Nuclear-Spent Fuel and High-Level Radioactive Waste Disposal

A Review of Options Considered in the United States

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Preface and Acknowledgments

The Nuclear Waste Policy Act (NWPA) was passed in 1982. Its main aim was the development of mined deep geologic repositories for the disposal of spent fuel and high-level waste resulting from reprocessing. It followed intensive study and consideration of alternatives, including an Environmental Impact Statement (EIS) published by the Department of Energy (DOE) in 1980 and a Record of Decision in 1981. But a number of events since the passage of the NWPA combined to frustrate that goal. Despite the expenditure of billions of dollars, many investigations, much scientific and technical effort, including field investigations, laboratory work, and development of performance models, the United States is still far from a clear path to geologic disposal.

This historical review is meant to provide a technical history of how the decision to focus on mined geologic disposal was made and, to a lesser extent, why spent fuel went from being regarded as a resource up to the mid-1970s to a dangerous waste that needed to be managed and disposed of. It also provides a brief technical update, whose purpose is to examine whether developments since the passage of the NWPA warrant a re-evaluation of the decision to dispose of spent fuel by geologic isolation. Two disposal options besides a mined repository are discussed. One of them, deep vertical-borehole disposal, was discussed in the 1980 EIS. The other, horizontal-borehole disposal, has been proposed in recent years by a private company, Deep Isolation, Inc. This report is focused on the United States.

The terms “geologic isolation” and “geologic disposal” are used interchangeably in this report. It is generally acknowledged that perfect isolation, in the sense of no radionuclides ever reaching the human environment, would be extremely difficult or impossible. In any case, demonstrating perfect isolation poses intractable problems due to the long periods of time involved. The term “geologic disposal” as used here means that the disposal will be demonstrated with reasonable confidence to be in conformity with post-disposal radiation-protection standards and other regulations. This is also the meaning of the term “geologic isolation” as used in this report. The terms “vertical” and “horizontal” boreholes do not mean exactly those orientations but rather general orientations from which there may be modest deviations.

This report was funded by Deep Isolation as an independent review. My contract with Deep Isolation guaranteed that I could commission reviews of a draft of this report and, at my sole discretion, determine how I would respond to them. It has long been my practice to take all review comments carefully into account and then decide on the content of the final report myself and take full responsibility for it. I have followed that practice in this case as well.

I asked three reviewers to independently evaluate and review my draft report. Two of them, Jaak Daemen and Deb Katz, reviewed the whole report. One reviewer gave some initial comments on the table in the last chapter and wishes to remain anonymous. I also invited Deep Isolation to provide comments, and Rich Muller, the company's Chief Technology Officer, did so. Their insights and experience have enriched and improved this work. Of course, as the author, I remain solely responsible for the contents of the report and any errors and deficiencies that remain. I appreciate the complete independence that I have enjoyed in the preparation of this work.

Arjun Makhijani, Ph.D.

President, Science Matters, LLC

Executive Summary

This report[1] is a technical history of how the decision to focus high-level and spent-fuel waste disposal on mined geologic disposal was made in the United States and, to a lesser extent, why spent fuel went from being regarded as a resource up to the mid-1970s to a dangerous waste that needed to be managed and disposed of. It also provides a brief technical update, whose purpose is to examine whether developments since the passage of the 1982 Nuclear Waste Policy Act (NWPA) warrant a re-evaluation of the decision to dispose of spent fuel by geologic isolation. Two geologic disposal options besides a mined repository are discussed. One of them, deep vertical-borehole disposal, was a backup concept in the NWPA. The other, horizontal-borehole disposal, has been proposed in recent years by a private company, Deep Isolation, Inc. This study was commissioned by Deep Isolation, Inc. The author had complete independence in its preparation and finalization.

i. Early considerations

Large amounts of highly radioactive waste were first created as part of military plutonium production during the Manhattan Project; they continued to be produced for decades during the Cold War. Civilian nuclear power made its debut in the 1950s, but the waste was also expected to be liquid high-level waste—the predominant leftover material after uranium and plutonium have been extracted from irradiated reactor fuel by a series of separation steps called reprocessing.

1 Citations are in the main body of the report and are not repeated in this summary.

The long-term management and disposal of high-level waste in the United States was first considered in depth in the mid-1950s by a panel of the National Academies. It mainly investigated the disposal of high-level waste by direct injection of the liquid into geologic formations—a method that has since been rejected as inappropriate.

The panel believed the danger of high-level waste was "so great that no element of doubt should be allowed to exist regarding safety," which meant that "the waste must not come in contact with any living thing." In other words, the aim of the regulatory regime governing disposal would be to prevent any contact between the waste and ecosystems.

Until the mid- to late-1970s, spent fuel from nuclear power plants was not considered a waste but rather a resource, since it was thought that the recovered uranium and plutonium could be used to advantage in "breeder reactors." These reactors are so named because they can produce more nuclear fuel than they consume by turning non-fissile uranium-238 (which is nearly 99.3 percent of natural uranium) into fissile plutonium-239. The context was the belief that uranium would be a scarce resource for the projected number of power reactors—1,000 reactors of 1 gigawatt-electrical each by the year 2000 in the United States alone.

The 1973 energy crisis and the 1974 Indian nuclear test, along with the economic and technical challenges encountered in commercializing breeder reactors and reprocessing, changed these calculations fundamentally. All reactors planned or ordered in and after 1974 were cancelled. Uranium was no longer scarce relative to demand. And after the Indian nuclear test, civilian nuclear technology, heralded by President Eisenhower in his 1953 "Atoms for Peace" speech, came to be seen as having a more dangerous aspect—nuclear proliferation—by both President Ford, a Republican, and President Carter, a Democrat. The combination of these factors led to a change in the official view of spent fuel from resource to highly radioactive waste.

ii. The 1980 Environmental Impact Statement and geologic disposal

A number of official studies on high-level waste and spent-fuel disposal were done in the mid- to late-1970s, including a review by an Interagency Taskforce appointed by President Carter. They led up to a Final Environmental Impact Statement (EIS) prepared by the Department of Energy; it was published in 1980. The Record of Decision (ROD) was published in 1981. Its main recommendation was that high-level waste and spent fuel be disposed of in a mined deep geologic repository. The isolation system would include engineered barriers to retard the spread of waste that was expected to slowly leak from the containers over thousands or tens of thousands of years. Deep-borehole disposal and sub-seabed disposal were named as backup approaches to be researched.

The 1981 ROD was based on a comprehensive consideration of alternatives in the 1980 Final EIS. In addition to the three approaches selected in the ROD, the concepts included disposal in space, in the Greenland or Antarctic ice sheets, in deep wells, or in rock cavities in which the waste would melt the rock and combine with it—a kind of in situ engineering of a waste form. Island geologic disposal was considered as a variant of geologic disposal—the remoteness of islands was considered an advantage.

Most of the approaches considered either required reprocessing or would be rendered more technically and economically feasible if spent fuel were reprocessed. For instance, well injection required a liquid waste form, which meant dissolving spent fuel—normally the first step in reprocessing. Ice-sheet disposal required a high thermal source term at the surface of the canister, which was judged to be possible for high-level waste. It could work for spent fuel that was less than two years old, however spent fuel is stored in spent-fuel pools at the reactor sites for three or more years for safety reasons.

Sending spent fuel into space was possible in theory, but the mass of the spent fuel and its cladding would make it prohibitively expensive. Thus, the 1980 Final EIS estimated it to be feasible (contingent on future technological development) only if the spent fuel was reprocessed and the fuel cladding and uranium were managed on Earth.

