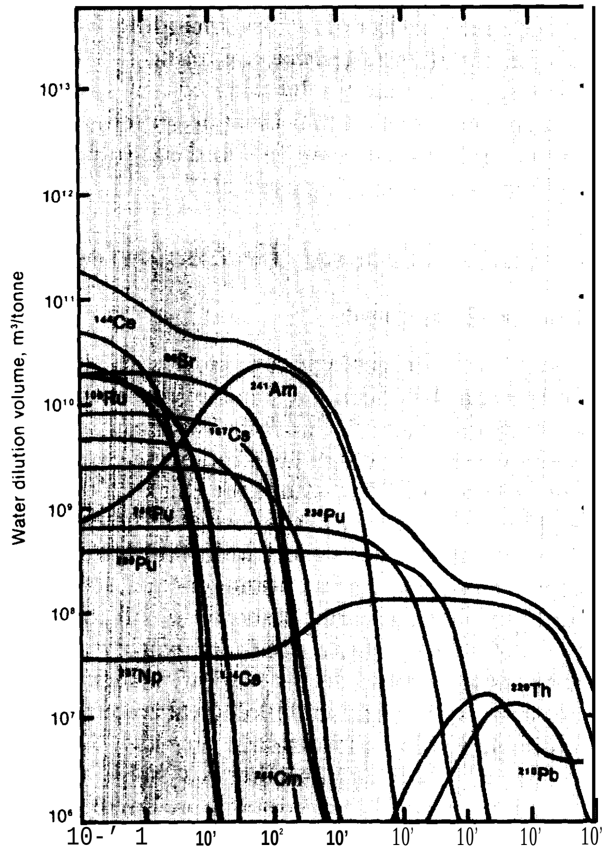
Table 3-3.—EPA Proposed Release Limits for Containment Requirements (cumulative releases to the accessible environment for 10,000 years after disposal)

Radionuclide	Release limit (curies per 1,000 tonnes)
Americium-241	10
Americium-243.	4
Carbon-14	200
Cesium-135	2,000
Cesium-137	500
Neptunium-237	20
Plutonium-238	400
Plutonium-239	100
Plutonium-240	100
Plutonium-242	100
Radium-226	3
Strontium-90	80
Technetium-99	10,000
Tin-126	80
Any other alpha-emitting radionuclide	10
Any other radio nuclide which does not emit alpha particles.	500

SOURCE US Environmental Protection Agency.

Figures 3-3 and 3-4 can also provide perspective on the point emphasized in chapter 2: that simple toxicity indices, such as water dilution volumes, are a misleading measure of the hazard posed by radioactive waste. Figure 3-5 shows the contribution made to the toxicity of spent fuel by each of the most significant radionuclides. Comparing that figure with figures 3-3 and 3-4 shows that, with the exception of neptunium-237 (Np^{237}) in the very long term, ***none of the radionuclides that are the principal contributors to the predicted dose from waste in a repository are major contributors to the total toxicity of the waste.*** The major contributors to the toxicity are in general expected to decay before they can reach the environment. Some, like strontium-90 and cesium-137, have short half-lives so that they will decay to negligible levels even within relatively short water travel times. Others with longer half-lives, like americium and plutonium, are expected to be retarded severely by chemical reactions with the surrounding rock so that they will move much more slowly than the ground water and thus will take a very long time to escape, even if the water travel time is not long compared to the half-life.

Figure 3-5.—Water Dilution Volume of PWR Spent Fuel



SOURCE: National Research Council, *A Study of the Isolation System for Geologic Disposal of Radioactive Wastes* (Washington, DC: National Academy Press, 19S3),

Cost

DOE estimates that the cost of designing, constructing, operating, and decommissioning a geologic repository having a capacity of 70,000 tonnes of spent fuel will range from $5 billion to $7 billion (in 1983 dollars), depending on a range of factors, including the nature of the site and medium.[33] Two repositories of this capacity should accommodate all of the radioactive waste generated over the 40-year expected operating lifetime of the nuclear

[33] U.S. Department of Energy, Mission *Plan for the Civilian Radioactive Waste* Management Program, draft, DOE/RW-0005 (Washington, D. C.: April 1984), vol. II, table 10-6, p. 10-14.

powerplants in existence or under construction in the United States. The actual number required will depend on a number of factors, including the physical capacity of the sites that are found, the repository designs that are finally adopted, the size of the nuclear power system that must be served, and the relative amounts of spent fuel and solidified high-level waste that are disposed of.[34]

Other Disposal Technologies[35]

Subseabed Disposal

Next to mined geologic repositories, the disposal concept that has been the focus of the most study is subseabed disposal. Subseabed disposal involves the emplacement of high-level radioactive waste beneath the ocean floor within the thick (200 to 500 feet [ft]) clay sediments that cover large expanses of the relatively deep (3 to 4 miles) midoceanic regions. These flat-lying, homogeneous sediments could provide sufficient disposal for all the high-level radioactive waste produced worldwide. Because these remote, deep-ocean areas lack significant levels of mineral and biological resources, the likelihood of human intrusion is very low. The mid-oceanic regions are among the most stable and predictable geologic environments on Earth. Moreover, the ocean itself provides an additional isolating barrier between the sediment surface and land-based ecosystems. On the other hand, subseabed disposal presents added safety risks from ocean transportation accidents. Although waste retrieval would be possible with existing technology, its cost would probably be prohibitive for all but safety reasons.

Additional work is needed before the scientific feasibility of seabed disposal can be determined. For example, further research is needed to determine whether the waste canister and the sediments will adequately contain the wastes, and models to predict the physical and biological transport of radionuclides in the ocean must be developed.[36]

In its relatively small subseabed research program (funded at $6 million in fiscal year 1982), DOE is studying not only the potential migration of radioactive material within the oceanic sediments and ecosystem, but also transport, emplacement, and isolation systems. Large regions of the ocean have been screened and many areas explored in more detail; several prospective sites have been selected for in situ testing. Resolving technical questions about the impacts from the international dumping of low-level radioactive waste onto the ocean floor may be required before the emplacement of high-level radioactive waste could be initiated.

With subseabed disposal, the domestic political difficulties associated with siting land-based mined repositories might be replaced with similar difficulties in siting the shipping facilities .37 In addition, significant national and international legal problems might require resolution before this concept could be implemented. The Ocean Dumping Act (Public Law 92-532~ can be interpreted to ban subseabed disposal of high-level waste. At the international level, the 1972 London Dumping Convention prohibits high-level radioactive waste from being dumped into the oceans or placed on the surface of the seabed. However, since subseabed disposal involves emplacing the waste beneath the sediment surface, the legal status of this option relative to existing international laws and the ongoing Law of the Sea negotiations is presently ill-defined, and there is currently no official U.S. position on the matter.[38] Implementation of this disposal alterna-

[34]DOE analysis that took such factors into account concluded that a maximum of five or six repositories would be needed for a nuclear power system that reaches a maximum of 250 GW_e of installed generating capacity. DOE, *FEIS*, table 7.3.10, p. 7.29.

[35]The conclusions about these other disposal technologies are drawn primarily from three sources in which these alternatives are analyzed: DOE, *FEIS, 1980;* IRG, op. cit.; and U.S. Department of Energy, Statement *of* Position *of* the United States Department *of Energy in the Matter of the Proposed Rulemaking on the Storage and Disposal of Nuclear Waste,* DOE/NE-0007 (Washington, D. C.: Apr. 15, 1980). For brevity, specific references to these sources will be omitted.

[36]Robert D. Klett, *Subseabed Disposal Program Annual Report: Systems, October 1981 Througl September 1982, SAND83-1835* (Albuquerque, N. Mex.: Sandia National Laboratories, February 1984), p. 8.

[37]A ful! discussio of th domestic and international issues in subseabed disposal is found in Edward Miles, Kai N. Lee, and Elaine Carlin, *Sub-Seabed Disposal of High-Level Nuclear Waste: An Assessment of Policy Issues for the United* States (Seattle, Wash.: University of Washington Institute for Marine Studies, July 21, 1982).

[38]K R. Hinga and D.R. Anderson, "The Institutional prOgram for an International Subseabed Repository, " in U.S. Department of Energy, *Proceedings of the 1982 National Waste Terminal Storage* Program Information Meeting (Washington, D. C.: December 1982), pp. 68-70. See also Seabed Programs Division, *The Seabed Disposal Program: 1983 Status Report,* SAND 83-1387 (Albuquerque, N. Mex.: Sandia National Laboratories, October 1983).

tive would probably require an international agreement as well as specific U.S. congressional action.

To enhance the level of international cooperation in the evaluation of subseabed disposal, an international seabed working group has been created with a membership that currently includes the United States, the United Kingdom, France, Canada, Japan, the Netherlands, the Federal Republic of Germany, Switzerland, and the Commission of European Communities. In addition, Italy and Belgium have participated as observers in the cooperative R&D efforts of this group. This high level of international interest and cooperation indicates that ***subseabed disposal is widely regarded as the most promising alternative disposal technology to mined geologic repositories.*** In addition to the potential value of subseabed disposal for the United States, it may be useful to maintain a viable seabed R&D program for both low- and high-level radioactive waste to ensure the safe and equitable use of the seabed by the international community and to provide an alternative for those countries that cannot dispose of radioactive waste on land.

Deep Holes

Deep-hole disposal involves the disposal of waste-filled canisters at the bottom of holes 12 to 15 inches in diameter, drilled to a depth of 20,000 to 50,000 ft, well below the maximum depth of ground water movement. At these extreme depths, the potential for disturbance by natural surface forces or human intrusion or for transport by ground water to the biosphere would theoretically be minimized. However, significant uncertainties remain about the character of the hydrogeologic environment and about waste/rock interactions at these depths. Simply determining the suitability of alternative sites at such depths is extremely difficult.

This concept requires larger holes and heavier drilling equipment than are currently available, although these technical requirements are probably manageable by extensions of existing technology. The difficulty of keeping holes of this depth open may complicate waste emplacement. Moreover, the logistics of deploying a full-scale, deep-hole system may be significant; as many as 2,000 holes may be required if the commercial spent fuel from existing reactors and those under construction are to be accommodated. This number could conceivably be reduced by a factor of 10 for high-level waste from reprocessing operations if the heat produced by the waste did not cause significant problems. Each hole would probably require 3 to 6 years to drill. Once emplaced, it might be practically impossible to retrieve the waste and extremely difficult to verify the degree of isolation obtained.

Rock Melting

Rock melting involves pumping newly generated high-level liquid waste into a conventionally mined cavity at depths of 5,000 to 6,000 ft. The high levels of heat produced by the waste would theoretically melt the surrounding rock within several decades; the resultant resolidification of the rock/waste mixture into a presumably insoluble matrix would require many hundreds of years. Rock melting can only be used for disposing of newly generated high-level waste from the reprocessing of unaged spent fuel. Therefore, any high-level waste generated from reprocessing older spent fuel, as well as the transuranic waste from reprocessing, will have to be disposed of in another manner.

Since the rock-melting concept has not been studied to any great extent, it contains numerous and potentially significant uncertainties about waste handling and emplacement techniques, about the physical and chemical interaction of the melted material with the host rock, and about the potential migration of the radioactive material after emplacement. Retrieval of the waste is not possible with rock melting, and verification of isolation after emplacement, even over the short term, may be difficult. The number of rock-melting disposal sites, of course, would depend on the size of the ***cavities*** used. For example, a mined cavity 80 ft in diameter would be capable of containing the high-level liquid waste generated by reprocessing 50,000 tonnes of spent fuel. Rock melting could offer substantial cost advantages over the development of mined repositories because the mining activity for rock melting is considerably less than that for the development of mined repositories.

Well Injection

From an operational point of view, a relatively simple means of permanently isolating liquid high-level waste from reprocessing would be to pump it to depths of 500 to 5,000 ft into a well in a suitable hydrogeological environment at or near a reprocessing plant. Two such injection wells would probably be required for a reprocessing plant with a capacity of 2,000 tonnes/year (yr). Retrieval of wastes injected into deep wells would be limited, if not entirely impractical.

In grout injection, certain suitable rock formations, such as shale, at depths of 300 to 500 ft would first be hydrofractured by injecting a fluid under high pressure down a borehole. A mixture of liquid radioactive waste and self-hardening grout, such as cement, would then be injected into the fractured rock, leaving the waste in a relatively immobile and essentially irretrievable form. Hydrofracturing has been used at the Oak Ridge National Laboratory to dispose of 1.8 million gallons of liquid defense waste at a single well site, and monitoring has shown no indication of any postinjection migration of radioactive material away from the grout sheets. Approximately 40 grout injection wells would probably be required at a reprocessing plant having a capacity of 2,000 tonnes/yr.

Well-injection techniques have already been used to dispose of various types of industrial wastes. In fact, there are approximately 300 industrial waste-disposal wells that have been or are in operation in the United States. However, at this time, there are only limited field data on the long-term containment of these wastes. In addition, deep-well injection of any waste is prohibited in 12 States and discouraged in another 7. Nine other States have regulations controlling its use.

Ice Sheets

The ice sheets of Greenland and Antarctica, where ice thickness reaches several thousand feet, could conceivably provide a remote, low-temperature environment for containing radioactive waste. The waste could be allowed to melt down through several thousand feet of ice to the bedrock under the ice, to be suspended in the ice to a depth of a few hundred feet from cables anchored at the ice surface, or to be stored in surface facilities that would gradually sink toward the bedrock under the weight of naturally accumulating snow and ice. In the first and second cases, refreezing of the water above the waste as it melts through the ice would theoretically seal the err placement hole. Cases two and three could theoretically provide a certain degree of retrievability for a few hundred years. However, once inside the ice sheet, the waste would migrate slowly (over an estimated period of tens to hundreds of thousands of years) with the ice toward the perimeter of the ice sheet where the ice breaks off as icebergs.

Although there are apparent advantages to this disposal concept, an international group of glaciologists recommended in 1974 that the Antarctic ice sheet not be used for waste disposal because of the many uncertainties about its general nature, evolution, and behavior, as well as the unknown relationship between ice sheet dynamics and as yet unpredictable climatic changes. The principal uncertainties concern the stability of the ice masses for very long periods (10,000 years or more) and the possibility that the waste, once in contact with the basement rock, would be broken up mechanically and escape along unknown pathways. As in subseabed disposal, international negotiations and the signing of treaties would be necessary before this concept could be implemented.

Space

Placing encapsulated radioactive waste into orbit around the Sun would eliminate the waste irretrievably from the Earth itself. According to concepts studied by DOE, spent fuel would first be reprocessed and the high-level liquid waste from reprocessing would be solidified into an acceptable waste form. After transporting the solidified waste to the launch site, an upgraded space shuttle would carry the waste into orbit around the Earth. An orbital transfer vehicle would then be used to carry the waste from the shuttle to the position of solar orbit between Earth and Venus. (Shooting the waste directly into the Sun would require too much fuel to be practical.) After the orbital transfer vehicle had been recovered, the shuttle would return to Earth for reuse.

Although conceptually attractive and probably technically feasible, space disposal is not considered an immediate and viable disposal option because of undeveloped technology, the large number of space shuttle launches required (a thousand or more per year for spent fuel or 4 to 6 dozen per year for high-level waste), and the uncertain, yet potentially serious, consequences of an accident during launch that might release significant quantities of radioactive waste into the atmosphere. Since space disposal appears to be economically feasible only for selected long-lived elements, or perhaps for the total amount of high-level reprocessed waste, reprocessing of commercial spent fuel would be required first. An alternative disposal system would then be needed for the remaining radioactive waste not destined for space.

Assuming adequate funding and the resolution of existing technical problems, this disposal concept could possibly be ready for use by the year 2000. However, resolution of numerous and potentially significant political and international issues as well as a large number of legal complexities could lengthen the time needed to implement this disposal option.