However, by the mid-1970s, reprocessing was already seen as a very problematic technology in terms of cost and proliferation. The preferred alternative in the 1981 ROD, disposal in a mined geologic repository, could accommodate both spent fuel and solidified high-level waste without reprocessing. The same applied to the two backup approaches, deep-borehole disposal and sub-seabed disposal.

iii. Retrospective on the geologic disposal decision

The passage of time has reinforced the reasons for rejecting the alternatives to geologic disposal. Commercialization of breeder reactors failed despite enormous expense and effort. Commercial reprocessing in this context has been, overall, a failure; a central indicator is that the commercial-sector global surplus of separated, and thus weapons-usable, plutonium that has not been used as a nuclear fuel now exceeds the combined military inventories of weapons plutonium in all nuclear-weapon states. The prospects of ice-sheet disposal have been dimmed by the added complications of climate disruption that has occurred since 1980. Sea-level rise has shown island disposal to be rather more dangerous than thought when it was proposed.

Space disposal of spent fuel has not been rendered more attractive despite technological developments since 1980. The risk of loss of payloads containing very long-lived radioactive materials remains; even if the packaging is made more secure, the very long half-lives of some radionuclides in spent fuel (tens of thousands to millions of years) essentially assure their dispersal over time, especially if lost in the oceans. Second, the opportunity cost of space disposal has become enormous. Specifically, the lost revenue from not using space assets for launching commercial payloads like communications satellites (or even for space tourism) by instead using them to shoot spent fuel into space could run into trillions of dollars for U.S.-spent fuel alone.

The terrorist attacks in the United States on September 11, 2001, have created yet another perspective on the spent-fuel management problem: spent fuel in pools at reactor sites and, to a lesser extent, in any accessible storage are now recognized to be potential targets for malevolent acts, as was analyzed by the National Academies in a 2006 report.

In sum, the considerations in the late 1970s and early 1980s that led to the selection of geologic disposal for long-term spent-fuel management have been reinforced since that time. Nuclear proliferation risks of reprocessing remain. The appalling consequences of malevolent acts against spent-fuel targets have been added to the list of reasons against indefinitely long surface storage and for geologic disposal.

iv. The 1982 Nuclear Waste Policy Act

The 1982 Nuclear Waste Policy Act codified into law the 1981 Record of Decision to dispose of high-level waste and spent fuel in a mined deep geologic repository. Political resistance following the 1986 announcements of sites in Eastern states, including New Hampshire, important in presidential primaries, led to the suspension of site selection and a Congressional mandate in 1987 to focus the effort on characterizing a single site: Yucca Mountain in Nevada. In the meantime, the Nuclear Regulatory Commission (NRC) had developed performance standards for deep geologic isolation (published in the Federal Register at 10 CFR 60); the Environmental Protection Agency (EPA) developed standards for protection of the environment (published at 40 CFR 191). Unless changed, these two regulations in their final form would still be the performance and environmental protection standards for all repositories except Yucca Mountain, for which both the NRC and EPA wrote site-specific regulations.

v. The Continued Storage Rule

Yucca Mountain was withdrawn from consideration by the Obama administration in 2009. The near-total lack of practical progress toward actual disposal despite billions of dollars in expenditures and considerable scientific and technical work led to an impasse for the Nuclear Regulatory Commission in reactor licensing. The NRC's repeated formal assurances in the context of reactor licensing that a repository would be available for disposal in time were no longer credible to a federal court, which ordered a review. The NRC prepared a Generic Environmental Impact Statement and the Continued Storage Rule (10 CFR 51), which concluded that, while a repository was preferable, storage of spent fuel for an indefinite period of time—stretching to thousands and even tens of thousands of years—in the absence of one would be safe. The rule assumed that the federal government would routinely provide the funds and its regulatory institutions would assure safety for periods far longer than human civilization has existed.

The Continued Storage Rule, in effect, negated decades of official findings that continued storage posed catastrophic long-term environmental risks, including to entire aquatic systems such as the Mississippi River, the Columbia River, the Great Lakes, and the tens of millions of people who depend on them. Proliferation risk would increase over time. Cesium-137 provides the main radiation barrier preventing the diversion of spent fuel and the extraction of plutonium from it. After a few hundred years, its decay would greatly lower the risk of theft of spent fuel; the danger that plutonium would be recovered from it would rise dramatically.

vi. Conclusions

Geologic disposal poses its own challenges. However, decades of analysis, review, research, and real-world events have shown that deep geologic disposal poses risks that are orders of magnitude smaller than any other approach for long-term spent-fuel management.

Geologic disposal can be done by one of three approaches:

- Disposal in a mined geologic repository (several hundred to 1,000 meters deep);
- Disposal in deep vertical boreholes (3,000- to 5,000-meter disposal depths);
- Disposal in deep horizontal boreholes (at depths greater than 1,000 meters).

Each approach has its advocates and its strengths and weaknesses. Mined disposal has been the most studied not only in the United States but in several other countries, including France, Sweden, Finland, the U.K., Belgium, and Switzerland. The work has included evaluation of specific states, pilot projects, laboratory work, development of performance models, and one repository under construction (in Finland) for spent-fuel disposal. In the last decade, considerable work has also been done on deep vertical boreholes, where the disposal horizon would be much deeper and hence farther from the human environment. Disposal in horizontal boreholes is a relatively new concept, put forward by a private company, Deep Isolation, Inc. Deep vertical- and horizontal-borehole drilling has been demonstrated extensively in the oil and gas industry; however, the field development of these concepts in the nuclear waste disposal context remains largely to be done.

I.
From the 1950s to the mid-1970s

The ultimate fate and management of highly radioactive waste was not an important priority in the first decade of the nuclear age. Other exigencies took center stage, including materials production for weapons (mainly plutonium, highly enriched uranium, and tritium) and the fabrication of the weapons themselves. High priorities included nuclear reactors and nuclear fuel for naval vessels. After President Eisenhower's famous "Atoms for Peace" speech in 1953, development of commercial nuclear power also became a high priority. The speech seemed to presage a world in which nuclear power could become a universal source of economical energy supply:

> The United States knows that if the fearful trend of atomic military build-up can be reversed, this greatest of destructive forces can be developed into a great boon, for the benefit of all mankind. The United States knows that peaceful power from atomic energy is no dream of the future. The capability, already proved, is here today. Who can doubt that, if the entire body of the world's scientists and engineers had adequate amounts of fissionable material with which to test and develop their ideas, this capability would rapidly be transformed into universal, efficient and economic usage?[2]

2 Eisenhower 1953. As it turned out, official and academic assessments of nuclear energy done before and after this speech by U.S. industry generally concluded that nuclear energy would be expensive. Makhijani and Saleska 1999, pp. 62-69.

Nuclear waste was a blip on the screen of policy concerns. Looking back on the 1950s from the perspective of the year 1979, when both spent fuel and reprocessing wastes were acknowledged to be significant waste-management issues, Carroll Wilson, the first general manager of the Atomic Energy Commission, noted:

> Chemists and chemical engineers were not interested in dealing with waste. It was not glamorous; there were no careers; it was messy; nobody got brownie points for caring about nuclear waste. The Atomic Energy Commission neglected the problem... The central point is that there was no real interest or profit in dealing with the back end of the fuel cycle.[3]

There was an exception to this lack of interest in the mid-1950s. The Atomic Energy Commission made a request to the National Research Council of the National Academy of Sciences[4] "to consider the possibilities of disposing of high-level radioactive waste in quantity within the continental limits of the United States."[5]

i. The 1957 National Research Council Report

A conference was held in Princeton in 1955 to discuss the issue of disposal of highly radioactive waste on land (as distinct

3 As quoted in Makhijani and Saleska 1992, p. 37.
4 Now called the National Academies.
5 National Research Council 1957, Abstract.

from "disposal in the oceans," which had been considered at a conference in Woods Hole, Massachusetts, in June 1954[6]); a report based on those deliberations and subsequent research and evaluation was published in September 1957.[7] Its purpose was not to make specific recommendations for disposal but rather to examine the possibilities for disposal and to make recommendations for research needed to establish its feasibility.