Transmutation

Transmutation is a treatment (not disposal) technique that theoretically could be used to convert (transmute) the long-lived radionuclides in radioactive waste (in particular, the transuranic radionuclides such as Np^{237}) into stable or short-lived radioisotopes by neutron bombardment in nuclear reactors. The process requires reprocessing spent fuel, with the addition of a step that would separate (partition) the long-lived radionuclides from the liquid high-level waste so that they could be incorporated into new fuel rods and recycled through nuclear reactors. Although this process should theoretically reduce the long-term hazards associated with the waste, recent work has indicated that the process may result in an increased radiation hazard during the short term because of the additional complex operations that are involved, along with a very small decrease in long-term hazards.[39] In fact, partitioning and transmutation involve such an increase in operational complexity that the process can be seen as a new fuel cycle rather than simply as an incremental modification of the reprocessing fuel cycle.[40]

[39] A. G. Croff J. O. Blomeke, and B. C. Finney, *Actinide Partitioning-Transmutation Program Final Report. I. Overall Assessment*, ORNL-5566 (Oak Ridge, Term.: Oak Ridge National Laboratory}, June 1980).

[40] Ibid.

Since only 5 to 7 percent of the recycled elements are transmuted while the fuel is in the reactor, numerous recycles would be required to transmute all the long-lived radioisotopes. Although specially designed reactors could conceivably increase the rate of the transmutation process, most of these advanced technologies would require 20 to 30 years to develop. Transmutation would substantially increase both the handling requirements and the volume of secondary wastes generated, thereby more than doubling the total costs of waste management. In addition, since fission products have to be disposed of after transmutation, the need for other waste disposal technologies would not be eliminated.

Comparison of Disposal Alternatives

The general attractiveness of a particular disposal option as a basis for the Federal waste management program is affected by the following factors: 1) the relative degree of safety it offers, 2) the type of waste it can accommodate, 3) its provision for retrieving waste, 4) the potential international complications from developing or deploying the option, and 5) cost .

Technology Status

Disposal in mined geologic repositories has received far more attention on a worldwide basis, and hence is far more advanced in development, than any of the other disposal technologies. As discussed above, subseabed disposal is also now the focus of an international research effort, and its scientific and engineering feasibility could conceivably be tested by the end of this century. The other technologies have received far less attention, and it would require considerable effort to develop the same level of understanding about their advantages and disadvantages that now exists about mined repositories and subseabed disposal.

Relative Degree of Safety

It is difficult to compare different waste emplacement and disposal options in terms of safety, not only because some have not been analyzed in much detail, but also because such comparisons involve a complicated balancing between differences in long-term isolation on the one hand and offsetting differences in near-term operational risks on the other. In general, the more remote the environment into which the waste is emplaced (e. g., outer space), the greater the isolation that can be achieved. At the same time, remote environments involve increased difficulty and risks during emplacement (e.g., the risk of accidental reentry of waste into the atmosphere in space disposal) and greater difficulty of monitoring the waste to detect unanticipated problems (and of taking corrective actions such as retrieval) if such problems arise.

An additional safety consideration arises in the case of those disposal alternatives, such as rock melting, that require that spent fuel be reprocessed. If reprocessing were undertaken specifically to allow use of such an alternative, the additional operational risks and worker exposures resulting from reprocessing would have to be balanced against any long-term safety advantages afforded by the disposal technology.

Type of Waste

Because of significant uncertainties about the future of commercial reprocessing in this country and the large quantities of spent fuel expected to be generated by the reactors that now are operating or are under construction, it appears possible that at least some spent fuel might be discarded directly as waste. Thus, the ability to accommodate spent fuel as well as high-level waste from reprocessing could be an important consideration in choosing a disposal system. Only some disposal technologies—e. g., mined repositories, deep holes, subseabed, and space—would have that ability, and in some of those cases (in particular, space disposal), technical considerations could make their use for spent fuel impracticable.

Ability to Retrieve Waste

Because of the uncertainties about the degree of long-term isolation that any disposal system would provide, it maybe desirable to maintain some ability to recover the waste after emplacement if the development of scientific understanding shows that the risks were greater than anticipated at the time of emplacement. In fact, EPA's proposed criteria for high-level waste disposal would require that removal of most of the waste be possible for a reasonable period after disposal.[41]

Because disposal systems rely heavily on natural barriers to prevent radioactive waste from being released into the environment, these same natural barriers make human access to, and retrieval of, the waste quite difficult after final emplacement. In some cases, retrieval could be practically impossible. Thus, for example, the proposed EPA retrievability requirements might preclude use of such technologies as deep-hole emplacement and rock melting.

In addition to such safety considerations, retrievability might also be desirable in order to keep the option of reprocessing spent fuel. The mined geologic repository appears to be the only disposal technology that could allow economic retrieval of spent fuel after emplacement, although this may only be possible before the repository has been backfilled and sealed.

Potential International Complications

Legal and institutional difficulties at the international level could be encountered in any attempt to use space, subseabed, or ice sheet disposal. However, the extent to which these problems could constrain the development of these disposal alternatives is uncertain. The potential for such complications could make some technologies relatively unattractive as a choice for the primary focus of the United States' radioactive waste-management program.

cost

Preliminary cost estimates by DOE indicate that mined geologic disposal and subseabed disposal could be the least expensive options (on the order of 0.1 C/kilowatt-hour [kWh] of nuclear-generated electricity), while deep-hole disposal could cost several times as much (around 0.3¢/kWh).[42] Estimates of the costs of other options are too incomplete to permit a similar calculation of the unit cost of disposal. All such estimates are uncertain at this point, in part because the final safety standards and reg-

[41] EPA, *DEIS on 40 CFR 191*, p. 127.
[42] DOE, *FEIS*, table 6.2.7, p. 6. 192.

ulations for high-level waste disposal have not been adopted yet, and thus the final performance requirements for disposal systems are not certain. In addition, the cost of those disposal options that require reprocessing is unknown because it is not clear if the cost of such reprocessing would be offset completely by the sale of the recovered uranium and plutonium or if part or all of the cost would have to be included as part of the cost of waste disposal. Nonetheless, since these estimated costs (excluding reprocessing costs) are a small fraction (a few percent) of the typical current new construction cost of generating nuclear electricity with a new facility,[43] it appears unlikely that the ultimate disposal costs would significantly affect the economics of nuclear power even if they are increased substantially over current estimates.

Conclusions

Based on analyses of the above factors, the de*velopment of mined repositories in the continental United States appears to provide the most immediately available disposal technology suitable for both spent fuel and high-level waste from reprocessing that could be developed by the United States.* Despite potential international problems, subseabed disposal presently provides the most promising alternative to the use of mined repositories. If commercial reprocessing is ever developed fully, it may be advantageous to consider other options, such as deep holes or rock melting, for disposing of the high-level waste from reprocessing. However, even if all spent fuel were reprocessed and the high-level waste were disposed of using another disposal alternative, there would still be other waste products generated by the reprocessing operation (in particular, large volumes of transuranic-contaminated waste) that may have to be disposed of in mined repositories.

Although the development of mined repositories could be deferred until more information about alternative disposal technologies is available, it is not clear what benefits would be gained by such deferral.[44] In fact, ***there is considerable consensus within the technical community that the development of mined repositories should not be deferred, and the Nuclear Waste Policy Act of 1982 (NWPA) made a commitment in law to operation of a geologic repository by 1998 (see*** ch. 5).

There is disagreement about the desirability of developing other disposal options as insurance against the remote possibility that mined repositories cannot be developed because of unforeseen technical or institutional problems. The annual budgets for the commercial waste management program have increased gradually from $1.7 million in fiscal year 1972 to approximately $317 million in fiscal year 1982. Of this latter amount, approximately 97 percent is devoted to the development of mined repositories. Subseabed, deep-hole, and space disposal options may be investigated further as technologies to back up or complement the development of mined repositories, but are not now planned for full development. NWPA also provides for accelerated investigations of such alternative disposal technologies.

[43] Ibid., pp. 7.50-7.51.

[44] See discussion in issue 1, app. B

WASTE STORAGE

Unlike disposal technologies, storage technologies are designed to allow easy retrieval of the emplaced material. Thus, they cannot rely as heavily on remoteness and impenetrable natural barriers to prevent accidental releases and human intrusion, but instead must use engineered features and continued human control. In effect, the price of easy retrievability is the need for continued care, maintenance, and monitoring of the storage facility.

As noted in chapter 2, large amounts of new storage capacity will be needed at least for the next several decades simply to hold the spent fuel generated by commercial reactors until adequate disposal or reprocessing capacity becomes available. Storage for considerably longer periods may also be used either to maintain access to spent fuel for possible future reprocessing or to allow waste (either spent fuel or high-level waste) to cool before emplacing it in a repository for permanent disposal. Some also view permanent storage as an acceptable way, in itself, to provide final isolation of the waste. (For further discussion, see issue 1 in app. B.) Thus, storage technology may be required to function for periods ranging from 10 years or less to 100 years or more.

Discussions about storage technology are sometimes clouded by the use of different terms (e. g., ' 'away-from-reactor' [AFR] and "monitored, retrievable storage' [MRS]) that have been associated with particular policy debates (see issue 4 in app. B). For example, the term "AFR' came into general use in the debate about whether the Federal Government should provide centralized (thus, away-from-reactor) storage facilities to enable the Government to accept spent fuel from utilities during a relatively short interim period until a geologic repository would be available, which was assumed to be as quickly as possible. In contrast, the term "MRS" was introduced in the context of a debate about whether the Federal Government should provide storage facilities designed for spent fuel and high-level waste that could provide an alternative to geologic repositories for an extended period—perhaps 100 years or longer. However, some also see an MRS facility as providing a cushion against relatively short slippages in the geologic repository program. In that event, there would be little practical difference between the two concepts.

In general, a system that can store spent fuel satisfactorily can also be designed to store high-level waste from reprocessing. Therefore, although the discussion of storage in this section focuses on spent fuel storage, for which there is the greatest immediate need, it also pertains to storage of solidified high-level waste from reprocessing.

Interim Storage Technology

Water-Filled Basins

Practically all the existing commercial spent fuel is currently stored at reactor sites in water-filled basins that were originally designed to store freshly discharged spent fuel for a short period (6 months) until it could be reprocessed. Such basins are an effective way to provide the high level of radiation shielding and thermal cooling needed during such initial storage periods.

Photo credit: Department of Energy

Spent fuel storage basin at a commercial nuclear powerplant

Since reactor basins were originally not intended to provide storage for an accumulating inventory of spent fuel, their potential capacity was not maximized. The capacity of those reactor basins, or of new independent water basins, may be increased in two ways: reracking and rod consolidation.

Reracking allows closer spacing of spent fuel elements by replacing the original, inefficient, but relatively inexpensive aluminum storage racks that hold the spent fuel assemblies with more expensive racks made of other materials. Because reracking in existing basins is by far the least expensive and easiest way to provide additional storage capacity, utilities have been doing it as needed since the mid-1970's. By reracking, utilities can increase the capacity of many reactor basins that were designed originally to hold up to 4 to 5 annual spent fuel discharges by up to 10 additional annual discharges. DOE assumes that utilities will exploit the potential for reracking to the maximum extent possible before considering other storage options.

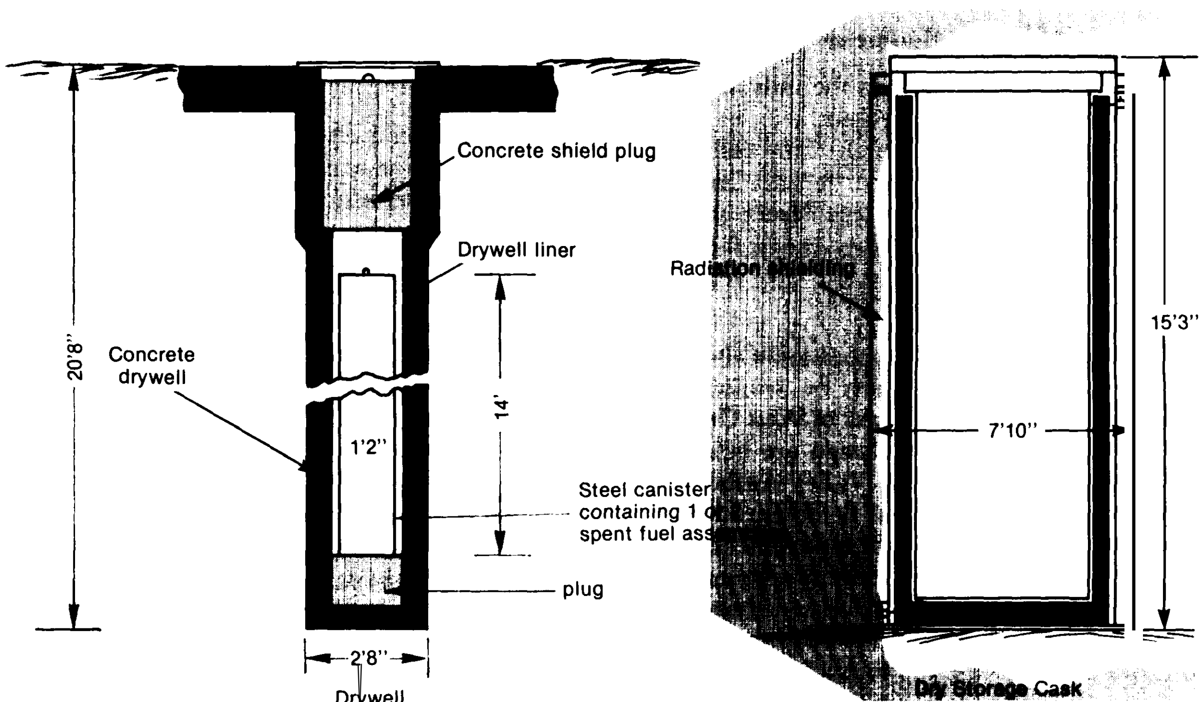
Rod consolidation involves disassembling spent fuel elements and packing the individual fuel rods more closely together in steel storage canisters. This technology could allow the capacity of existing storage basins to be nearly doubled in some instances (subject to structural limitations on the ability of the basin to withstand the additional load) at a cost comparable to reracking. Although large-scale rod consolidation has not been demonstrated yet, such demonstrations are planned for the next few years, If successfully demonstrated, this method could reduce the need for additional storage facilities to some extent by the end of the decade, and substantially by the end of the century. However, rod consolidation will probably not be usable at every reactor because of structural limitations on the total weight of spent fuel that can be placed in some water basins. Rod consolidation could also be used to increase the storage capacity of the dry storage technologies discussed next.

Dry Storage

Several concepts for dry storage of spent fuel are under consideration for new storage facilities (see fig. 3-6). Since dry storage appears to be suited for storage over long and uncertain periods, it has been selected over water basins in each major Federal analysis of extended storage options .45 Most of the following dry storage concepts require sealing spent-

[45] U.S. Atomic Energy Commission, *Preliminary Draft Environmental Statement, Retrievable Surface Storage Facility* (Richland, Wash.: November 1974); U.S. Department of Energy, *The Monitored Retrievable Storage Concept: A Review of Its Status and Analysis of Its Impact on the Waste Management System*, DOE/NE 0019 (Washington, D. C.: December 1981); D. E. Rasmussen, *Comparison of Cask and Drywell Storage Concepts for a Monitored Retrievable Storage/Interim Storage System, PNL-4450* (Richland, Wash.: Battelle Memorial Institute, Pacific Northwest Laboratory, December 1982.

Figure 3-6.-Dry Storage Concepts for Spent Fuel



Each drywell would hold a steel canister containing about 0.5 tonnes of spent fuel (1 or 2 fuel assemblies depending upon the type of reactor).

Each cask would contain about 10 tonnes of spent fuel (24 to 52 assemblies).