The 1957 report considered reprocessing high-level waste but not spent fuel from nuclear power plants because spent fuel was not considered a waste. The prevailing opinion in nuclear circles was that uranium, as a scarce resource, should be used as fully as possible. Only 0.7 percent of natural uranium is uranium-235, which is fissile, while almost all the rest is uranium-238, which is not. But "breeder reactors" can convert non-fissile uranium-238 into fissile plutonium-239 in larger amounts than the fuel needed to run those reactors, whence the use of the term "breeder" to describe them. Breeder reactors could, in theory, use almost the entire uranium resource, except for the amounts lost to waste streams in mining, milling, processing, reprocessing, and fabricating the fuel. Reprocessing, the term for chemical processing of spent fuel into its various components, is essential to the concept of using breeder reactors and most of the uranium resource as fuel.[8]

6 National Research Council 1957, Appendix B.

7 National Research Council 1957.

8 Reprocessing can be integral to each reactor installation or physically separate from reactors.

Reprocessing separates spent fuel into a uranium stream (mostly uranium-238),[9] a plutonium stream, and a waste stream, which is mainly fission products. This last contains the vast majority of the radioactivity in the spent fuel; it was the focus of the 1957 report.

At that point, the vast majority of the high-level waste was reprocessing waste generated at Atomic Energy Commission sites as part of the AEC's production of plutonium-239 and other materials for the U.S. nuclear weapons program. Much of the 1957 report consists of a discussion of the direct injection of liquid high-level wastes into geologic formations, how the geologic medium may be affected, and the fate of the waste in that context. Direct injection of liquid high-level waste has since been rejected as inappropriate. Hesitations about the practice are even evident in the 1957 report.[10] There was no discussion of direct disposal of spent fuel, which was considered a resource due to its content of plutonium, unfissioned uranium-235, and the large amount of uranium-238 that could potentially be converted into fissile plutonium-239 in a suitable breeder reactor.

9 Typical spent-fuel composition from 4% enriched fresh fuel at burnup of 45 gigawatt-days thermal per metric ton of heavy metal would be: U-234: 0.02%; U-235: 0.68%; U-236: 0.52%; U-238: 93.05%, Pu isotopes: 0.99%; minor actinides: 0.095%; Fission products: 4.62%. International Atomic Energy Agency estimates as cited in Makhijani 2010, Table 1, p. 15. For each kilogram of 4% enriched fresh fuel, 6.44 kilograms of depleted uranium are produced (~0.2% U-235, and 99.8% U-238, and trace amounts of U-234). Some reprocessing techniques produce slightly different streams of materials with the aim of increasing proliferation resistance of the plutonium stream. See Makhijani 2010 and references therein.

10 National Research Council 1957, Chapter 3, p. 3.

The 1957 report does contain some useful pointers and reminders for the present debate. The discussion of safety, for instance, is still important:

> Unlike disposal of any other type of waste, the hazard related to radioactive waste is so great that no element of doubt should be allowed to exist regarding safety. Stringent rules must be set up and a system of monitoring and inspection instituted. Safe disposal means that the waste must not come in contact with any living thing. Considering the half-lives of the isotopes in waste this means for 600 years if Cs^{137} and Sr^{90} are present or about one-tenth as many years if both isotopes are removed.[11]

Despite the stringent standard of zero exposure ("must not come in contact with any living thing"), the committee that authored the report was "convinced that radioactive waste can be disposed of safely in a variety of ways and at a large number of sites in the United States."[12] Still, the committee was mindful of the difficulties of finding a suitable site and getting it approved for disposal of high-level waste:

> We stress that the necessary geologic investigation of any proposed site must be completed and a decision as to safe disposal means established before authorization to begin construction is given. Unfortunately such an in-

11 National Research Council 1957, main body of the report, p. 3.
12 National Research Council 1957, main body of the report, p. 3.

> vestigation might take several years and cause embarrassing delays in the issuing of permits for construction. This situation can only be handled by starting investigation now of a large number of potential future sites as well as the complementary laboratory investigations of disposal methods.[13]

The committee recommended salt sites for preferential investigation because, among other things, "no water can pass through salt" and "[f]ractures in salt are self-sealing."[14]

It is important to remember the technical context of the report and the limited nature of its considerations:

- Military high-level liquid reprocessing waste was the main issue analyzed in the report. Almost all (but not all) plutonium-239 had been removed from this waste.
- The notion that radionuclides would eventually leak out of containers and reach the human environment that has been the subject of probabilistic analysis in recent decades was not in evidence at this stage of waste-disposal considerations.
- Very long-lived fission products were essentially ignored. Of these, later analyses often found iodine-129, half-life about 16 million years, to be troublesome, despite the relatively

13 National Research Council 1957, main body of the report, p. 4.
14 National Research Council 1957, main body of the report, p. 4.

small total radioactivity content in high-level waste,[15] due to its mobility in groundwater and stringent drinking water standard implicit in the regulation developed two decades later (about 1 picocurie per liter).[16]

- The large amounts of actinides in military high-level waste, including plutonium-239 and uranium-238, were also ignored.[17]

A stringent standard of safety would be more complex today since these longer-lived radionuclides must be taken into account in assessing impact on the human environment. Moreover, there is now much greater appreciation of the difficult problem of estimating radiation dose over long periods of time. Standards of safety have become stricter (or less lax, depending on one's point of view) over the decades. In 1957, there were not even separate radiation exposure limits for members of the public and nuclear-industry workers.

Finally, nuclear-material security is a much more significant issue with spent fuel, which contains large amounts of plutonium. If separated, this plutonium can be used to make nucle-

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15 For instance, Savannah River Site high-level waste contained an estimated 150 million curies of Sr-90 and 160 million curies of Cs-137 but only about 20 curies of I-129 in 1981. (Makhijani, Alvarez, and Blackwelder 1986, Tables 3.2 and 3.3). Yet the total mass to be mobilized was not as different due to the much higher specific activity of the much shorter-lived Sr-90 and Cs-137. For instance, the mass of Sr-90 was estimated as 1,100 kilograms; the mass of iodine-129 was on the order of 10 kilograms.

16 The EPA drinking water standard, at 40 CFR 141 at 141.66, limits radiation doses from most man-made beta-particle and photon-emitting radionuclides, including iodine-129, to 4 millirem per year. The drinking water limit of 1 picocurie per liter for I-129 is derived from the 4 millirem limit.

17 Makhijani, Alvarez, and Blackwelder 1986, Table 3.4.

ar weapons. This makes human intrusion into the repository, whether inadvertent or deliberate, an important issue.

The preliminary nature of the report's consideration of the entire problem of high-level waste disposal is well illustrated by one of its general recommendations:

> The education of a considerable number of geologists and hydrologists in the characteristics of radioactive wastes and its disposal problems is going to be necessary.[18]

ii. Lyons, Kansas

Pursuant to the recommendations of the 1957 National Research Council report, the AEC selected a salt formation near Lyons, Kansas, for investigation. The investigation was called Project Salt Vault; the site was a former salt mine that operated until 1948. According to a 2010 history of the project[19]:

> The primary objective of Project Salt Vault was to demonstrate the safety and feasibility of handling and storing high level nuclear waste (HLW) solids from power reactors in salt formations. The engineering and scientific objectives were to:
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> - Demonstrate waste-handling equipment and techniques required to handle packages containing HLW [high-level waste] solids from the point of production to the disposal location;

18 National Research Council 1957, Chapter 3, p. 7.
19 Peltier 2010.

- Determine the stability of salt formations under the combined effects of heat and radiation (approximately 4,000,000 curies of radioactive material, yielding up to 109 rads);
- Collect information on creep and plastic flow of salt needed for the design of an actual disposal facility;
- Monitor the site for radiolytic chemical reactions, if such should occur.