If licensed, dry storage technologies like these may provide a relatively inexpensive, flexible alternative to water-filled basins for in-

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fuel elements in steel canisters prior to emplacement:

- Air-cooled vault—a large concrete structure using natural air convection for cooling.
- Concrete surface silo-a concrete cylinder sitting vertically on the ground.
- Casks—large metal casks (which may be designed to be used for transportation as well) sitting vertically in warehouselike sheds.
- Surface drywell (dry caisson)—a steel- and concrete-lined hole that will hold one or several spent fuel elements.
- Tunnel drywell storage—drywells sunk in the floor of subterranean tunnels.
- Tunnel rack storage—movable racks placed in tunnels inside a mountain.

Comparison of Interim Storage Technologies

Status of Technology Development

Because the water-filled basin is the only storage technology now in use in licensed facilities, it has been considered until recently the only viable option for new facilities in the next decade. Estimates of the time required to design, construct, and license an independent basin facility range from about 7 years at a licensed reactor site to 9 years at a new site.

However, recent studies indicate that some alternative dry-storage technologies may be available for use before 1990.[46] A cast iron cask of West German design and a cask of U.S. design are being used by DOE and the Tennessee Valley Authority (TVA) for tests and a licensed demonstration expected to be completed in 1987. It is possible that such cask technology could be licensed on a generic basis, i.e., approved for use at any licensed reactor site, thereby reducing the lead time required for a decision by a utility to use the technology. Both drywells and surface silos are being tested currently by DOE at the Nevada Test Site.

Because of the significant potential advantages of these technologies in stiety, cost, time, and speed of implementation, it seems important to determine their licensability and actual cost quickly, particularly for at-reactor use. NWPA includes measures to accomplish this. If no major licensing problems are encountered, cask or drywell facilities could be constructed at reactor sites in about 4 years .47 Additional research, development, and demonstration of dry storage will be required to develop a full-scale system that can reliably receive, package, and emplace waste at the very high annual rates (2,000 tonnes/yr) that would be involved in a large, centralized storage facility.[48] There is, however, no apparent technical reason why this cannot be done.

The cask and the surface drywell are currently considered to be leading candidates for new storage capacity both at existing reactor sites[49] and at centralized facilities for interim or extended storage.[50] A DOE study estimates that a centralized dry storage facility using either casks or drywells could be designed, sited, and constructed in about 11 years.[51] Other dry-storage technologies, such as the tunnel-rack system, have received less study to date .52

NRC has adopted regulations for licensing independent spent fuel storage facilities using wet or dry technologies for periods up to 20 years .53 Since these regulations were designed for interim storage, it is not clear whether additional issues might be raised in the case of extended storage (for periods up to 100 years or longer) .54 If extended storage facilities were intended to be used for terminal isolation, for example, more sophisticated engineered features such as waste packages might be required to control releases that might occur if institutional control were lost or abandoned. If existing regulations had to be modified for licensing facilities for extended storage, additional time could be required to construct such a facility.

Safety

There appear to be no fundamental questions about the technical ability to design, construct, and

[46] E. R. Johnson Associates, Inc., *A Preliminary Assessment of Alternative Dry Storage Methods for the Storage of Commercial Spent Nuclear Fuel, JAI-180, DOE/ET/47929-1* (Reston, Va. : November 1981).

[47] Ibid.
[48] Rasmussen, op. cit., p. 6.46.
[49] E. R. Johnson Associates, Inc. , op. cit.
[50] Rasmussen, op. cit.
[51] DOE, Th*e Monitored Retrievable Storage Concept.*
[52] Ibid.
[53] 10 CFR, pt. 72.
[54] DOE, Monitored Retrievable *Storage Concept,* p. *2-14*

operate interim spent fuel storage facilities to meet applicable radiation protection standards as long as continuing surveillance and maintenance of the facilities is provided. Safe storage in water basins has already been demonstrated, and it appears likely that equally safe, perhaps safer, storage can be provided with dry-storage technologies.[55] While there may be disagreements about the safety of particular system designs (e. g., certain methods for expanding the capacity of existing storage basins at reactors), these disagreements do not challenge the conclusion that safe storage is technically feasible.

Water basins are simple structures that have been used successfully for the storage of radioactive materials, including spent fuel, for 30 years. The engineering practices and procedures involved in their design and construction are well established. Experience shows that spent fuel can be stored under water safely without significant deterioration of the fuel elements for periods of at least 20 years and perhaps considerably longer, particularly if the fuel assemblies are sealed in stainless steel canisters to contain leakage.

Although there has been much less experience with dry storage than with water basins, dry technologies may have potential safety advantages. First, unlike water-filled basins, they do not rely on an active cooling system. Furthermore, the heavily shielded containers required in most dry technologies would provide a massive physical barrier against accidents (e. g., airplane crashes) or sabotage and would limit the effects of such an event to a few fuel elements. However, longer aging (about 5 years) is required before spent fuel can be placed into dry storage, and the fuel, once encapsulated, becomes hotter than in a water basin. While there has been relatively little experience with dry storage of spent fuel from light-water reactors (LWRs), NRC regulations for independent interim storage facilities contemplate licensing dry-storage facilities.[56]

The conclusion that high-level radioactive waste can be stored safely is based on the assumption that the storage facilities will continue to be controlled and maintained.[57] ***However, extended (or permanent) storage raises a safety issue that does not arise with interim storage: the possibility that institutional control of the storage facility would be terminated before the waste decays to innocuous levels.*** This situation could result either from the loss of society's ability to care for the facility (through war or social regression) or, perhaps more likely, from carelessness or declining concern by later generations, leading to a decision not to continue to bear the costs of maintenance despite the potential long-term consequences.

No detailed quantitative analysis yet compares the safety of extended storage to that of direct disposal as a means of providing final isolation.[58] Existing analyses of the safety of storage facilities deal only with the releases that might occur during a period of temporary storage under continuous human control. No analyses of accidents that could cause releases from a storage facility over a very long period are comparable in thoroughness to the many studies of the possible ways that wastes could escape from a mined repository. In particular, there are no studies of the consequences of premature termination of institutional control, the "accident' in a storage facility that is most comparable to a physical breach of containment in a mined repository.

Flexibility

Water basins and dry vaults are fixed structures with physical limits to their storage capacity. While they can be designed to allow modular expansion, such expansion is usually economical only for large increments of capacity. In addition, they require relatively long lead times for construction and licensing—about 7 years for a basin or dry vault at a reactor site, compared to as little as 3.5 years for a cask storage facility.[59] contrast, the dry technologies that use separate, freestanding containers for individual fuel elements (shipping casks, drywells, and silos) all allow expansion of capacity in

[55]M. S. Plesset, "ACRS (Advisory Comittee on Reactor Safeguards) Comments on Proposed Rulemaking on the Storage and Disposal of Nuclear Waste, " Letter (Dec. 10, 1980) to John F. Ahern, U.S. Nuclear Regulatory Commission. Quoted in DOE, Monitored *Retrievable Storage Concept. See* also U.S. Nuclear Regulatory Commission, *Waste Confidence Decision.*

[56]10 CFR, pt. 72.

[57]Plesset, op. cit.

[58]A brief qualitative comparison is found in the discussion of issue 1 in app. B.

[59]E. R. Johnson Associates, Inc. , op. cit., table 7.1, p. 7-3.

very small increments and on relatively short notice once the required packaging facilities are available. As a result, they appear better able to meet the uncertain storage requirements that now face utilities.

cost

The total undiscounted costs of constructing and operating a 1 ,000-tonne storage facility at a reactor site are estimated to range from $82 million (for casks using fuel consolidated in the reactor basin) to $260 million (for unconsolidated fuel in a dry vault).[GO] The comparable undiscounted totals for a centralized dry-storage facility with a 48,000 -tonne capacity range from $2.4 billion (for surface drywells and tunnel racks) to $5.3 billion (for tunnel drywells).[61] A comparison of capital and operating costs for a range of at-reactor spent fuel storage options is shown in table 3-4.

The wide range of technical and financial assumptions used in the available studies of storage technologies precludes any simple comparison of the cost per tonne of using each of the storage technologies at different locations. Examination of the available DOE studies, however, leads to several general conclusions:

1. ***For both at-reactor and away-from-reactor use, those technologies providing relatively large, fixed capacities (water basins or dry vaults) appear*** to be ***more expensive per tonne of*** storage than ***do the dry*** technologies that allow expansion in annual modules (drywell, ***silos, and casks). 62*** The principal reason is that the modular dry technologies have a lower initial capital cost, and their remaining costs can be spread out over time as additional containers are built. Deferring much of the total costs in this way reduces the discounted cost of storage and thus makes the expandable technologies even more attractive financially as capital costs increase. It also lowers the financial risk involved in making a large investment in fixed storage capacity when the total amount of storage needed is uncertain.

Table 3-4.—Comparison of Capital and Annual Operating Costs of At= Reactor Storage Options
($/kilogram of uranium–operating costs in parentheses below capital costs)

Storage option	Facility capacity (tonnes) 500	1,000	2,000
Cask (5-tonne capacity).	118	109	103
	(1.3)	(0.7)	(0.4)
Vault (fuel canned).	100	87	81
	(1.9)	(1.6)	(1.5)
Cask (l O-tonne capacity). . . .		75	73
	(0!;	(0.2)	(0.2)
BWR reracking (stainless steel to berated stainless steel)		61	60
	(1;;	(1.1)	(1.1)
Pool		59	42
	(4.9)	(3.0)	(2.0)
Silo		59	42
	(4:$	(3.0)	(2.0)
Vault (fuel not canned)		48	39
	(2.1)	(1.5)	(1.2)
Drywell.		41	35
	(0::	(0.7)	(0.6)
PWR reracking (stainless steel to berated stainless steel)		38	38
	(0:;	(0.5)	(0.5)
Rod consolidation within existing pool[a].	40	—	—
PWR reracking (low density to stainless steel)		25	25
	(Oi;	(0.4)	(0.4)
BWR reracking (low density to berated stainless steel)		22	22
	(1%;	(1.0)	(1.0)
BWR reracking (low density to borate stainless steel) .		20	20
	(1%;	(1.0)	(1.0)
PWR reracking (low density to berated stainless steel)		18	18
	(Oi;	(0.4)	(0.4)
Double tiering[b].	—	—	—

aNo operating cost data available.
bNo cost data, but reracking costs represent lower limits.

SOURCE: Electric Power Research Institute, Cost *Comparisons for On-site Spent-Fuel Options,* EPRI NP-3380, May 19S4, tables 12-1, 12-2.

2. ***The least expensive way to provide storage using casks or drywells appears*** to be to locate ***the storage facility at I-he site of a reactor, reprocessing plant, orgcologic repository where existing staff and equipment can be used for packaging and handling spent fuel (or solidified high-level waste) fiwstorage.*** A major part of the capital cost for a modular dry-storage facility at an independent site is for the equipment and facilities needed for handling and packaging the spent fuel prior to insertion in

[60]Ibid., table 8-1, p. &a, Amounts are in 1981 dollars.
[61]DOE, *The Monitored Retrievable Storage Concept,* table 2-3, p. 2-20. Amounts are in 1981 dollars.
[62]E. R. Johnson Associates, Inc., op. cit., p. 2; DOE, *FEIS,* vol. 2, app. A, table A-8, p. A-1OO.

individual storage units.[63] A recent study of centralized extended storage using casks and drywells concluded that substantial savings would be achieved if the cost of handling facilities (several hundred million dollars) could be avoided by locating the storage facility at a repository or reprocessing plant that would have such facilities in any case, rather than at an independent site.[64] Since it may also be possible to use modular dry storage at reactors with only relatively minor modifications to existing facilities, decentralized storage at reactors may also prove to be less expensive than centralized storage at a stand-alone facility. However, there is as yet no consistent comparison of centralized v. decentralized storage using dry-storage technologies and using the same financial assumptions for both cases.

3. ***Once a spent fuel element has been stored at an interim storage facility, it may be less expensive to leave it there indefinitely than to remove it and transport it elsewhere.*** For example, DOE estimates that the annual cost of caretaker operations at a 48,000-tonne dry-storage facility would be at most about $2.7 million, or about $56/tonne/yr. In contrast, annual retrieval operations would range from $4.1 million to $10.7 million, while transportation to another site would cost at least $15,500/tonne— nearly 300 times the annual caretaking cost.[66] Thus, an important consideration in planning the full-scale operation of a waste disposal system will be how rapidly to draw down the backlogs of spent fuel that will already have been placed in storage by the time disposal begins. This point is discussed further below and in chapter 6.

[63] DOE, *The Monitored Retrievable Storage Concept;* Rasmussen, op. cit.
[64] Rasmussen, op. cit.
[65] DOE, *The Monitored Retrievable Storage Concept, table 2-1, p. 2-18.*
[66] Ibid., table 2-4, p. 2-22.

WASTE TRANSPORTATION

Spent fuel is transported using heavily shielded containers called shipping casks. At present three types of casks are used:[67]

- Legal weight truck casks weigh about 23 tons and hold one pressurized water reactor (PWR) fuel assembly or two boiling water reactor (BWR) fuel assemblies. There are 11 such casks in the United States.
- Overweight truck casks weigh about 35 tons and hold 3 PWR fuel assemblies or 7 BWR fuel assemblies. They are restricted in movement because of their weight. There is one such cask under construction.
- Rail casks weigh from 64 to 90 tons and hold from 7 to 10 PWR fuel assemblies or from 18 to 24 BWR fuel assemblies. There are six rail casks in the United States.

Solidified high-level waste from reprocessing would also be shipped" in similar heavily shielded casks, although such casks are still in the conceptual design stage.

The combined capacity of the existing truck and rail casks is 28 tonnes. DOE estimates that this capacity would be adequate for shipments through 1988, even if all additional storage capacity beyond existing basins were provided at a centralized storage facility, and that it would be possible for the industry to meet the demand for additional casks after that time.[68]

Future casks may be somewhat different from those now in operation. New casks may be able to carry up to twice as much fuel as current ones if designed to carry only fuel that is at least 5 years

[67] These data are drawn from U.S. Department of Energy, ***Spent Fuel*** *Storage* ***Fact*** *Book, DOE/NE-0005,* April 1980, p. 54. OTA is currently conducting a more detailed examination of container testing, safety standards, and risks associated with transportation as part of its ongoing assessment of *Transportation of Hazardous Materials.* Information systems and regulatory and institutional issues relating to the safe transport of nuclear waste and other hazardous materials will also be studied as part of this assessment.

[68] Ibid., p. 39.

old.[69] Such fuel has about one-tenth the output of heat and radiation as 150-day-old spent fuel, for which existing casks were designed. Since it appears unlikely that spent fuel less than 5 (or even 10) years old would be moved for the next few decades,[70] there will be strong financial incentives to develop and use casks that hold more spent fuel than current designs. In addition, transportation in the future may be done in casks that are designed for storage,[71] and perhaps for disposal for 72 as ‘en ”

Safety

Standards

Transportation of highly radioactive materials is governed by NRC and U.S. Department of Transportation (DOT) regulations requiring that shipping casks be designed to limit radiation exposure to bystanders during normal operations (10 millirems/hour at 6 ft from the cask) and to prevent release of radioactive materials from the cask even in severe accidents. Casks must be designed to withstand a sequence of hypothetical tests without releasing more than a specified small amount of radioactive material.[73] (It should be noted that the ability of a cask design to pass these tests is assessed by analytical methods rather than by actual performance of the tests on sample casks.) These design criteria, which are intended to encompass a range of very severe accident conditions, include sequential exposure to:

- a 30-ft drop onto a flat, unyielding surface with the cask oriented to cause the greatest damage;
- a 40-inch drop onto a 6-inch-diameter steel pin mounted on an unyielding surface; and
- 30-minute, all-engulfing thermal environment (fire) radiating at 1,4750 F.