Initial work on the project began in 1963. The first radioactive waste to be put into the salt mine, in November 1965, consisted of 14 spent-fuel assemblies from an experimental reactor in Idaho.[20] Such testing of the properties of salt, with spent-fuel canisters in it, continued until June 1967, when the last canisters were removed.

The experiment indicated, at least over the relatively short period of the test (less than two years), that "[t]he structural properties of salt were not significantly altered by the high radiation levels"; however, brine inclusions in the salt "had a tendency to migrate up a thermal gradient toward a heat source placed in the salt." [21] This tendency resulted in damage to the stainless steel canisters:

> In fact, the salt did have some deleterious effects upon the canisters. When the heated canisters were removed

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20 The Idaho National Laboratory was then the principal testing location for nuclear reactor designs and was then known, appropriately, as the Nuclear Reactor Testing Station.
21 Peltier 2010.

> from their holes, cracks penetrating halfway through the stainless steel walls were noted, and heavy corrosion was observed on the stainless steel conduits supplying power to the heaters.[22]

The project had also demonstrated that spent fuel could be lowered and removed from a deep disposal site. Reportedly, the highest external radiation dose was to the hands of a worker—200 millirem in one quarter. Equally important, there had been no serious political opposition up to that point; indeed, the community seemed hospitable to the project. No attempt to develop the site as a permanent repository was made in the research phase; the site was put on standby in February 1968.[23]

The 1969 fire at Rocky Flats, the AEC site between Denver and Boulder, Colorado, where plutonium triggers for nuclear weapons were made, changed all that. Cleanup generated a large volume of plutonium-contaminated waste that was to be sent to the Idaho National Laboratory. Idaho resisted becoming the “dumping ground” for wastes generated in another state. As fate would have it, Glenn Seaborg, who led the team that first isolated plutonium during the Manhattan Project, was Chairman of the AEC at the time. Under pressure from elected officials, including Idaho’s Senator Frank Church, Seaborg made a commitment that the waste would

22 Lipschutz 1980, p. 118.
23 Peltier 2010.

be removed from Idaho by 1980.[24] This commitment implied a suitable disposal site that the AEC did not have at the time.

Prior to that commitment, plutonium-contaminated waste had been treated much like any other low-level waste and disposed of in shallow landfills, including in unlined trenches. In 1970, a new category of low-level radioactive waste was defined—that containing more than 10 nanocuries of alpha-emitting transuranic radionuclides per gram of waste. This was called "transuranic waste" (or TRU waste, for short); it was one of the types of waste generated at Rocky Flats. Pursuant to Glenn Seaborg's commitment to the state of Idaho, it had to be disposed of by 1980. Its designation as TRU waste, a special category, meant that it could no longer be dumped in unlined trenches, as it had been prior to that time.[25]

The AEC needed a site; it had done some research at the Lyons, Kansas, site. In 1970, the agency announced that the Lyons, Kansas, site was preferred as the country's first geologic disposal site. There were other similar sites, in New York and Michigan, with the former being closer to a reprocessing plant in that same state. The AEC announced that further tests would be done; despite that, the salt mine near Lyons was declared as the site for the first geologic repository for nuclear waste.[26] Indeed, Milton Shaw, who headed the AEC's reactor development division, in seeking funding for the site, confidently tes-

24 Peltier 2010 and Lipschutz 1980, pp. 118-119.

25 Lipschutz 1980, p. 34; Fioravanti and Makhijani 1997, p. 64. The threshold for transuranic waste was changed in 1984 to 100 nanocuries per gram. Makhijani and Saleska 1992, p. 18.

26 Peltier 2010.

tified to Congress that the Lyons, Kansas, site was "equal or superior to the others [in the country]."[27] He made this claim despite the very limited research at the Lyons site and the lack of comparable in situ research at other sites.

The lack of sufficient geologic and hydrologic work turned out to be a serious flaw, notably in the face of rising political opposition in Kansas at both the state and local levels. Scientific concerns with the Lyons site emerged quickly, including notably in the Kansas Geological Survey:

> A widely held view among leaders of the Kansas Geological Survey was that there was insufficient knowledge about repository design, the heat-flow models were primitive, and there were large gaps in the understanding of waste-rock interactions and rock mechanics.[28]

For one thing, there were oil and gas wells in the area; that meant there were holes in the formation. Twenty of them could not be plugged "and the unexpected disappearance of water from a nearby solution mining operation raised many questions about the geologic integrity of the salt domes for storing liquid nuclear waste."[29]

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27 As quoted in Lipschutz 1980, p. 119, including the part of the quotation in square brackets.

28 Peltier 2010.

29 Peltier 2010. Lipschutz 1980 (p. 119) states that 180,000 gallons of water, pumped in to dissolve salt and be brought up to the surface as brine, had disappeared without a trace.

In this context, Representative Joe Skubitz and Governor Robert Docking became opponents of the project. Both Kansas senators, Robert Dole and James Pearson, also expressed concerns; the latter "sponsored an amendment…[that] prohibited buying land or burying waste materials at Lyons until such time as an independent advisory council, appointed by the president, reported to Congress that the establishment of a repository and burial of waste could be carried out safely."[30]

Through 1971, the AEC insisted that the Lyons site was suitable. The facts and intense public and high-level opposition led the AEC to withdraw from the site in 1972.

Project Salt Vault began as an experiment and a research project. It was a limited project that had some technical success; it had community support. But the research had also revealed problems, such as corrosion of the canisters. Under intense political pressure from Idaho, the site's designation abruptly changed from inactive to a preferred radioactive waste repository, with scant regard for the community's views on the change and manifestly insufficient hydrologic research for disposal of long-lived transuranic waste.

The loss of trust in the AEC on nuclear waste management and disposal came in the context of a larger loss of trust in the agency. During the peak period of the Lyons debacle in 1971 and 1972, public concerns arose about reactor safety—and specifically about whether their emergency core cool-

30 Peltier 2010.

ing systems would perform as designed to keep the reactor core covered with water in case of a severe loss-of-coolant accident. The AEC's own experiments could not conclusively demonstrate the level of performance that would be needed. The AEC started hearings in January 1972, ostensibly to calm public fears. The contrary happened, in large measure because some of its own scientists felt not that the reactors were unsafe but that the level of performance required of emergency core cooling systems in worst-case accidents had not been demonstrated.[31]

The safety hearings lasted until about the end of 1973—nearly two years instead of the six weeks hoped for by the AEC. The airing of safety concerns by its own technical staff led to a serious loss of confidence and contributed to the breakup of the Atomic Energy Commission into a regulatory arm, the Nuclear Regulatory Commission, and the Energy Research and Development Administration (ERDA), which later, in 1977, became a cabinet-level agency, the Department of Energy (DOE). ERDA would research nuclear energy as well as other forms of energy and run the U.S. nuclear weapons complex, among other functions. The split was consummated in 1975.

In the midst of all this, two events complicated every atomic-energy calculation in the United States: the 1973 energy crisis and the 1974 Indian nuclear test.

31 Ford 1982, Part Two.

II.
The changing framework in the 1970s

i. The energy front

For a considerable time prior to the rapid rise in oil prices in 1973, energy growth and economic growth in the United States grew roughly in parallel; electricity grew faster than energy—at about twice the rate of economic growth. These historical trends since the 1950s had achieved the status of what appeared to be an economic-technical truth but turned out in fact to be dogma based on insufficient analysis. It was based on extrapolations of recent historical trends. In this context, the faith that nuclear energy was the future of electricity was routinely proclaimed, including by the AEC. A part of this faith was that there would be 1,000 nuclear power reactors in the United States by the end of the twentieth century.

However, the energy-Gross Domestic Product (GDP) and electricity-GDP ratios changed abruptly in the 1973–1975 period (Figure II-1). Between 1973 and 1985, the economy grew at 2.8% per year, but energy use grew hardly at all—less than 0.1% per year. Subsequently, energy growth resumed somewhat but peaked in 2007.[32]

32 Energy use in the last decade has been exaggerated significantly because a hypothetical thermal loss component is added to solar- and wind-generated electricity, though such losses do not in fact exist. Thus, while Energy Information Administration estimates show that energy use in 2018 was above 2007, the actual Btus consumed were in fact lower when the nonexistent solar and wind thermal losses were removed from the data. The same should be done for hydro, but that does not affect the conclusion about relative consumption since hydro generation has remained about the same (with annual variations mainly due to precipitation).

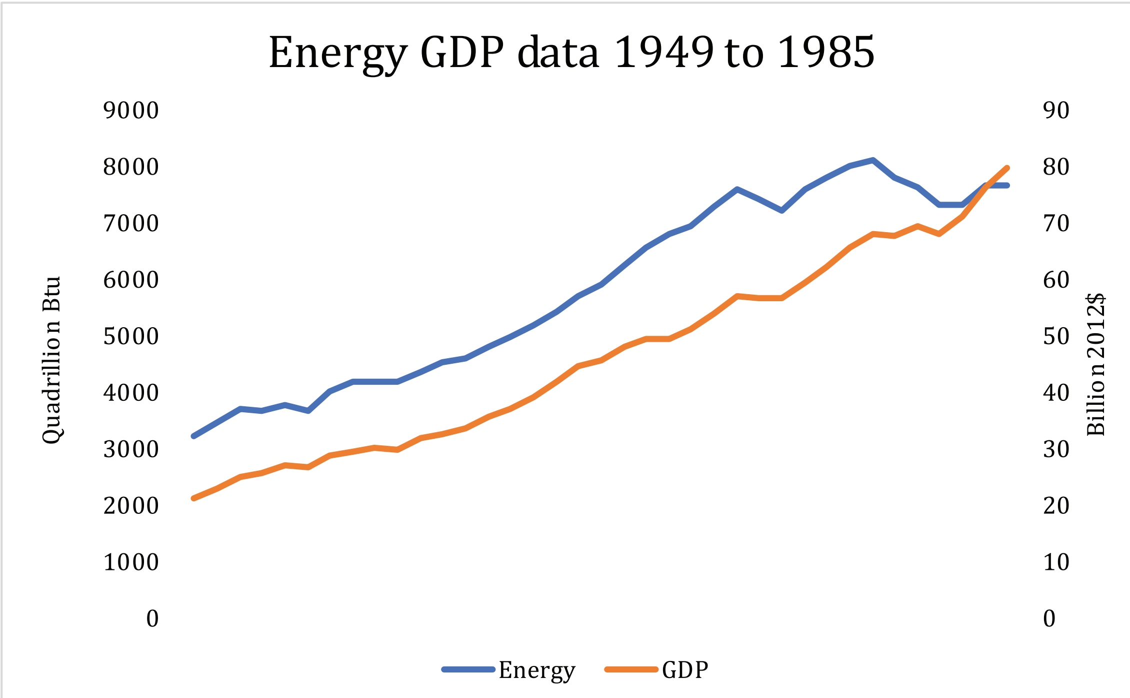

Figure II-1: Energy and GDP data showing the relationship changed in the 1973–1985 period. Sources: Energy information Administration and St. Louis Federal Reserve.

ii. A change in nuclear power prospects

The 1970s were the heyday of reactor orders, but every reactor planned or ordered starting in 1974 was cancelled. Instead of more than 30 reactors per year envisioned in the early 1970s, the average rate at which reactors were brought on line between 1973 and 2000 was only about four per year.

A far smaller number of reactors meant much lower uranium demand. Uranium prices fluctuated, partly in concert with oil prices; overall, however, uranium turned out not to be a scarce resource relative to demand. Rather, it was in surplus by 1970, the year the U.S. government stepped out of its role as the sole purchaser of uranium:

> Procurement of uranium concentrates by the AEC spanned the period from 1947 through 1970. During those years, in definable stages, the market for uranium concentrates changed from a monopsony with the Federal Government as the only buyer, to a completely commercial market with no Government purchases. From the viewpoint of the Government as a consumer, the foreseeable supply of uranium increased from desperately short of that which was required for defense needs to adequate, to surplus.[33]

Even as uranium was going from scarcity to abundance, breeder reactors and reprocessing were getting deeper into trouble. The first commercial-breeder-reactor effort in the United States, Fermi I, near Detroit, suffered a partial meltdown in 1966. It was not viable even after repairs and was closed in 1972.[34]

The AEC continued to believe that breeder reactors would be necessary—the sodium-cooled breeder was the top research, development, and demonstration project for the agency. The decline in the prospects for nuclear power was not yet strongly evident in the electricity marketplace. A 400-megawatt-thermal prototype, the Fast Flux Test Facility, was built at the AEC's Hanford, Washington, site. And a middle-scale, 975-megawatt-thermal, 340-megawatt-electrical power reactor, the Clinch River Breeder Reactor, was planned

33 Albrethson and McGinley 1982, p. 3.
34 IPFM 2010, p. 95.

to be built in Oak Ridge, Tennessee, another Manhattan Project site. The costs for the latter quickly spun out of control even in the early stages, rising to an estimated $1.7 billion in 1974[35]—or more than $6 billion in 2016 dollars. This amounts to about $18,000 per kilowatt-electrical (2016 dollars).

The AEC persisted with the Clinch River Breeder Reactor project at least partly because it believed that uranium resources could only support about 1,000 gigawatts-electrical of light water reactor capacity—roughly what was projected for the year 2000. By this reasoning, sustained further growth of nuclear power would require conversion of non-fissile resources, notably uranium-238, to fissile materials, notably plutonium-239. More than 1,500 gigawatts of nuclear capacity were projected by the end of the first decade of the twenty-first century.[36]

In the event, electrical growth dropped sharply, nuclear costs increased, and nuclear-capacity growth stalled at roughly 100 gigawatts-electrical by the end of the 1980s. The Clinch River Breeder Reactor project was abandoned in 1983 but was in trouble earlier on non-proliferation grounds (see below).

Commercial reprocessing in the United States also suffered serious setbacks. A privately owned plant was built and started up in western New York State in 1966. But operational problems and other issues led to a permanent closure in

35 IPFM 2010, pp. 101-102.
36 IPFM 2010, p. 101, Figure 7.5, including caption text.

1972. Still, hopes and plans for breeder reactors and commercial reprocessing were alive and well until about the mid-1970s. A private consortium, Allied General Nuclear Services (AGNS, pronounced "Agnes") was formed in 1971 to build a large reprocessing plant in South Carolina. Construction continued in the wake of the 1973 energy crisis, and the plant was basically ready for tests in 1977. It was never started up as a reprocessing plant, though it was used for testing approaches to transportation and nuclear proliferation.[37]

iii. The Indian nuclear test

Even as the economic prospects for breeder reactors and reprocessing were dimming in the mid-to-late 1970s, another equally powerful concern, proliferation, arose that would effectively end, in the United States, the notion that commercial high-level waste management would consist of managing and disposing of high-level reprocessing wastes. Spent fuel was on its way to becoming a category of nuclear waste.