The same requirements have been adopted by the International Atomic Energy Agency and are in general use worldwide,

Questions have been raised about the adequacy of these requirements (and of existing casks designed to meet them) in view of the conditions that might be encountered in realistic accidents. For example, it is noted that some actual fires are hotter than 1,475° F and some accidents involve impacts at higher velocities than those involved in the drop test. In this regard, the regulatory test conditions are engineering criteria that provide a well-defined basis for designing and analyzing casks. They are intended to create stresses on the cask at least as great as those produced by a wide range of extreme accident conditions that could actually be encountered.[74] Thus, while an individual aspect of a specific test (e. g., drop height or temperature) might be exceeded in real accidents, other test aspects are more severe than could he encountered in the real world. For example, objects in the real world are not completely unyielding; if struck by a transportation cask, they would absorb some of the energy of the cask. Similarly, actual fires are not likely to surround all surfaces of a cask completely, as specified in the regulatory test, and a fire that surrounds only part of a cask would have to be hotter and/or longer than the regulatory fire to provide the same heat input to the cask.

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[69] Ibid., p. 39. See also J. A. Bucholz, A Summary *Report* on *Optimized Designs for Shipping Casks Containing 2-, 3-, 5-, 7-, or 10-Year-Old PWR Spent Fuel,* ORNL/CSD/TM-150 *(Oak* Ridge Term.: Oak Ridge National Laboratory, April 1983), table 4a, p. 25. The maximum capacity of an optimal rail cask design for 10-year-old spent fuel is 21 PWR assemblies, compared to existing rail casks holding 12 PWR assemblies.

[70] Analyses generally assume that the oldest fuel would be reprocessed or disposed of first. DOE analysis suggests that even if reprocessing began at large scale by 1990, the youngest spent fuel being reprocessed in 2020 would still beat least 10 years old. U.S. Department of Energy, *Spent Fuel and Radioactive Waste Inventories, Projections, and Characteristics,* DOE/NE-001 7/2, September 1983, table 1.4., p. 20.

[71] D. E. Rasmussen, op. cit., p. 6.32.

[72] Westinghouse Electric Corp., *Engineered Waste package Conceptual Design, Defense High-Level Waste (Form 1), Commercial High-Level Waste (Form 1), and Spent Fuel (Form 2), Disposal in Salt,* AESD-TME-3131 (Pittsburgh, Pa.: September 1982).

[73] 49 CFR 173.398 (c). Transport regulations are 10 CFR 71 and 10 CFR 73.

[74] For example, it has been estimated that the regulatory 30-ft drop onto an unyielding surface would be more severe than about 99.9 percent of all accidents, while the 30- minute fire requirement is longer in duration than 99.8 percent of actual fires involved in rail or truck accidents. See Edwin L. Wilmot, *Transportation Accident Scenarios for Commercial Spent Fuel,* SAND80-2124 (Albuquerque, N. Mex.: Sandia National Laboratories, February 1981), pp. 47-48. Analysis of the 1982 Caldecott Tunnel fire near San Francisco, in which a gasoline tanker burned in a highway tunnel, concluded that the fire could have produced a heat input into a shipping cask ranging from a minimum of one-fourth to a maximum of twice the heat input from the standard regulatory fire conditions. D. W. Larson, R. T. Reese, and E. L. Wilmot, "The Caldecott Tunnel Fire Thermal Environments, Regulatory Considerations and Probabilities" (Albuquerque, N. Mex.: Sandia National Laboratories, undated), table 2.

Experiments that have been performed using shipping casks show how the regulatory tests can be more severe than actual accident conditions that, at first glance, appear to exceed the requirements. For example, a cask would only reach a speed of about 30 miles per hour (mph) in the regulatory 30-ft drop test. Yet in an experiment in which a truck carrying a spent fuel cask was driven head-on into a reinforced concrete target at 61 mph, the actual forces experienced by the cask were less than those that would result from the drop test.[75] In 1984, the British Central Electricity Generating Board performed the 30-ft drop test on an actual 48-tonne steel spent-fuel shipping cask, with no reported damage to the cask.[76]

Similarly, experiments in which spent fuel shipping casks were exposed to fires that were hotter and/or longer than the standard fire specified in the regulations showed that the actual environments produced by those fires were comparable to, or less severe than, the regulatory test requirements.[77] Additional tests to determine the actual properties of various fire environments are now underway at Sandia National Laboratories under DOT sponsorship. Such tests could be quite valuable in resolving questions about the relationship between existing regulatory requirements and actual accident conditions.

In 1981 NRC determined that no immediate changes in current regulations were needed to improve safety. At the same time, it initiated a "Modal Study of Transportation Safety" designed to:

- collect data on severe accident conditions and their relative frequency;
- devise package tests that simulate those accident conditions;
- analyze and/or test packages under severe accident conditions and assess their performance; and
- using this information, evaluate further the adequacy of present standards to protect against potential high consequence accidents and develop possible changes to NRC standards, if appropriate. 78

This study is expected to be completed by the end of 1985.

Whtie OTA did not attempt in this study to evaluate any particular technology designs or regulations, its review of the debate about transportation safety did not reveal any fundamental technical challenges to the conclusion that shipping casks can be designed to prevent significant radioactive releases in realistic accident conditions.[79] At the same time, it is clear that the central role of shipping cask integrity in providing transportation safety places considerable importance on ensuring that great care is taken in the manufacture, testing, use, and maintenance of casks. A transportation panel of the National Academy of Sciences' Committee on Radioactive Waste Management concluded that:

> . . . the transportation of radioactive materials is not a major factor in the total hazards associated with the nuclear power system. However, this conclusion is supportable only if the highest standards of care are applied in all aspects of waste preparation and transportation. 80

[75] Michael Huerta and Richard H, Yoshimura, A *Crash Test of a Nuclear Spent Fuel Cask and Truck Transport System, .SAND77-0419* (Albuquerque, N. Mex.: Sandia Laboratories, January 1978), p. 16. It should be noted that this test was designed to assess the accuracy of analytical techniques for predicting the response of a cask to a collision, rather than to evaluate regulatory standards or cask designs.

[76] *The* Energy *Daily,* Mar. 8, 1984, p. 4.

[77] ,,s,s involving a 30-minute, 1,200° C torch fire led to cask heating that was substantially less than would be produced by the regulatory fire. Manuel G. Vigil, Amado A. Trujillo, and H. Richard Yoshimura, "Measured Thermal Response of Full-Scale Spent Fuel Cask to a Torch Environment, " *Nuclear Technology, vol. 61,* June 1983, pp. 514-520. Analysis of exposure of a shipping cask in a railcar to a 2-hour petroleum fuel fire concluded that the amount of heat input to the cask was about equivalent to that resulting from the 30-minute regulatory test fire. J. E. Hamann et al., " Modelling of Pool Fire Environments Using Experimental Results of a Two-Hour Test of a Railcar/Cask System, *Proceedings of the 6th International Symposium, Packaging and Transportation of Radioactive Materials,* Nov. *10-14, 1983,* pp. *1081-1088.*

[78] NRC comment in preface to P. Eggers, *Severe Rail and Truck Accidents: Toward a Definition of Bounding Environments for Transportation* Packages, NUREG/CR-3499 (Washington, DC.: U.S. Nuclear Regulatory Commission, October 1983), p. iii.

[79] Recent critiques of radioactive waste transportation have focused on the adequacy of existing cask designs and regulatory requirements and have suggested that suitable casks could be designed. Marvin Resnikoff, *The Next Nuclear Gamble (New* York: Council on Economic Priorities, 1983), pp. 20-21. See also Robert M. Jefferson, ' 'Transporting Spent Reactor Fuel: Allegations and Responses, SAND82-2778 (Albuquerque, N. Mex.: Sandia National Laboratories, March 1983); and Robert M. Jefferson et al., "Analysis of Recent Council on Economic Priorities Newsletter' SAND82- 1250 (Albuquerque, N. Mex.: Sandia National Laboratories, May 1982).

[80] Report of the Panel on Transportation to the Committee on Radioactive Waste Management, August 1974, cited in letter from John C. Frye, Chairman of the Committee on Radioactive Waste Management, to Dr. Robert C. Seamans, Jr., Administrator of the U.S. Energy Research and Development Administration, Feb. 12, 1975.

Thus, confidence in the safety of waste transportation will depend on confidence that shipping casks will in fact be designed, constructed, and operated according to packaging regulations. Past ***experience with lax enforcement of packaging regulations concerning low-level waste shipments,[81] and recent criticisms of the adequacy of enforcement of regulations concerning spent fuel shipping casks, 82 suggest that enforcement could become an issue of increasing concern as shipments of spent fuel increase.*** A recent review of the regulatory structure of high-level radioactive waste transportation concluded that it is inadequate in several respects and recommended a careful evaluation of Federal regulation of highway transport of radioactive waste .83

Risk Analyses

Analyses of the risks of transporting spent fuel (or solidified high-level waste) in casks designed to existing regulatory standards generally suggest that the radiological risks to the public from accidental releases of radioactive materials during transportation would be very small in comparison to the health effects from normal operation of the fuel cycle.[84] For example, a recent study evaluated the costs and impacts of shipping 72,000 tonnes of spent fuel (or the wastes from reprocessing that amount of fuel) to five possible repository sites over a 26-year period. This study concludes that for a repository at Hanford, Wash., there would be, at most, 78 nonradiological fatalities and 16 long-term cancer fatalities if the material were all moved by truck, or about 6 nonradiological fatalities and 36 long-term cancers if it were moved by rail.[85] In comparison, EPA's analysis of waste disposal, discussed earlier in this chapter, concluded that a repository containing 100,000 tonnes of spent fuel could cause 1,000 or more deaths in a 10,000-year period after disposal.

These risk studies also indicate that even a worst-case situation, involving a major breach of a cask as a result of an accident or deliberate sabotage, would not lead to catastrophic effects, but rather might result in at most 10 to 15 deaths from cancer in the long term. For example, an NRC study of the effects of releases from transportation of radioactive materials in urban areas concluded that the maximum consequences of accidental penetration of a spent fuel cask would be one cancer death in the long term, with no early fatalities.[86] A DOE study of transportation by truck that examined accident environments much more severe than those specified in the regulatory tests (e. g., a collision producing a large breach in the cask and failure of all of the fuel rods, followed by a 2-hour, 1,850° F fire) concluded that the maximum number of resulting deaths would be about 10, and that the probability of an accident of that magnitude would be less than 1 in 1 million per year.[87]

The NRC study of transportation of radioactive materials in cities also examined the possible effects of deliberate sabotage involving the use of explosives to penetrate a shipping cask, to pulverize part of the contained material, and to disperse that material into the environment. Using conservative assumptions about the amount of material that could be released by sabotage, this study calculated that such an attack on a truck cask loaded with 6-month-old spent fuel in New York City could cause from tens to hundreds of cancer fatalites, while an attack on a rail cask could produce hundreds to thousands of cancer fatalities, depending on the precise time and location of the attack and the weather conditions.[88] (While there would be no early deaths from radiation, the explosion itself could be expected to cause about 10 deaths.[89]) However, a

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[81] U.S. Department of Transportation (DOT) and U.S. Department of Energy, *National Energy Transportation* Study, July 1980, p. 118.

[82] Resnikoff, op. cit., ch. V.

[83] National Research Council, *Social and Economic Aspects of Radioactive Waste Disposal* (Washington, D. C.: National Academy Press, 1984), pp. 123-128. See also Paul F. Rothberg, "Nuclear Materials Transportation: Safety Concerns, Governmental Regulations and Activities, and Options to Improve Federal Programs, Congressional Research Service Report No. 84-45 SPR, Mar. 15, 1984.

[84] U.S. Nuclear Regulatory Commission, *Final Environmental Impact Statement on the Transportation of Radioactive Material by Air and Other Modes,* NUREG-01 70, vol. 1, December 1977, p. 5-52.

[85] Edwin L. Wilmot et al., *A Preliminary Analysis of the Costs and Risk of Transporting Nuclear Waste to Potential Candidate Commercial Repository Sites, SAND83-0867* (Albuquerque, N. Mex.: Sandia National Laboratories, June 1983), table 4, p. 12.

[86] Sandia National Laboratories, *Transportation of Radionuclides in Urban Environs: Draft Environmental Assessment,* NUREG/CR-0743, SAND79-0369 (Washington, 11. C.: U.S. Nuclear Regulatory Commission, July 1980), table 3-11, p. 66.

[87] Pacific No rthwest Laboratory, *An Assessment of the Risk of Transporting Spent Nuclear Fuel by Truck, PNL-2588* (Seattle, Wash.: Battelle Memorial Institute Pacific Northwest Laboratory, November 1978), fig. 2.1, p. 2-4.

88 Sandia National Laboratories, op. cit. , table 5-20, p. 131.

[89] Ibid., table 5-20, p. 131.

more recent assessment, based on experiments using explosives to determine how much material actually might escape from a cask as a result of sabotage, concluded that, at most, 14 cancer deaths might result in the long term, with 4 deaths expected.[90]

While the risk of fatalities from releases of radioactive material during spent fuel transportation is calculated to be very low, the economic impacts from a substantial release could be very high. These impacts are estimated to be roughly comparable for a worst-case accident and deliberate sabotage—from $2 billion to $3 billion for an incident in a City.[91] The major costs of both are almost entirely attributable to the denial of use of the contaminated area while cleanup occurs; once an area has been contaminated to the level that nonuse is necessary, futher contamination does not appear to increase the cost.[92] By way of comparison, accidents involving shipments of other common hazardous materials (e. g., gasoline, anhydrous ammonia, or chlorine) that are less well protected and more likely to escape if a shipping tank ruptures may be more likely to cause significant numbers of deaths than accidents involving shipments of spent fuel .93 However, the costs of a worst-case accident with radioactive waste could be higher because of the cost of cleaning up the resulting radioactive contamination, a problem that does not occur with most other hazardous materials .94

[90] Robert P. Sandoval et al., *An Assessment of the Safety of Spent Fuel Transportation* in Urban Environs, SAND82-2365 (Albuquerque, N. Mex.: Sandia National Laboratories, June 1983). This analysis was based on experiments with fresh fuel. Similar results, in terms of the estimates of the amount of material that would escape, were obtained in experiments using spent fuel. E. W. Schmidt et al., *Final Report on Shipping Cask Sabotage Source Term Investigation,* Battelle Columbus Laboratories, NUREG/CR-2472 (Washington, D. C.: U.S. Nuclear Regulatory Commission, October 1982).

[91] Sandia National Laboratories, op. cit. The maximum direct economic impact for an accident is $2 billion (table 3-11, p. 66) while the maximum for sabotage is $3 billion (table 5-17, p. 128).

'* Ibid., p. 126.

[93] The Probability of an accident leading to one or more deaths is estimated to be about 2.2 in 100,000 per year for shipment of spent fuel in trucks. See Pacific Northwest Laboratory, op. cit., p. 11-3. No such accident has ever occurred. In comparison, DOT reports a number of accidents involving one or more deaths associated with the shipment of gasoline and anhydrous ammonia in 1977 alone. DOT and DOE, *National Energy Transportation Study, table 6-2,* p. 108.

g+ Ibid, This report shows that although there were 1,500 incidents involving the transportation of gasoline, leading to 21 deaths and 47 injuries, the total damage came to $6,981,317.

The adequacy of the worst-case accident analyses that have been performed to date has been questioned on the grounds that substantial uncertainties remain about the severity of ' 'real-world' accidents and about the amount of radioactive material that might be released .95 On the other side, some argue that the analyses deal adequately with the uncertainties by using conservative assumptions that tend to overestimate the consequences.[96]

Transportation risk analyses have not been subject to the same degree of independent peer review as have studies of the risks of geologic disposal. Such a review, taking into account the results of the experiments and studies that have been performed in the last 5 years, could help resolve some of the disagreements about transportation safety and the adequacy of the existing regulatory structure.