India, a non-signatory to the Nuclear Non-Proliferation Treaty, tested a nuclear "device," which it called a peaceful nuclear explosion, on May 18, 1974. Prior to that time, the main official security concern relating to reprocessing, as expressed in the environmental review of the use of mixed oxide plutonium fuel, had been access to potentially weapons-usable plutonium by non-state parties. The Indian test greatly enlarged those con-

37 Smith 1978.

cerns by extending them in an urgent fashion to nonnuclear states that might want to acquire nuclear weapons.[38]

Less than three months after that May 1974 test, Gerald Ford was inaugurated as president of the United States upon the resignation of President Nixon. The plutonium for India's test had come from a reactor supplied by Canada; the heavy-water moderator for the reactor was supplied by the United States. It was the leading edge of proliferation concerns that came to include other countries. The proliferation underbelly of President Eisenhower's "Atoms for Peace" program was increasingly exposed.[39]

The breeder reactor (coupled with reprocessing) went from being a "magical" energy source that would produce more fuel than it consumed (by converting non-fissile uranim-238 into fissile plutonium-239) to being increasingly seen as economically unnecessary and a proliferation danger:

> A new study, *Moving Toward a Life in a Nuclear-Armed Crowd?*, released by the ACDA [Arms Control and Disarmament Agency of the U.S. State Department] in late 1975, sharpened the perception in Congress and elsewhere that nuclear fuel reprocessing was going to give more and more countries enough separated plutonium to build nuclear weapons if they chose. This study by University of Chicago political scientist Albert Wohlstetter

38 Carter 1987, pp. 114-117.

39 The proliferation issues of this period constitute a vast topic. For the purposes of this report, a good summary is to be found in Carter 1987, pp. 114-119.

> and his associates at Pan Heuristics concluded that the use of plutonium not only represented a grave proliferation hazard but was unnecessary. It argued that projections as to the rate of growth of nuclear power around the world had been much exaggerated; that future supplies of uranium had been grossly underestimated; and that plutonium fuel, when all the costs were counted, was going to come at a relatively high and unattractive price.[40]

Proliferation became a high-profile political issue in the election year of 1976. Governor Jimmy Carter, running for president, expressed his doubts about pursuing reprocessing; if pursued, he believed it should be internationalized. A few days before the 1976 election, President Gerald Ford issued a statement saying that "*non-proliferation objectives must take precedence* over economic and energy benefits if a choice must be made."[41]

In the months after he assumed office, President Carter announced a policy of indefinite deferral of commercial reprocessing in the United States and a suspension of government support of the technology. Spent fuel became, in effect, a part of the nuclear-waste-management problem, which had now acquired new technical, economic, and safety dimensions. Management of spent fuel for much longer periods than were considered in the 1957 National Research Council report was now on the policy table.

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40 Carter 1987, p. 117.

41 President Ford's October 28, 1976, statement, "Nuclear Power," as quoted in Carter 1987, p. 117, italics added.

III.
Options for spent-fuel and high-level waste disposal

Starting in 1975, and more definitively after President Carter's April 1977 statement on reprocessing, attention turned increasingly to interim storage of spent fuel as well as to methods for its long-term disposal. The concern with disposal of high-level reprocessing waste continued because large quantities of such waste already existed; they consisted mainly of weapons-related high-level waste but included high-level commercial waste at the closed West Valley, New York, reprocessing plant and the high-level waste generated by reprocessing of naval spent fuel in Idaho. In addition, the AGNS plant in South Carolina had not yet been permanently abandoned for reprocessing commercial spent fuel. That would happen in the 1980s. Disposal of transuranic waste was also considered as part of the review process for waste management and disposal.

In this chapter, we survey the various options that were studied and why deep geologic disposal was chosen as the option to be pursued for long-term management of high-level waste and spent fuel. A number of assessments were done in the 1975–1980 period. President Carter established an interagency review taskforce, which reported to him in October 1978.

There were other agency and non-agency reports. Some evaluated a single approach; others evaluated multiple approaches and compared them. The EPA prepared an extensive report in 1979, examining a variety of alternatives.[42] We will not exam-

42 EPA 1979.

ine most of these studies. Rather, we mainly consider the definitive document that officially examined a variety of options as part of an Environmental Impact Statement (EIS). This EIS was done during the Carter administration; the Final EIS was published in October 1980.[43] However, the Record of Decision was published in May 1981,[44] after the change in administrations in January 1981.

In describing and evaluating the various options, the Final EIS refers to a variety of studies that were done by various agencies and national laboratories. We will refer to other studies for supplementary information as necessary for the purposes of this report, which is mainly to recount how the disposal choice was narrowed to a mined geologic repository in the 1981 Record of Decision, with sub-seabed disposal and very deep hole disposal as possible backup approaches:

> The United States Department of Energy has decided to (1) adopt a strategy to develop mined geologic repositories for disposal of commercially-generated high-level and transuranic wastes (while continuing to examine subseabed and very deep hole disposal as potential backup technologies) and (2) conduct a research and development program to develop repositories and the necessary technology to ensure the safe long-term containment and isolation of these wastes.[45]

43 DOE 1980.
44 DOE 1981.
45 DOE 1981, p. 26677.

This formal Record of Decision was followed by the enactment of the Nuclear Waste Policy Act of 1982, which, in amended form (1987), is still the operative law for high-level waste and spent fuel.

The following sections summarize the approaches for disposal that were evaluated in the 1980 Final EIS. Each option was examined from the point of view of feasibility, environmental impact, cost, and safeguards requirements for the security of sensitive materials, notably plutonium. The next chapter provides a retrospective assessment of these options by the author of this report.

The EIS examined the following options:

- Transmutation;
- Disposal in space;
- Ice-sheet disposal;
- Sub-seabed disposal;
- Island disposal;
- Well injection;
- Rock melt;
- Disposal in very deep holes; and
- Disposal in a mined geologic repository.

i. Transmutation[46]

Transmutation in the context of spent fuel and high-level waste disposal refers to extended (multistep) reprocessing in which spent fuel would be separated into three material streams:

- Uranium and plutonium, to be fabricated into reactor fuel (or possibly packaged for disposal);
- Other actinides such as neptunium, usually called minor actinides;
- Fission products.

The main goal would be to eliminate the minor actinides by transmuting them into fission products. The main approach would be to mix them with reactor fuel. A variety of options were described in the Final EIS, including mixing them with mixed oxide (MOX) fuel, which consists of a mixture of uranium and plutonium oxides. MOX fuel can be used in a variety of reactors, including light-water reactors. At the time of the publication of the Final EIS in 1980, reprocessing had been suspended, but it had not been definitively ended. Opening the Allied General reprocessing plant in South Carolina was still a possibility. Further, the Clinch River Breeder Reactor, which was to be the U.S. demonstration reactor for sodium-cooled breeders, had not yet been cancelled.

46 Unless otherwise mentioned, this section is based on Section 6.1.7 of DOE 1980.

Transmutation would only address a small fraction of the spent fuel (both in terms of mass and radioactivity): the minor actinides, which would be converted into fission products by transmutation. Transmutation was thus not disposal as such but rather decreasing one stream of radionuclides (minor actinides) while increasing another (fission products).[47]

The vast majority of the radioactivity in spent fuel is in the fission products; these would, in any case, go into a deep geologic repository according to the Final EIS, which also notes that transmutation would not affect two long-lived fission products: technetium-99 (half-life 211,000 years) and iodine-129 (half-life about 16 million years). Finally, while transmutation of minor actinides, if carried out repeatedly, would reduce disposal risks in the intermediate term (thousands of years), it would not significantly affect long-term risks (over hundreds of thousands or millions of years), which would be dominated by these two long-lived fission products, according to the Final EIS.

Repeated reprocessing and repeated irradiation of minor actinides in a reactor would be required. The Final EIS notes that each irradiation of minor actinides would reduce the amount by 5 to 7 percent. The Final EIS states that the cycle of irradiation would have to be repeated "numerous times."

47 DOE 1980 notes this in the following words: "The concept is actually a method of waste treatment or conversion to a more benign form; it is not an independent disposal method."