Conclusions

OTA did not undertake a detailed evaluation of risks associated with any stage of waste management— storage, transportation, or disposal. However, a brief review of the areas of disagreement between transportation risk analyses suggests that many of the arguments are based on the assumption that very young spent fuel (150 days old or less) is being transported— the assumption that was usually made when rapid reprocessing of all spent fuel was anticipated. Such fuel generates so much heat from radioactive decay that loss of the coolant used to keep the temperature inside the cask to acceptable levels can lead to rapid overheating of the fuel, release of radioactive materials from the solid fuel pellets into the cask cavity, and subsequent escape of those materials into the environment. It should be noted that the analyses leading to the conclusion that the maximum consequences of a worst-case accident would be 10 to 15 cancer deaths take such overheating into account. Others, however,

‹5 Resnikoff, op. cit.

[96] A Federal court has reviewed NRC risk analyses and has concluded that they are adequate as a basis for transportation regulations. *The* City *of New York and the State of New York v.* The United States *Department of Transportation, Et Al. and Commonwealth Edison Company,* Et *Al.,* United States Court of Appeals for the Second Circuit, Docket Nos. 82-6094, 82-6200, decided Aug. 10, 1983. This decision overturned a lower court decision invalidating in part the DOT Reg. HM- 164 governing the highway transportation of large quantities of radioactive materials.

argue that much higher temperatures (and thus much greater release of radioactivity) could result if fuel were shipped that has been cooled after discharge from the reactor less than the 120 days required by NRC regulations-or if a cask were exposed to a fire that is longer and/or hotter than the fire specified in the regulatory test.[97]

These arguments could be rendered moot, or at least greatly reduced in force, by the fact that the only spent fuel likely to be shipped in the foreseeable future will be at least 5 years old, and more likely more than 10 years old.[98] As noted above, the heat output of 5-year-old fuel is about one-tenth that of 150-day-old fuel. As a result, the maximum temperature of the fuel resulting from self-heating will be much lower than is possible with young spent fuel. This has several important implications for analysis of the risk of transporting spent fuel.

First, the consequences of a breach of a cask or failure of its seals would be substantially reduced. Shipment of young spent fuel requires a coolant (generally water) to keep the temperature of the fuel at an acceptable level. Existing studies show that loss of the coolant through a breach in the cask or a failed seal or valve is a principal contributor to total risk because it leads to rapid overheating of young spent fuel. Because the heat output of older spent fuel is so much lower, no coolant is required in the shipping cask to keep the temperature down. In fact, old spent fuel is now shipped without coolant in existing shipping casks,[99] and casks designed especially for transporting older fuel will probably not use a special coolant.[100] As a result, accidents that could breach the cask or cause its seals to fail would not lead to a rapid increase of the fuel temperature, as would be the case if the coolant escaped from a cask carrying 150-day-old fuel.

Because self-heating from radioactive decay is much less of a problem with old spent fuel, fire appears to be the only potential mechanism for heating spent fuel to the high temperatures some have suggested could lead to major releases. One study that argues that very large releases of radioactive materials could occur in a worst-case accident bases this conclusion on the assumption that under certain circumstances the temperature of the fuel might reach as high as 2,000° F, exceeding the temperature at which the fuel cladding would deteriorate (about 1,688° F).[101] Analyses of currently licensed casks show that the hypothetical regulatory fire (30 minutes at 1,450° F) would lead to an average maximum fuel temperature of only about 1,000° F in 120- to 150-day-old spent fuel.[102] An analysis that considered fires more severe than the regulatory fire concluded that even a 2-hour, 1,850° F fire could produce a maximum temperature of about 1,600° Fin 150-day-old spent fuel in a truck cask.[103] Furthermore, this analysis indicates that the major effect of a fire of that length and temperature would be to cause a loss of coolant from the cask, which in turn would lead to rapid overheating of the fuel. This self-heating, rather than the fire itself, would cause most of the sharp temperature increase.[104] This situation in turn implies that a substantially longer and/or hotter fire would be required to produce excessive heating in old spent fuel in a shipping cask, since decay heat from the fuel would play a much less important role. Analysis shows that the regulatory fire would produce a maximum temperature of 660° F in 5-year-old fuel in a rail cask designed for such older fuel. This is only 148° F higher than the normal operating temperature of 502° F. With 10-year-old fuel, the maximum temperature would be 559° F.[105]

These considerations suggest that the risks of transporting spent fuel could be substantially reduced if only older fuel were shipped. One study calculates that the risk from transporting spent fuel by truck in existing shipping casks could be reduced by a factor of about 6 if the fuel were cooled for 4 years before shipment.[106] As noted earlier, there could be strong economic incentives to ship older fuel in casks that have been optimized for that purpose. Designing the casks for fuel that is at least 10 years old would provide an additional margin

[97] Resnikoff, op. cit., pp. 266-267.

[98] U.S. DOE, *Spent Fuel and Radioactive Waste Inventories, Projections, and Characteristics*, DOE/RW-0006, fig. C.2, p. 284, fig. C.3, p. 285.

[99] Jefferson et al., *Analysis of Recent Council on Economic priorities Newsletter*, p. 19.

[100] Bucholz, op. cit., p. 7.

[101] See Resnikoff, op. cit., pp. 266.267.

[102] See Edwin L. Wilmont, *Transportation Accident Scenarios*, p. 17. lessee pacific Northwest Laboratory, op. cit., pp. G-7—G-11.

[103] This study calculates that loss of coolant with no fire would lead to a maximum fuel temperature of 1 360° F (738° C). Addition of a 2-hour, 1,850° F fire increased that maximum to 1,598° F, an increment of 238° F. Pacific Northwest Laboratory, op. cit., app. G.

[105] Bucholz, op. cit., table 3, p. 22

[106] Pacific Northwest Laboratory, op. cit., p. 11-3.

of conservatism compared to 5-year-old fuel since, as noted, it would reduce the maximum temperature reached in the regulatory fire by about 100° F.

cost

A truck cask for spent fuel shipment is estimated to cost about $700,000, while rail casks cost up to $3.9 million.[107] The total cost of shipping 1 tonne of spent fuel for a distance of 1,500 miles is estimated to be about $21 ,000; the cost of transporting the high-level waste from 1 tonne of spent fuel is estimated to be about $3,000.[108] Total transportation costs should represent less than 20 percent of the cost of waste management.[109] These costs can be reduced by using casks designed to ship larger quantities of older spent fuel and by using regional repository sites located to reduce transportation distances to the greatest extent possible.[110]

[107] U.S. Department of Energy, *Report on Financing the Disposal of Commercial Spent Fuel and Processed High-Level Radioactive Waste,* DOE/S-0020, June 1983, table 3-9, p. 18.

[108] Ibid., table 3-8, p. 17.

[109] Ibid., tables A-1, A-2, A-3, A-4, pp. 42-45.

[110] K. D. Kirby et al., Evaluation *of the Regional Repository Concept for Nuclear Waste Disposal,* USDOE Office of Nuclear Waste Isolation Report ONWI-62 (Columbus, Ohio: 1979), pp. 183-186.

REPROCESSING

Status of Reprocessing

The commercial nuclear power system was envisioned originally to include reprocessing of all spent fuel and reuse of the recovered uranium and plutonium. However, while reprocessing and recycling can reduce the requirements for uranium ore, it will not be attractive commercially until the cost of the recovered material becomes competitive with the cost of fresh uranium. At present, nuclear reactors are being delayed or canceled, and no new orders are being placed because of uncertainties about the demand for electricity, the cost of reactors, and other factors.[111] As a result, it appears that there may be an excess capacity in the uranium mining industry and uranium enrichment worldwide through the 1990's,[112] a situation that bodes ill for the commercial attractiveness of reprocessing in the next few decades. At present, there appears to be no private interest in undertaking reprocessing in the United States.[113] Moreover, there is growing agreement within the technical community that large-scale commercial reprocessing will not be attractive economically except as part of a nuclear power system including breeder reactors,[114] and breeder reactors themselves may not become economically competitive with LWRs for decades.[115]

Reprocessing of commercial spent fuel is under way currently in several countries, including France and the United Kingdom, which are contemplating eventual use of breeder reactors. The quickest path for initiating the large-scale reprocessing of commercial spent fuel in the United States appears to be the completion of the Allied General Nuclear Services (AGNS) facility at Barnwell, S.C. However, the owners of that facility have recently abandoned the project, and completion and operation of the plant would therefore probably require Federal intervention.[116] At present, the AGNS chemical separation facility, with a design capacity of 1,500 tonnes/yr, and the spent fuel receiving and storage station have been completed. Full-scale operation of the plant would require construction of additional major facilities for conversion of

[111] U.S. Congress, Office of Technology Assessment, *Nuclear Power in an Age of Uncertainty,* February 1984,

[112] Congressional Budget Office, *Uranium Enrichment: Investment Options for the Long Term,* October 1983. See also "Uranium Shortage Turns to Glut, *Science,* vol. 225, Aug. 3, 1984, p. 484.

[113] " Jilted Reprocessor Vents Spleen, " *The Energy Daily,* Apr. 16, 1984, p. 2.

[114] The International Nuclear Fuel Cycle Evaluation (I NFCE) concluded that recycle of plutonium in LWR'S would be an *economically* marginal proposition and that most countries now planning to use plutonium are planning to use breeder reactors. INFCE, *Summary Volume* (Vienna: International Atomic Energy Agency, 1980), p. 145.

[115] In the United States, the experimental Clinch River breeder reactor project has been canceled, and European breeder programs are experiencing increasing delays. See " Europe's Fast Breeders Move to a Slow Track, " *Science,* vol. 218, Dec. 10, 1982, pp. 1094-1097.

[116] "Jilted Reprocessor, " op. cit.

recovered plutonium into solid plutonium dioxide (PuO_2) and solidification and storage of high-level waste from reprocessing. A number of regulatory issues must also be resolved before a reprocessing facility could be completed and operated. Licensing and operation of the AGNS facility or any new reprocessing plant would require a generic proceeding dealing with reprocessing and plutonium recycle and a licensing proceeding to resolve site- and design-specific issues associated with the particular facility.[117]

The AGNS facility could probably be completed, licensed, and operating in about 10 years.[118] Estimates of the cost for constructing the additional required facilities at AGNS range from $580 million to $950 million.[119] A new reprocessing facility with the same annual capacity is estimated to cost from $1 billion to $1.6 billion, assuming a predictable schedule is maintained.[120] Since there is no experience with much of the required technology at commercial scale in the United States, and since there are substantial remaining regulatory uncertainties (e.g., waste solidification criteria), these schedule and cost estimates should be viewed with caution.[121]

Reprocessing for Waste Management

Because it was generally assumed until the mid-1970's that spent fuel would be reprocessed to recover the usable uranium and plutonium, plans for waste management focused on solidified high-level waste from the reprocessing operation. However, the increasing uncertainty about the economic incentive for reprocessing has focused attention on the option of direct disposal of spent fuel. In this context, some have suggested that reprocessing might be desirable as a waste management step, in view of its potential advantages over disposing of unreprocessed spent fuel—for example, 1) removing the plutonium and uranium produces a more benign waste product with lower volume, toxicity, and long-term heat output than spent fuel, and 2) reprocessing allows the use of potentially better disposal technologies (e. g., less soluble waste forms or alternative approaches, such as isotope partition and transmutation).

Despite such potential advantages, major studies that have considered reprocessing in the context of waste management have concluded that reprocessing of commercial spent fuel is not required for safe waste isolation. Mined repositories can be designed for the safe isolation of either spent fuel or high-level waste from reprocessing, or both.[122] Moreover, reprocessing—which generates additional radioactive waste streams and involves operational risks of its own—does not appear to offer advantages that are sufficient to justify its use for waste management reasons alone.[123] Thus, while large-scale reprocessing of commercial spent fuel would have significant implications for waste management, those implications would not be a major factor in the decision on whether to undertake such reprocessing. Instead, the decision to reprocess would depend on whether the recovery and recycling of unused fissionable material in the spent fuel is more attractive from an economic and energy policy point of view than using freshly mined uranium.[124]

117 U.S. *Department* of Energy, ***Nuclear** Proliferation and **Civilian** Nuclear Power: Report of the Nonproliferation Alternative Systems Assessment Program* (NASAP), vol. IV, DOE/NC-0001/4, June 1980, p. 184.

118 Ibid., p. 184; International Energy Associates Limited (IEAL), *Study of the **Potential** Uses of the **Barnwell** Nuclear **Fuel Plant*** (BNFP), IEAL-141, Mar. 25, 1980, fig. 4-13, p. 145.

119 IEAL, op. cit., p. 137; DOE, Nuclear Proliferation and *Civilian Nuclear Power, vol.* IV, p. 185.

120 DOE, ***Nuclear** Proliferation and Civilian Nuclear **Power,*** vol. IV, p. 185.

121 IEAL, op. cit. , p. 144.

122 INFCE, *Summary **Volume,*** p. 2 1; APS, op. cit., p. S107; National Research Council, ***Isolation** System,* p. 1 1; and K. D. Closs and H. Geipel, "Some Preliminary Results of the FRG (Federal Republic of Germany) Alternative Fuel Cycle Evaluation, " presented at the International Meeting on Fuel Reprocessing and Waste Management, Jackson, Wyo., Aug. 25-29, 1984.

123 INFCE, Summary *Volume,* p. 2 1: "Working Group 7 generally concluded, taking into account not only health and safety and environmental impacts but also the other assessment factors, that the difference in the impacts of waste management and disposal among the reference fuel cycles does not constitute a decisive factor in the choice among them. Employing technology assumed, the radioactive wastes from any of the fuel cycles studied can be managed and disposed of with a high degree of safety and without undue risk to man or the environment. " APS, op. cit., p. S1 12: "Although influencing details of repository design, none of the factors we have identified concerning waste management are of determining importance in the choice among fuel cycles. Page S107: "In particular, arguments concerning . . . waste management are not important in deciding between recycle and non-recycle fuel cycle options.'' While the National Research Council Waste Isolation System Panel concluded that adequate isolation could be provided for spent fuel as well as high-level waste, it did not address the question of the implications of waste management considerations for the choice of fuel cycles.

124 APS, op. cit., p. 5 8 .

The principal reason for this conclusion is that reprocessing and recycling do not produce a large net improvement from a waste management point of view because: 1) the benefits are not large, and 2) reprocessing and recycling generate new waste management problems that offset some of the benefits. This can be seen by considering some of the complications introduced by the two separate steps of reprocessing and recycling.

Reprocessing Operations and Costs

Reprocessing involves dissolving the spent fuel in acid and separating the fission products and unusable TRU elements from the reusable material (uranium and plutonium). Dissolving the spent fuel has several waste management benefits even if the uranium and plutonium are not removed for recycling. First, it allows the radionuclides to be separated into several streams for different types of treatment and disposal. For example, the short-lived, hot fission products (in particular, strontium-90 and cesium-137) could be segregated for separate disposal so that the long-lived fission products and transuranics could be disposed of without the complications caused by high heat output. Second, the dissolved material can then be resolidified into a low-volubility waste form, which can reduce the rate at which the waste could escape from a repository if it comes into contact with ground water.

A recent National Research Council study of geologic disposal shows that it is these effects, rather than the removal of plutonium, which give high-level waste from reprocessing an advantage compared to spent fuel. This can be seen by comparing figures 3-3 and 3-4, which show the study's best estimates of the expected doses from a basalt repository containing high-level waste and spent fuel, respectively. These figures show that, for the ground-water travel times greater than the 1,000 years required by NRC regulations, the major difference between the doses from spent fuel and high-level waste is caused by carbon-14 (C^{14}) and iodine-129 (I^{129}).[125] These two nuclides are released as gases when the spent fuel is dissolved, and can then be concentrated in a relatively few packages in a chemical form that can limit the rate at which they dissolve into ground water to a level far below the rate that is expected if they are distributed uniformly throughout a large number of spent fuel packages.[126]

The other advantage that results from dissolving the spent fuel is that it is possible to resolidify the material in a waste form that is much less soluble than the original spent fuel pellets. As noted earlier, several studies have indicated that this could be one of the most effective ways to improve repository performance significantly. As will be discussed in chapter 6, additional work on insoluble waste forms could be useful. Recent analysis suggests that both spent fuel and borosilicate glass may be unable to meet the current NRC release rate requirement for some radionuclides,[127] although NRC can modify the requirements for some radionuclides on a case-by-case basis. In any case, use of a less soluble waste form for spent fuel would not require removal of the plutonium and uranium, and dissolution and resolidification has been considered by DOE as one method for treating spent fuel for direct disposal in a once-through fuel cycle.[128]

Dissolving spent fuel, packaging the C^{14} and I^{129} separately, and resolidifying the rest of the material in an insoluble form could thus improve expected repository performance. However, the important question from a waste management perspective is whether the improvements are sufficient to warrant undertaking those relatively complex steps, if reprocessing is not otherwise being done anyway to recover the plutonium and uranium. There are several considerations that underlie the judgment cited above that the advantages are not sufficient:

1. ***Reprocessing involves increased near-term operational risks.*** Reprocessing spent fuel would increase the amount of handling and processing of highly radioactive materials prior to disposal of the waste, increasing worker exposures and population exposures during normal operations and producing addi-

[125] The doses resulting from the differences in content of plutonium or uranium, and their decay daughters, like radium-226 (Ra^{226}), are at much lower levels because they are expected to dissolve much more slowly than the the waste form that contains them, and to be retarded strongly by the material surrounding the repository so that they substantially decay before they escape to the environment.

[126] National Research Council, Isolation *System*, p. 282.

[127] Ibid., p. 239.

[128] DOE, *FEIS*, p. 4.20.

tional possibilities for accidents that could release radioactive material. For example, DOE analysis shows that normal waste management operations for a 250-gigawatts-electrical (GW_e) once-through cycle could be expected to cause from none to 2 health effects worldwide, while a comparable reprocessing cycle could cause from 6 to 750 health effects worldwide, with about 95 percent of those resulting from predisposal waste treatment operations.[129 130] This relatively certain increase in near-term operational risks would have to be weighed against the more uncertain reduction in long-term risks that could result from reprocessing.

This same consideration also applies to any of the more sophisticated waste-management techniques that reprocessing would allow, such as use of a highly insoluble waste form, to the extent that they also involve more complex handling and processing operations. In this regard, a National Research Council panel recently concluded that the choice of solid waste forms for high-level waste from reprocessing should take into account the release of radioactivity into the environment from all stages of waste management, including waste form manufacture, rather than just the differences in expected releases after the waste is placed into a repository.[131] Similarly, as noted, analysis of the possible benefits of separating out the long-lived, toxic TRU elements and recycling them along with uranium and plutonium so that they can be destroyed by fission in reactors has concluded that the increase in operational risks and complexity involved would offset the limited advantages.

2. ***Reprocessing, or even simply dissolving spent fuel and resolidifying it in another form, produces other waste forms—principally, large volumes of TR U waste—that must also be*** managed and ultimately disposed ***of. 132*** If reprocessing were initiated before a disposal facility were available, it would change the nature of the waste-from spent fuel to high-level waste from reprocessing, TRU, low-level waste, and, perhaps, unrecycled plutonium—but would not eliminate the need for waste storage. DOE estimates that the capital cost of storage facilities at a reprocessing plant could amount to around $350 million for 5 years' output of waste and at least $280 million for storage of separated plutonium, which would have to be provided unless the plutonium were recycled without delay.[133] In addition, these large quantities of additional waste forms could significantly increase the costs and risks of waste transportation.[134] Finally, TRU wastes will require the same sort of long-term isolation as the high-level waste and thus may be disposed of in the same facility. Depending on resolution of regulatory issues, such reprocessing wastes might require more repository space than spent fuel for a given amount of electricity generation.[135]
3. ***Reprocessing could increase the costs of waste management if*** undertaken ***for*** *that* ***purpose.*** It is not at all clear that there would ever be a demand for all of the plutonium that could be obtained by reprocessing all of the spent fuel from LWR's, even if a system of breeder reactors were operated.[136] In addition, there may be a financial incentive to discard some plutonium after three or more recycles, in any case, because of the buildup of undesirable radionuclides.[137] If reprocessing were required as a waste management step, then the costs

[129] Ibid., pp. 7.39-7.40.

[130] The recent German fuel cycle study has also concluded that a reprocessing fuel cycle would increase worker and population exposures compared to direct disposal of spent fuel. Closs and Geipel, op. cit.

[131] National Research Council, *Isolation System, p.* 14.

[132] See DOE, *FEIS, sec. 4.3.1* for TRU wastes produced by spent fuel processing options and sec. 4.3.3 for TRU wastes produced by reprocessing.

[133] DOE, *FEIS*, vol. 2, app. A, table A.8.8, p. A. 102. APS, op. cit., p. 62, notes that the cost of storing separated plutonium for 10 years is much greater than the cost of storing spent fuel for the same period.

[134] Wilmot et al., A *Preliminary Analysis*, op. cit. See also T. 1. McSweeney, R. W. Peterson, and R Gupta, "The Costs and Impacts of Transporting Nuclear Waste to Candidate Repository Sites in *Proceedings of the 1983 Civilian Radioactive Waste Management Information Meeting* (Washington, E. C.: U.S. Department of Energy, February 1984), pp. 351-361.

[135] DOE, *FEIS*, p. 7.29, table 7.3.1). This analysis takes into account the effects of plutonium recycle on the heat output of, and thus the repository space required for, high-level waste.

[136] The MITRE Corp., *Analysis of Nuclear Waste Disposal and Strategies for Facility Deployment* (McLean, Va.: April 1980), a report prepared for the Office of Technology Assessment; and Brian G. Chow and Gregory S. Jones, "Nonproliferation and Spent Fuel Disposal Policy," a report prepared for the Council on Environmental Quality (Marina Del Ray, Calif.: Pan Heuristics, October 1980).

[137] DOE, *FEIS, p.* 7.30.

of reprocessing that were not offset by sale of recovered plutonium and uranium would have to be added to the waste management costs.

Comparisons of the costs of disposing of spent fuel and high-level waste show relatively little difference between the two approaches, with some studies showing an advantage for high-level waste and others an advantage for spent fuel.[138] For example, current DOE estimates show that the cost of disposal of spent fuel would be about $122 to $125/kilogram (kg), while the cost of disposing of the reprocessing waste equivalent would be $115 to $1 19/kg; if the $8/kg cost of solidification of the high-level waste is included, total waste management costs for high-level waste would slightly exceed the costs for direct disposal of spent fuel.[139] In comparison, the costs of reprocessing could be several times as high. For example, DOE currently uses $390/kg as a reference cost for reprocessing LWR fuel, with a possible range of from $200 to $600/kg.[140] Since the range of uncertainty in the cost of reprocessing is greater than the total estimated cost of waste disposal, it is highly unlikely that the very small difference in disposal cost between spent fuel and high-level waste would play a significant role in a decision about whether to undertake reprocessing.

Even if high-level waste could be disposed of for free, the cost advantage would not by itself offset the cost of reprocessing. Thus, a waste policy requirement for reprocessing spent fuel that would otherwise not be reprocessed for economic reasons could substantially increase the costs of waste management. (This would be the case even if the only processing involved were dissolution of spent fuel and resolidification in borosilicate glass, without separating the plutonium and uranium-a step which DOE estimates would increase the cost of waste management in a once-through cycle by about 60 percent.[141])

Since neither EPA nor NRC have concluded that unprocessed spent fuel would not be an acceptable waste form, there may be little incentive for incurring the additional costs and operational risks of reprocessing (or other processing) simply to improve repository performance beyond a level that is already judged to be satisfactory. Similar considerations also would apply to any more complex and expensive waste processing steps allowed by reprocessing that promise to reduce long-term risks below the level presented by direct disposal of spent fuel. Reprocessing could allow use of more complex disposal system technologies than those possible with direct disposal of spent fuel. For example, it could allow separation and separate disposal of the heat-producing, but relatively short-lived, fission products from the cool, but very long-lived, transuranics, or the use of disposal systems such as space disposal, which are not practical with spent fuel. Similarly, it could allow use of very insoluble waste forms and/or waste forms that are tailored to the characteristics of the repository host rock.

However, unless these alternative disposal options prove less expensive than simpler systems or are required by law or by regulation for safety reasons, they may not be used—even if ***reprocessing*** were undertaken for resource recovery reasons. For example, as mentioned earlier, recent analysis has shown that increased waste management costs, as well as increased operational risks, would probably preclude partition and transmutation of long-lived radionuclides in reactors, even if spent fuel were already being reprocessed routinely.[142] Similarly, if a very low-volubility waste form proved to be significantly more expensive than a more soluble but still acceptable one (which borosilicate glass may prove to be), it is not clear that the additional expenditures would be made unless there were a regulatory requirement for the more expensive waste form. The same reasoning, of course, would apply to the choice between spent fuel and reprocessed waste as a waste form.

Effects of Plutonium Recycle on Waste Management

So far, we have considered only the waste management benefits and costs associated with chemi-

[138] Ibid., p. 7.50 shows slightly higher costs for reprocessing waste; INFCE, *Summary Volume,* p. 232, shows about a 10-percent advantage for reprocessing waste.

[139] DOE, *Report on Financing the Disposal,* op. cit., p. 2.

[140] U.S. Department of Energy, *Nuclear Energy Cost Data Base, DOE/NE-0044/2* (Washington, D. C.: March 1984), table 2.12, p. 24.

[141] Derived from *FEIS,* table 4.9.7, p. 4.110.

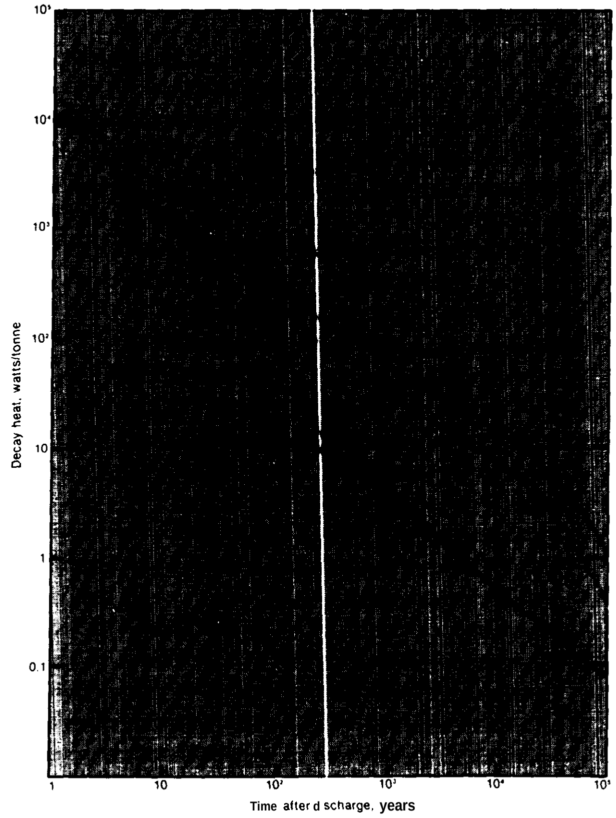
[142] Croff et al., Op. cit.

cal processing of spent fuel per se. Some of the potential waste management advantages of high-level waste compared to spent fuel result from removing the plutonium and recycling it so that it is destroyed by fission in nuclear reactors rather than being disposed of. However, like the initial step of reprocessing, which is required for separating the plutonium in the first place, the additional step of plutonium recycle generates waste management problems that offset the advantages to some extent.

First, recycle of plutonium reduces the difference between once-through spent fuel and high-level waste. As noted in chapter 2, plutonium recycle increases the toxicity and heat output of the resulting high-level waste. Thus, as recycle continues, the resulting high-level waste from reprocessing spent mixed-oxide (MOX) fuel containing recycled piutonium becomes more and more similar, in toxicity and heat output, to once-through spent fuel containing no recycled plutonium.[143] This effect is increased by the delay in reprocessing, which, as discussed in chapter 2, will also increase the toxicity and heat output of the resulting high-level waste.

The effect of plutonium recycle on the heat output of high-level waste can be seen in figure 3-7, which shows the heat output of once-through spent fuel (SF UO_2), high-level waste with no plutonium recycle (HLW UO_2), and high-level waste with plutonium recycle (HLW MOX). The heat output of HLW MOX is actually higher than once-through spent fuel for the first 100 years, the period during which the maximum temperature increases in a repository are expected.[144] This could reduce one of the advantages sometimes cited for reprocessing—i.e., its ability to reduce the volume of waste, since the unused uranium and plutonium (representing about 95 percent of the volume of the spent fuel) would be separated for reuse. The actual reduction that could be achieved will depend on the amount of heat-producing, high-level waste that can be placed in each canister, which in turn will depend on the temperature limits established for the waste package and the repository and on the heat output of the waste. The nearer the heat output of high-level waste to that of once-through spent fuel, the less the advantage of high-level waste in terms of

Figure 3=7.—Decay Heat Power for Different Nuclear Fuel Cycles for a Pressurized Water Reactor



SOURCE: Wang, et al., Thermal Impact of Waste Emplacement and Surface Cooling Associated With Geologic Disposal of Nuclear Waste, NUREGICR-2910 (Washington, DC: U.S. Nuclear Regulatory Commission, 19S3).

volume and number of waste canisters. Furthermore, any volume reduction that results from reprocessing and recycle may not reduce proportionately the total amount of repository space needed to dispose of the waste from the generation of a given amount of nuclear electricity, since it is the total amount of heat-producing isotopes in the waste, rather than the waste's physical volume, that is the principal determinant of the total repository area required.

Secondly, considerable centralized control of the nuclear power system may be needed to eliminate all of the plutonium recovered by reprocessing. While recycle destroys plutonium by fission in reactors, it also produces plutonium from U^{238}, so that the total amount of plutonium present in a reprocessing cycle is greater than that in the once-through cycle.[145] Thus, if reprocessing and recy -

[143] DOE, *FEIS*, p. 7.53.
[144] Ibid., app. K.
[145] Ibid., p. 7.30.

cle were undertaken to reduce the amount of plutonium that must be disposed of compared to a once-through cycle, careful planning and management would be needed to minimize the amount of plutonium left when the nuclear power system is eventually phased out.

In addition, recycle may have to be continued for an extended period to obtain major reductions of plutonium compared to those from a once-through cycle. For example, DOE calculates that a once-through nuclear power system that reaches 250 GWe. in the year 2000 and phases out by 2040 would produce about 1,900 tonnes of plutonium to be disposed of in spent fuel. In comparison, a reprocessing cycle for the same generating scenario would produce about 3,400 tonnes of plutonium, about 1,100 tonnes of which would still be unrecycled in 2040 even if reprocessing and recycle began as early as 1990.[146] Clearly, nuclear power generation and recycle would have to be continued considerably beyond 2040 to reduce the amount of unrecycled plutonium to a small fraction of the plutonium discarded in the once-through cycle. Since it is not clear that economic factors would lead utilities to manage their systems so as to reprocess all spent fuel and to recycle all of the recovered plutonium, some form of Federal intervention (e. g., a regulation requiring that utilities deliver solidified high-level waste for disposal, or Federal operation of reprocessing facilities and of reactors for using the plutonium), might be needed to minimize the amount of unrecycled plutonium.