The Final EIS does not discuss the fate of the MOX-spent fuel in any detail. However, a flow diagram and a set of bullet points describing it indicate that the MOX-spent fuel would also be repeatedly reprocessed; the plutonium and uranium would then be repeatedly re-fabricated into fuel for use in a reactor.[48] Methods of transmutation other than fission reactors are mentioned in the Final EIS; they include particle accelerators, nuclear explosions, and tokamak fusion reactors.[49] The document does not discuss the fate of the plutonium and uranium, notably in case of transmutation by nuclear explosions.

The Final EIS discusses a number of difficulties with the transmutation concept, including the fact that it is not actually a waste disposal method as well as the fact that an extended period of technical research and development would be required for addressing just one component of spent fuel. The higher requirements for safeguarding plutonium and other materials (called "sensitive materials") required are also noted:

> The transmutation concept depends on processing of the spent fuel elements and the recycle of transmutable materials. The extra processing and transportation, and the availability of sensitive materials at all points in the back end of the fuel cycle would increase the opportunity for diversion of these materials. In ad-

48 This is indicated in Figure 6.1.21 on p. 6.121 of DOE 1980.
49 DOE 1980, Figure 6.1.20, p. 6.120.

> dition, because of the necessity to process and recycle material eight or nine times to ensure full transmutation, the annual throughput of sensitive materials would greatly increase. Material accountability would also be more difficult because of the large quantities and high irradiation levels. Safeguards of recycled plutonium would be simplified because of the higher concentration of ^{238}Pu. Also, recycled actinides containing ^{252}Cf and ^{245}Cm would require shielding from neutrons that should simplify safeguard requirements.[50]

The Record of Decision did not include transmutation as one of the approaches to be developed as a complement to or backstop for geologic disposal.

ii. Disposal in space

NASA conducted a study of space disposal in 1978;[51] the Final EIS drew on that study. The amount of spent fuel considered in the NASA study was for a nuclear power scenario in which there would be 380,000 megawatts-electrical of nuclear-installed capacity by the year 2000.[52]

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50 DOE 1980, p. 6.135. The estimate of recycling transmutable materials “eight or nine times to ensure full transmutation” appears incorrect at least for the minor actinides. At the highest rate of transmutation of 7 percent per cycle cite in the Final EIS, minor actinides would have to be recovered and recycled more than 30 times to be reduced by 90 percent (0.93)^31 = 0.105, or 10.5 percent remaining; (0.93)^32 = 0.098 = 9.8 percent remaining. This assumes perfect recovery of minor actinides from spent fuel.

51 Burns et al. 1978.

52 Burns et al. 1978, p. 5. This was considered a low-growth scenario for nuclear power at the time.

A variety of concepts for sending the waste into different parts of space were considered; the Space Shuttle, which was due for test flights in 1981, was considered an important vehicle in the process of disposal. For instance, the waste could be put into high earth orbit, sent into orbit around the moon, disposed of on the surface of the moon, put into orbit around the sun, or shot out of the solar system altogether.

The main advantage cited for space disposal was that the duration of risk to people would become very short compared to disposal on Earth. In effect, the period of risk for all disposal options except Earth orbit would be the period during which the waste was prepared for space disposal and then shot into space.

The mass of the spent fuel would pose the largest problem. Shooting tens of thousands of tons of spent fuel into space would require a massive number of flights and be very costly. Further, a very large number of flights would be required and "the possibility of an ascent failure is obviously increased."[53] As a result, the approach considered was reprocessing of spent fuel and a variety of possible partitions of the waste to reduce the mass to be sent to space. At a minimum, the fuel cladding and the uranium would be removed. The fuel cladding would remove one-fourth to one-third of the mass of spent fuel assembly. The uranium in the spent fuel would be roughly 95 percent of the rest.[54] The rest of the mass of

53 Burns et al. 1978, p. 12.
54 Burns et al. 1978, p. 14. The masses represent fuel and reactor operation typical of the time.

spent fuel, mostly fission products, could be packaged and sent into space.

Other possible reductions of waste mass, such as removal of plutonium and of certain fission products, were also considered. But the main point was that practical space disposal required that the spent fuel would be reprocessed so that the vast majority of its mass would be retained on Earth.

The preferred space disposal option in the Final EIS was the use of an advanced space shuttle to launch the reprocessing waste stream containing fission products and minor actinides into orbit around the sun.[55] The waste stream would be solidified into a "cermet" matrix. The term "cermet" is a condensation of the words "ceramic" and "metal"; the waste would consist of "ceramic particles uniformly dispersed in a metallic matrix."[56] The terrestrial aspects of the process would include processing and waste fabrication facilities, the launch site, as well as a mined geologic repository.

It is important to note that space disposal, as described in the Final EIS, does not avoid the need for a geologic repository. This is stressed in the Final EIS, which notes that "(1) chemical processing would definitely be required for space disposal of waste and (2) the mined geologic repository would be part of the total system."[57]

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55 DOE 1980, Figure 6.1.22, p. 6.137.

56 DOE 1980, p. 6.138.

57 DOE 1980, p. 6.138 and Figure 6.1.23 on p. 6.139.

The process of actually putting waste into space would be complex. Here is the description in the Final EIS for putting the waste into orbit around the sun[58]:

> The shielded waste container would be loaded into a ground transportation shipping cask...
>
> For launch, the shielded waste form would be integrated with:
>
> - A reentry vehicle, which would protect and structurally support the waste in the Space Shuttle orbiter cargo bay;
> - A solar orbit insertion stage (SOIS), which would place the waste payload into its final solar orbit;
> - An orbit transfer vehicle (OTV), which would take the waste from low Earth orbit into a solar orbit transfer trajectory.

Figure III-1 shows the schematic for solar orbit disposal in the Final EIS.