146 Ibid., table 7.3.12, p. 7.31.

Conclusion

Available analysis strongly supports the conclusion that reprocessing is best viewed as a possible measure for extending energy resources rather than as a waste management step. Analysis of the merits of reprocessing and recycle from the perspective of energy needs is beyond the scope of this study. However, it is not necessary at this time to decide when and how much spent fuel will be disposed of or reprocessed, since that decision will not be faced until a disposal capability is available. At that time, if commercial reprocessing has not commenced, a decision will have to be made either to maintain the spent fuel in surface (or near-surface) storage facilities at reactor sites, repository sites, or other independent sites; to store the spent fuel in a geologic repository that could be backfilled at a later date; or to dispose of the spent fuel in mined repositories. If that decision is to be based primarily on the resource value of the spent fuel rather than on the capability to dispose of spent fuel or high-level waste from reprocessing, the capability to dispose of both spent fuel and high-level reprocessing waste will have to be developed. (For further discussion of this point, see issue 3 in app. B.)

INTEGRATED WASTE MANAGEMENT SYSTEM

To manage the annual flow of spent fuel generated by operating nuclear reactors, waste management will entail the construction and operation over a long period of time of some combination of the technologies described above. Most analyses of radioactive waste management to date have concentrated on individual components—spent fuel storage, transportation, or disposal-rather than on their integrated operation in a full-scale system.[147] Only in the last several years have the analytical tools been developed that (if properly combined) would allow a systematic comparative analysis of different waste management system designs and optimization of the entire system.[148] As a result, there are a number of important questions of system design for which relatively little systematic analysis exists. For this reason, OTA'S analysis of these questions has been based on inference from a num-

147 The DOE *FEIS* did use a systems model to analyze the impacts of operation of the total waste management system.

148 Recent analysis of waste transportation system issues concludes that greater interaction is needed among persons involved in repository design, transportation system development, and waste generation. Comments of NWTS Transportation Interface Technology Peer Review Panel, in Clinton G. Shirley, *NWTS Transportation Interface Technology Development Priority Report,* SAND82-1804 (Albuquerque, N. Mex.: Sandia National Laboratories, July 1983), p. 9-14.

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ber of partial analyses, some performed specifically for this assessment.

A more comprehensive analysis of system design must await development and use of an integrated system model that combines the partial models that have been developed by DOE. In particular, we note 'that integration of the capabilities of the existing Integrated Data Base[149] (projections, source-terms, and process tradeoff analyses), transportation systems analysis capabilities[150] (routing and logistics), repository systems analysis capabilities[151] (design/cost tradeoffs), repository risk analysis[152] (radiological impact of repository), and any one of numerous health impact models[153] would result in a system model capable of performing a variety of cost/risk/benefit/scheduling studies necessary for efficient planning and operation of the waste management system. The complexity of these models and the specialized expertise necessary to implement them will likely require implementation of the integrated model in pieces at various sites, with results being communicated using computer-compatible methods (magnetic tapes). The importance of developing an integrated system model is discussed further in chapter 6.

System Impacts

Health Effects

Waste management may result in small, localized releases from accidents during waste handling, transportation, and storage activities prior to disposal. However, there appears to be little, if any, chance of massive, uncontrolled releases of radioactivity into the environment in a short period of time that would cause a large number of health effects (in contrast to the possibility, however remote, of a meltdown in a reactor). Instead, the principal radiological effects during waste management prior to disposal would result from radiation doses to workers and the public during routine operations.[154]

Analyses indicate that after disposal in a geologic repository, the two principal modes of release would be: 1) small, concentrated releases produced by human intrusion (from digging a well either near or into a repository) that could result in large doses of radiation to a few individuals; or 2) the gradual release of radioactivity from the repository into ground water (and ultimately into drinking water or food supplies), leading to very small doses (compared to background radiation) to a large portion of the population. DOE analysis calculates that normal operation of a waste management system without reprocessing could be expected to produce, at most, two health effects genetic disorders or fatal cancers) over a 70-year period, even if the level of nuclear power generation increased to 500 GW_e by 2040.155 The addition of reprocessing increases the maximum expected health effects to 37 on a regional basis and 1,100 worldwide for the same level of generation.[156] While this is a large number in absolute terms, it nonetheless represents only a small fraction (0.003 percent) of the health effects to the world population expected to result from natural sources of radioactivity over the same period.[157] A review of the risks associated with nuclear power, conducted by the National Academy of Sciences, concludes that the total exposure to future generations from wastes released from a repository should not exceed the doses to the present generation from normal operation of the nuclear fuel cycle.[158]

Nonradiological Impacts

Even if there are no significant direct health effects from radioactive releases, management of high-level radioactive wastes will have ecological, land-use, manpower, and community adjustment impacts. In general, the nonradiological health and environmental effects from constructing and operating a geologic repository should be no more severe than those associated with other large construction

*'⁸K. J. Notz, "Radwaste Inventories and Projections: An Overview, " USDOE Report ORNL/TM-8322, July 1982.

150D. S. Joy, B. J. Hudson, and M. W. Anthony, "Logistics Characterization for Regional Spent Fuel Repositones Concept, " USDOE Report ONWI-124, August 1980.

151L. L. Clark and B. M. Cole, "An Analysis of the Cost of Mined Geologic Repositories in Alternative Media, " USDOE Report PNL-3949, February 1982,

152D. J. Silviere et al., "A Short Description of the AEGIS Appreach, " USDOE Report PNL-398, September 1980.

153M. Mills and D. Vogt, "A Summary of Computer Codes for Radiological Assessment, " USNRC Report NUREG/CR-3209, March 1983.

154Closs and Geipel, op. cit.

155DOE, *FEIS*, table 7.4.3, p. 7.40.

156Ibid., table 7.4.4, p. 7.40.

157 1 bid., p. 7.39

158National Academy of Sciences, *Risks Associated with Nuclear Power: A Critical Review of the Literature*, Summary and Synthesis Chapter (Washington, D. C.: 1979), p. xi.

projects. In particular, the anticipated nonradiological impacts arising from the resource and economic requirements of nuclear waste management occur in similar and ongoing activities associated with preparation of fresh nuclear fuel and coal mining. For example, the largest coal mines dwarf mined geologic repositories as geographically concentrated sources of nonradiological, ecological, and community impacts.[160] The waste storage and disposal system should add, at most, about 20 percent of the land area to the land area required for the mills and reactors they serve. When all of the other facilities such as uranium mines and enrichment plants are taken into account, it appears unlikely that high-level radioactive waste management would ever require an appreciable fraction of the total land area serving the nuclear fuel cycle.[161]

Construction and operation of waste storage and disposal facilities are likely to have effects on nearby communities similar to those of mining or industrial warehousing. Development of a repository could create a noticeable increase in local population, particularly during the construction phase, that could require careful planning for expanded public services and housing. Such "conventional" impacts have been experienced and dealt with during industrial developments of many kinds; they are not unique to radioactive waste management. (See table 3-5.) However, the socioeconomic impacts of a repository are likely to be very site-specific and difficult to predict on the basis of experience with other types of facilities at other sites.

A less tangible and familiar community impact of waste management and disposal would be the effect of public concerns about the radiological health and safety risks of waste management operations—concerns that would not exist to such a degree about more familiar industrial activities.[164]

Table 3-5.—Conventional Site Effects of a Large Industrial Facility

1.0	**Economic Effects**
1.1	Change in property value
1.2	Change in rental costs
1.3	Change in cost of goods and services
1.4	Higher property taxes
1.5	Change in employment
1.6	Change in prevision of jobs
1.7	Change in travel costs
1.8	Change in market areas and competitive position of economic activities
2.0	**Environmental and Health Effects**
2,1	Noise
2.2	Air pollution
2.3	Damage to soil quality
2.4	Water drainage damage
2.5	Vibration
2.6	Congestion and access
2.7	Accidents
2,8	Aesthetic changes
3.0	**Social Change Effects**
3.1	Social pathologies (alcoholism, drug abuse, mental illness, divorce, juvenile delinquency)
3.2	Crime
3.3	Personality adjustment
3.4	Affectual relations
3.5	Use of community facilities
3.6	Intergroup conflict
3.7	Quality of public services
3.8	Sense of community (includes sense of attachment, support networks)
4.0	**Location Transfer Costs and New Location Effects**
4.1	Searching
4.2	Moving
4.3	Capital financing costs
4,4	Start-up and operating costs (businesses)
4.5	Personality adjustment
5.0	**institutional Adaptations**
5.1	Land-use functions
5.2	Development planning
5.3	Negotiations with contractors, government agencies
5.4	Conflict resolution
5.5	Jurisdictional issues
5,6	Public service bureaucracies; direct-sewice agencies
5.7	Division of responsibilities

SOURCE: National Research Council, *Social and Economic Aspects of Radioactive Waste Disposal* (Washington, DC: National Academy Press, 1984).

There might also be important community impacts resulting from the controversy that could surround the siting of waste facilities.[165] In any case, evidence suggests that the public perceives radioactive waste management to be qualitatively different from other

159 National Research Council, Social *and Economic Aspects*, p. 93.

160 The MITRE Corp., *Assessment of the Non-Radiological Impacts of Managing Commercially Generated Spent Fuel*, April 1981, a report prepared for the Office of Technology Assessment, pp. 2-22, 2-23.

161 1 bid., p. 2-8.

162 Ibid., p. 2-13. See also Roger Kasperson, *Anticipating the Socio-economic Impacts of Nuclear Waste Facilities on Rural Communities, Center* for Technology, Environment, and Development, Worcester, Mass., Testimony prepared for the Rural Development Subcommittee of the Committee on Agriculture, Nutrition, and Forestry, U.S. Senate, Aug. 26, 1980, p. 6.

163 National Research Council, Social *and Economic Aspects*, p.12.

164 Steve H. Murdock, F. Larry Leistritz and R ita R. Harem, *Nuclear Waste: Socioeconomic Dimensions of Long-Term Storage* (Boulder, Colo.: Westview Press, 1983), p. 112.

165 Kasperson, *Anticipating the Socioeconomic Impacts.*

superficially similar operations and industries.[166] This has led some analysts to conclude that a systematic effort to identify and understand those impacts that cause the greatest public concern might be needed to avoid repetition of past conflicts in the implementation of the Federal waste management program.[167] A National Research Council panel recently concluded that the "special" effects associated with the radiological aspects of radioactive waste management might be particularly difficult to assess, but could exceed the conventional effects of a repository and prove difficult to mitigate or eliminate.[168]

The acceptability of waste management activities to a community may depend not only on their actual or perceived impacts but also on the benefits the community expects to receive from the activities. While studies of the socioeconomic effects of radioactive waste management facilities have generally focused on the negative impacts, operation of a geologic repository will have some positive impacts as well. As with any industrial facility, the repository will bring some jobs to the community. In addition, the first repository—which is likely to be the first such facility in the world—may well become an international research center on radioactive waste disposal for a period extending well beyond the time when the repository ceases active operation. This could lead to long-term community benefits that might to some extent offset the more immediate but short-term impacts of repository construction. In fact, some communities that are already familiar with nuclear activities and are interested in the financial benefits of waste management have indicated willingness to host waste facilities.[169]

Generally, Federal activities are less attractive financially to local communities than those of commercial industry because the Federal Government does not pay local taxes. Because the adverse impacts of repository development and operation have the potential for substantial harm to the host community, provision of resources to reduce, mitigate, and compensate for such impacts may be required.[170] Authority for this response was included in the NWPA (see chs, 5 and 8).

Transportation

The transportation of high-level radioactive waste will be the aspect of waste management that affects the largest number of States and communities. The actual risks posed by transportation appear to be low, although transportation is the predisposal waste management step with the potential for the most serious accidental release of radioactive material.[171] The transportation of high-level radioactive waste through a community will place some demands on State and local governments to maintain some emergency response capability for shipping accidents, whether or not any release of radioactive material occurs. The actual number of communities affected in this way will be highly dependent on the nature of the waste management system that is developed—whether it is highly centralized, with one large repository or interim storage facility operating at any one time, or decentralized, with several operating facilities distributed around the country. The more centralized the system, the greater the number of communities affected by transportation of spent fuel from reactors to storage or disposal.

A qualitative idea of the different transportation implications of centralized and decentralized waste management systems can be obtained by comparing figures 3-8 and 3-9. These figures show the projected annual shipments to a single western storage site and to three regional storage sites in the year 2004, assuming that 113 reactors are in oper-

166 Roger E. Kasperson et al., "Public Opposition to Nuclear Energy: Retrospect and Prospect, *Science, Technology, and Human Values 31*, spring 1980, pp. 11-23; and J. A. Herbert et al., *Nontechnical Issues in Waste Management: Ethical, Insitutional, and Political Concerns* (Seattle, Wash.: Human Affairs Research Centers, Battelle Memorial Institute Pacific Northwest Division, May 1978).

167 Gene I. Rod-din, "The Role of Participatory Impact Assessment in Radioactive Waste Management Program Activities, Institute of Governmental Studies (Berkeley, Calif.: 1981), pp. 43-44.

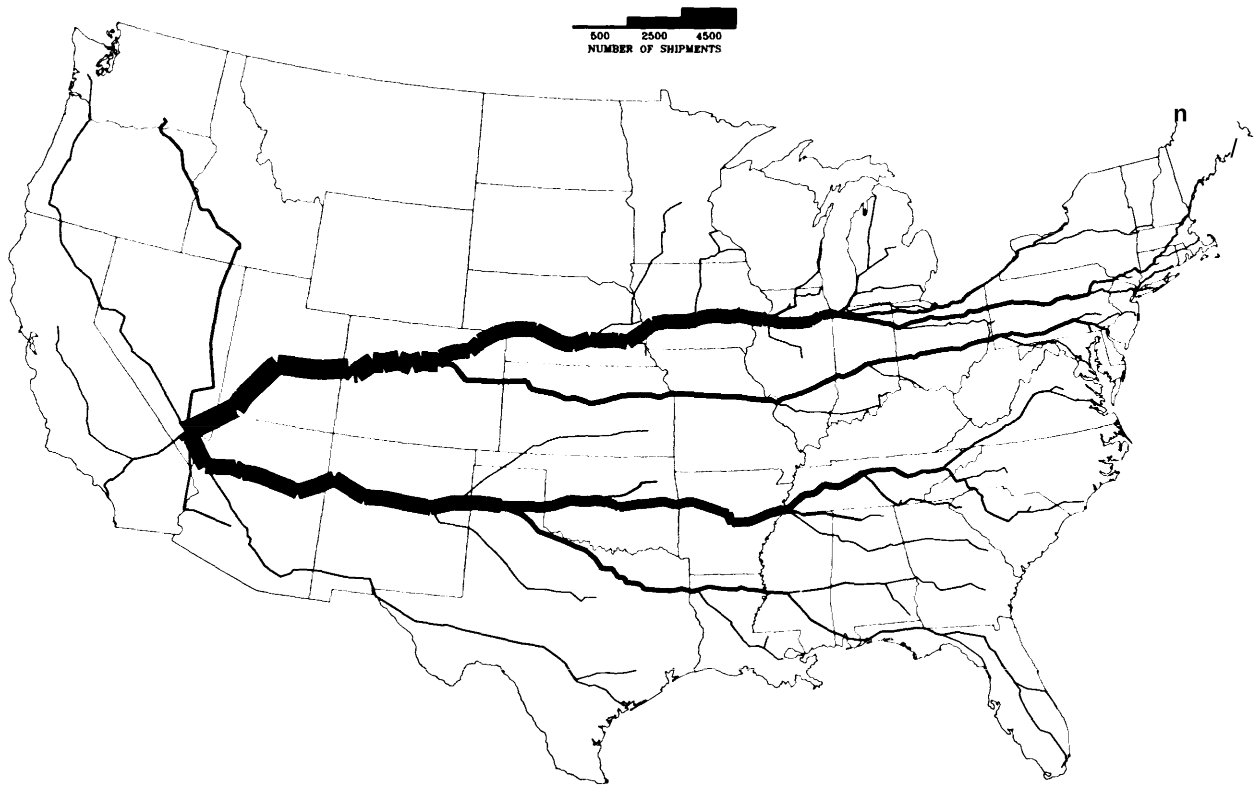
168 National Research Council, *Social and Economic Aspects,* p.101.

169 "Nuclear Waste War Cry: 'Not Here, You Don't!'," U.S. News & *World Report,* Aug. 15, 1983, pp. 23-24; "To Keep Their Town Alive, the Residents of Naturita, Colo. Want a Nuclear Dump, " The *Wall Street Journal,* July 1, 1982, p. 1.

170 National *Research* Council, *Social and Economic Aspects,* p.12. *See also S.* A. Carries et al., *Incentives and the Siting of Radioactive Waste Facilities,* ORNL-5880 (Oak Ridge, Term.: Oak Ridge National Laboratory, August 1982).

171 DOE, *FEIS,* p. *4.98.*

Figure 3-8.—Spent Fuel Shipments in a Centralized Waste Management System



Projected annual shipments to a western site in 2004, assuming **truck shipments from all reactors. (Site selected for demonstration purposes only. The site shown is only one of several western sites now under consideration for a repository, and is used as a convenient hypothetical example only.) The actual number of annual shipments is likely to be lower because of use of new casks designed for eider spent fuel, which will carry more per shipment, and shipment of some fuel using much larger rail casks.**

SOURCE: National Research Council, *Social and Economic Aspects of Radioactive Waste Disposal* (Washington, DC: National Academy Press, 1984).

ation at that time and that all shipments are made by truck.[172] The shipments represent about 13,000 spent fuel assemblies containing about 3,700 tonnes of fuel.[173] One rough indicator of the difference between the centralized and decentralized systems is the total shipping distance involved. Assuming for simplicity that all shipments were made by truck, the shipping distance in 2004 would be about 9 million miles for the regional system, compared to about 33 million miles for the single western site.[174] Both the costs and risks of transportation will increase with the total transportation distance. For example, a recent analysis showed that the costs and risks (from radiation exposure and nonradiological accidents) would be about two to three times greater for a repository in the westernmost area now under consideration, Hanford, than for a repository in the easternmost area under consideration, the Gulf Interior region.[175] Other analysis has con-

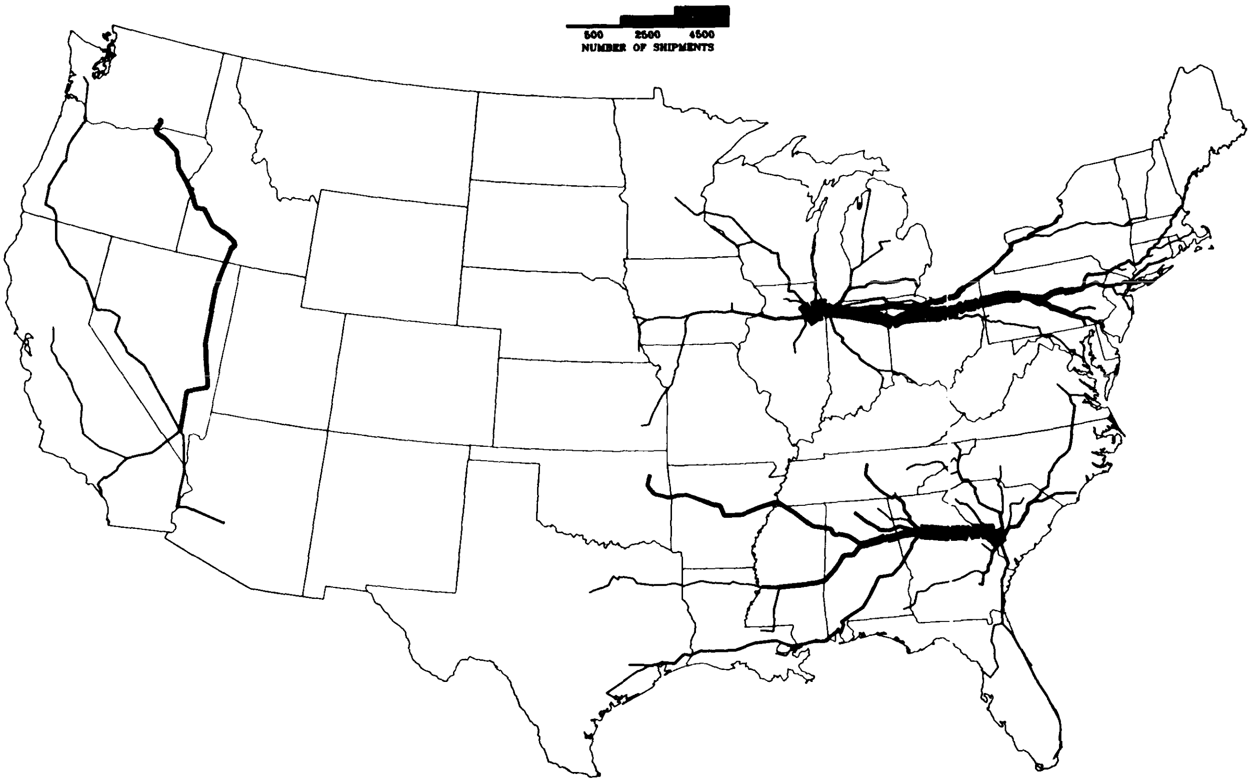
[172]These examples are drawn from a more extensive analysis of the effects of centralized and decentralized systems on transportation in National Research Council, *Social and Economic Aspects,* ch. *3.* The sites shown were selected for demonstration purposes only, to show the effects of regional v. centralized storage or disposal. Only one of the sites, in southern Nevada, is now under consideration for a geologic repository. The two eastern sites are the inoperative reprocessing facilities at Morris, Ill., and Barnwell, S. C., which were considered by the Carter administration as possible sites for Federal away-from-reactor storage facilities, and which were sometimes used as hypothetical storage sites for analytical purposes. The Nuclear Waste Policy Act of 1982 forbids the acquisition of these facilities for Federal interim storage, and the sites have not been, and are not now, under consideration for geologic repositories.

[173]Ibid., app. A, p. 151.

bid, table A. 18, p. 166, and table A. 14, p. 162.

[175]T. I. McSweeney et al., "The Costs and Impacts of Transporting Nuclear Waste to Candidate Repository Sites, *Proceedings of the 1983 Civilian Radioactive Waste Management Information Meeting* (Washington, D. C.: U.S. Department of Energy, 1984), pp. 357-359.

Figure 3=9.-Spent Fuel Shipments in a Decentralized Waste Management System



Projected annual shipments to regional sites In 2004, assuming truck shipments from all reactors. (Sites selected for demonstration purposes only. The eastern sites are *not* under consideration for repositories and are used as convenient hypothetical examples only.) The actual number of annual shipments is likely to be lower because of use of new casks designed for eider spent fuel, which will carry more per shipment, and shipment of some fuel using much larger rail casks.

SOURCE: National Research Council, *Social and Economic Aspects of Radioactive* Waste *Disposal* (Washington, DC: National Academy Press, 19S4.)

eluded that the costs and risks of waste transportation could be reduced by as much as a factor of 2 with an optimally sited system using two or three repositories compared to a single repository. [176]

cost

The aggregate costs of high-level radioactive waste management will be in the tens of billions of dollars, the actual amount depending on the scale of nuclear power generation, the time that disposal occurs, and the geologic medium used for the repository. DOE has estimated that if disposal began in 2010, the cost of waste management would be up to $18 billion for the currently operating reactors and up to $68 billion for a 250-GW$_e$ system. [177] These very large absolute figures are relatively small, however, compared to the total capital cost of the nuclear power system that would be served.

Since the expenditures for waste management occur substantially later than do the initial capital expenditures for the reactor system, discounting to take into account the time value of money reduces the relative effect of waste management on the overall cost of generating nuclear electricity. As a result, it appears unlikely that the costs of waste management could ever represent more than a relatively small fraction of the total cost of nuclear power generation. DOE, in its analysis of waste management alternatives for a range of nuclear power futures,

[176] K. D. Kirby et al., Op. cit.

[177] DOE, *FEIS,* table 7.62, p. 7.47. Also, the most recent DOE analysis concludes that the cost of disposing of 144,000 tonnes of spent fuel or equivalent high-level waste—about the amount expected to be generated by the reactors now in o)eration or under construction-is between $18 billion and $20 billion in constant 1982 dollars. U.S. Department of Energy, *Report on Financing the Disposal,* op. cit., p. 2.

concludes that the costs of waste management would add not more than 2 to 10 percent, and most likely not more than 3 percent, to the cost of nuclear electricity.[178] For this reason the fees for radioactive waste disposal are likely to be small in comparison to the effects on the costs of coal-generated electricity resulting from clean air regulations.[179]

Since these fees would be seen by the utility as an annual cost, instead of an increase in the capital cost of building a nuclear powerplant, it appears unlikely that waste management costs could significantly affect a utility's decisions about whether to construct a new nuclear reactor. This conclusion is strengthened by the fact that the estimated cost of waste disposal is small compared to the total cost of fresh fuel,[180] and in fact, may be no greater than the range of uncertainty in the estimates of the cost of fresh fuel.[181]

The greatest potential cost impact of nuclear waste management policy may not be the direct costs of the management system, but the indirect costs that would result if problems in development or operation of such a system led to shutting down reactors or to a moratorium on operation of new ones. For example, the cost of replacement power for a l-GW_e reactor for 1 year could exceed the estimated cost of storing and disposing of the total amount of high-level radioactive waste generated from the operation of that reactor during its lifetime.[182]

Distribution of Impacts

Since waste management is apt to represent only a small part of the total costs, logistics, and social impacts of the entire nuclear fuel cycle,[183] the choice among management systems will have little incremental effect on the overall impacts of nuclear power generation. However, available studies have considered only the aggregate impacts of alternative systems. The distribution of those impacts among the private sector, the Federal Government, and regions of the country has not been analyzed rigorously, even though it underlies the equity judgments that are at the heart of the political decision-making process.[184] Usually, the Federal Environmental Impact Statement, the primary tool for identifying impacts, focuses almost entirely on aggregate impacts and not at all on their distribution. While alternative waste management systems may be little different in their aggregate impacts, they may differ significantly in their equity implications.[185] For example, a highly centralized system with only one repository operating at a time could substantially increase the number of communities affected by waste transportation. Thus, concerns about equity issues—in particular, the regional distribution of the costs and benefits of waste management— may play a major role in decisions about both spent fuel management and waste disposal policies.

Rigorous analysis of the regional impacts of waste management would require development of an integrated waste system model capable of dealing with specific sites and transportation routes. As noted earlier, although important components that could be used in such a model have been developed, they have yet to be combined.[186]

System Interrelationships

High-level radioactive waste management at operational scale will involve handling highly radioactive materials in quantities and at annual rates that are unprecedented. For example, from

[178] Ibid., pp. 7.50-7.51. Analysis by the Congressional Budget Office supports this conclusion. CBO, *Financing Radioactive Waste Disposal,* September 1982, p. 27.

[179] Ibid., p. xvii.

[180] A recent DOE analysis shows an example levelized fresh fuel cost of 7.7 mills/kWh, compared to a waste disposal fee of 1 mill/kWh established by the Nuclear Waste Policy Act of 1982. U.S. DOE, *Nuclear Energy* Cost *Data Base,* table 4.2, p. 66.

[181] MITRE, *Nonradiological Impacts,* table 2-6, p. 2-20.

[182] Ibid., pp. 2-21.

[183] Ibid., ch. 2.

[184] Roger E. Kasperson, "Institutional and Social Uncertainties in the Timely Management of Radioactive Wastes, Center for Technology, Environment, and Development, Clark University, June 30, 1980. Testimony prepared for the California Energy Commission for the Nuclear Regulatory Commission Confidence Rulemaking on the Storage and Disposal of Nuclear Waste.

[185] See National Research Council, Social *and Economic Aspects,* ch. 3.

[186] Site-specific highway and rail routing models have been developed by Oak Ridge National Laboratories. See D. S. Joy et al., *HIGHWAY, A Transportation Routing Model: Program Description and User's Manual, ORNL/TM-8419,* December 1982; and D. S. Joy et al., "Predicting Transportation Routes for Radioactive Wastes," *Waste Management 1981, vol.* 1, p. 415. These are used in Edwin L. Wilmot et al., *A Preliminary Analysis.* A nonsite-specific integrated systems model was developed for use in the U.S. DOE, *FEIS,* ch. 7.

the beginning of the use of nuclear power to the end of 1980, a total of about 5,000 spent fuel assemblies were transported from reactor sites.[187] About 10,000 assemblies would have to be transported each year to feed a 3,000 -tonne/yr repository.[188] Nonetheless, available analyses indicate that the flows of radioactive waste produced by existing and projected levels of nuclear power generation should be manageable, provided that careful planning is done to avoid bottlenecks and minimize the strains that could result from the rapid increase in transportation and handling when a repository or reprocessing plant begins operation.[189]

The annual handling capacity of the elements of the waste management system is as important as the total amount of the waste in determining the behavior of the system. For example, the buildup of spent fuel in storage is determined by the difference between the rate at which spent fuel is generated by reactors and the rate at which it can be reprocessed or disposed of. If the Barnwell reprocessing plant were to begin operating at its maximum capacity of 1,500 tonnes/yr in 1995, it would take 20 years to reprocess the amount of spent fuel that had gone into storage by that time.[190] It would take somewhat more than the capacity of one additional plant of the same size to handle the 2,200 tonnes of spent fuel expected to be generated each year by the reactors that will by operating in 1995,[191] Similarly, a single waste repository of the current reference loading capacity, 3,000 tonnes/yr, would be sufficient to stop the buildup of spent fuel in storage, but not to reduce the backlogs very quickly. Thus, it appears likely that up to 90 percent of the spent fuel generated in this century will still be in temporary storage facilities (most of it at the original reactor basins) at the end of the century, even if the Barnwell reprocessing plant were put into operation or a repository began direct disposal of spent fuel during the 1990's.[192]

Increasing the annual handling capacity of the waste management system is expensive. The capital cost of a 1 ,500 -tonne/yr reprocessing plant is estimated at $2 billion,[193] and a 3,000 -tonne/yr repository is estimated to be about $3 billion.[194] The initial capital cost of a centralized spent fuel dry storage facility capable of receiving about 1,500 tonnes/yr would be about $500 million, while an additional 500-tonne/year handling module at the same site would cost about $90 million.[195] Since leaving spent fuel once it has been placed in storage at the reactor is relatively inexpensive, as noted in the discussion of storage technology, the decisions about how fast and when to remove spent fuel from storage at reactor basins will have significant cost implications that must be considered in planning for the operation of a full-scale waste management system. (For further discussion, see the analysis of the Mission Plan in ch. 6.)

[187]Edwin L. Wilmot, *Transportation Accident Scenarios*, table XXV, p. 44.

[188]Based on an average of 3.5 assemblies/tonne of spent fuel, derived from utility projections of spent fuel discharges contained in app. B of the U.S. Department of Energy, *Spent Fuel Storage Requirements*, DOE/SR-0007, March 1981.

[189]DOE, *FEIS;* MITRE, Analysis *of Nuclear Waste Disposal; National Research Council, Social and Economic Aspects.*

[190]DOE, *Spent Fuel and Radioactive Waste Inventories,* table 1.2, p. 30.

[191] Ibid.

[192]Ibid., fig. C.2, p. 284; fig. C.3, p. 285.

[193]DOE, *Nuclear Energy Cost Data Base,* table 2.13, p. 27 (1983 dollars).

[194]DOE, Report *on Financing the Disposal,* table 3-4, p. 13 (1982 dollars).

[195]D.E. Rasmussen, *Comparison of Cask and Drywell Storage,* op. cit., table A.27, p. A.28 (1982 dollars).