58 DOE 1980, p. 6.140.

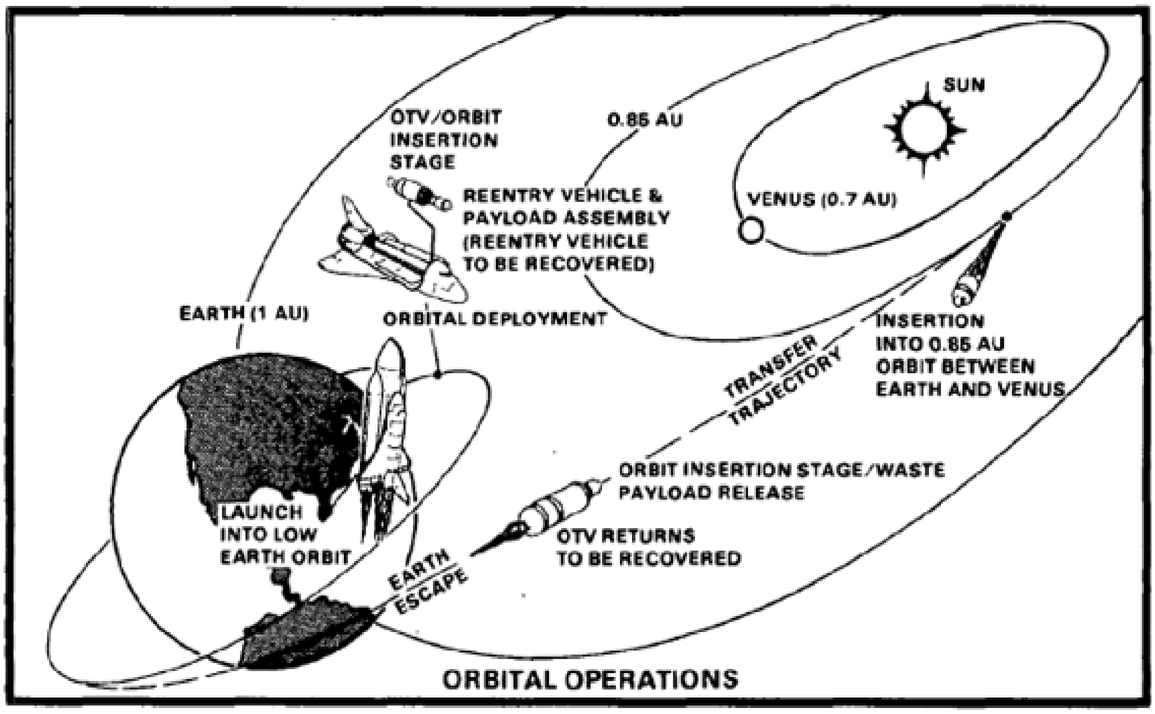

Figure III-1: Space Disposal in Solar Orbit.
Source: DOE 1980, p. 6.141

According to the Final EIS, considerable technological development would be needed to make the system practical. At that point, one launch of high-level waste per week would be required for a 170,000-megawatt nuclear reactor system. At about 100,000 megawatts, the actual nuclear power system developed was about 40 percent smaller; however, most reactors are now licensed for 60 years, extending the originally anticipated time of operation by 50 percent (if the reactors operate to the end of their granted licenses). Thus, the order of magnitude of the spent fuel expected from the actual set of reactors in the U.S. is comparable to that used in the Final EIS estimate. It would take one shuttle flight per week. Further, it is important to recall that roughly 95 percent of the mass of the spent fuel as well as all the cladding would be removed prior to packaging for space disposal. These removed materials would have to be managed on Earth.

The Final EIS describes the limitations of the system as follows[59]:

> Major uncertainties, shortcomings, and advantages of the concept are summarized below:
>
> - The concept does not permit ready corrective action;
> - The concept is susceptible to single mode (launch pad) failure, unless well-engineered multiple barriers are developed to protect the waste;
> - Significant technology advances and equipment development will be required;
> - Waste form and package concept development are in a very preliminary stage;
> - The concept's usefulness would be limiteto waste from reprocessing or further limited to selected isotopes.

Thus, disposal in space would involve reprocessing with its cost, waste, and material-diversion risks. It would involve keeping the vast majority of the mass of spent fuel on Earth. And it would necessitate a geologic disposal system.

Accidents on the launch pad, during flight, and during injection into the required orbit would be major considerations. Avoiding accidents such as high-intensity fires, explosions, and un-

59 DOE 1980, p. 6.145.

intentional atmospheric reentry of the waste would be major design objectives. Another major objective was to minimize the impact of accidents, should they occur. The radiation dose to the global population from dispersal of radionuclides due to burnup of waste upon accidental reentry was cited as 10 million rem, even though individual exposures were estimated to be small. The maximum exposure to an individual from a launch pad accident was estimated to be 80 rem.[60]

The international legal issues would be significant. For instance, people of other countries not involved in the nuclear waste disposal system would also be exposed in the event of an accident. Other legal issues would include whether such disposal was allowed under international treaties and what the licensing requirements might be.

iii. Ice-sheet disposal[61]

In this concept, either spent fuel or high-level reprocessing waste would be disposed of in either the Antarctic or Greenland ice sheets. The disposal approach relies on the heat generated by the radioactive decay occurring in the waste to melt the ice. An emplacement hole 50 to 100 meters deep would be drilled for initial placement of the waste; this depth would shield surface personnel from the radiation. The waste canisters would then sink gradually into the ice sheet.

60 DOE 1980, p. 6.149.

61 Based on Section 6.1.5 of DOE 1980 unless otherwise specified.

Figure III-2 shows the ice-sheet disposal concept from the Final EIA.

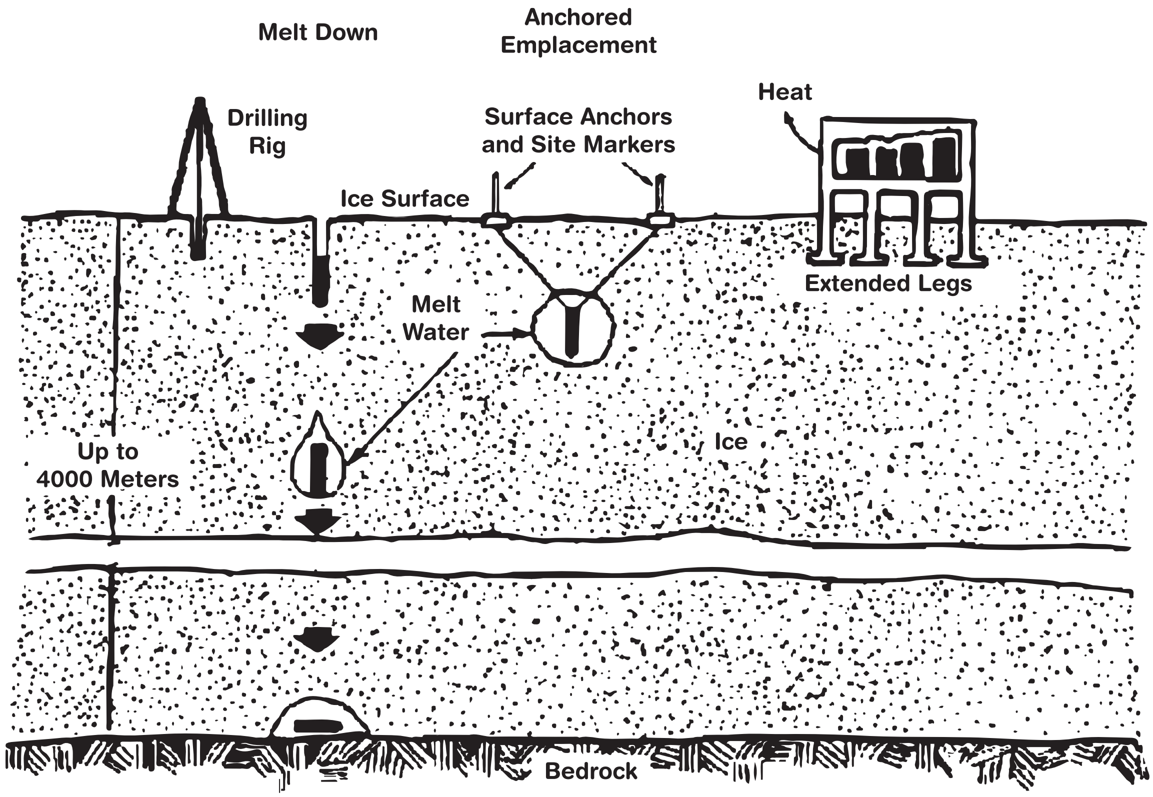

Figure III-2: Schematic Diagram of Ice-Sheet Disposal
Source: DOE 1980, p. 6.87.

The waste canisters would, of course, have to have a sufficient thermal output to melt the ice around them in order to sink; this process would have to continue for years for disposal at the depth of the rock under the ice sheet. The Final EIS estimates that a high-level waste canister would sink at the rate of 1 to 1.5 meters per day; at this rate, it would take five to ten years to reach the bedrock on the assumption of continuous vertical descent and no obstacles along the way. Further, the Final EIS assumes a spacing of one kilometer between holes "to avoid individual canisters interfering with each other during descent and possible concentration at the ice sheet base."[62] This is one square kilometer per canister; assuming they are disposed of in a symmetrical square array, a vast area of thousands of square kilometers would be needed for disposal.

According to the Final EIS, the thermal output of a canister containing spent fuel would be marginal for melting the ice if the spent fuel is emplaced more than two years after reactor discharge.[63] However, the Final EIS does not discuss the fact that the short window available for spent fuel disposal in an ice sheet conflicts with the normal storage time for which spent fuel is stored in spent-fuel pools. This period is at least three years; more typically it is five years.

The long-term impacts are described as follows[64]:

> Long-term impacts with the greatest potential significance are related to glacial phenomena that are not well understood. For example, ice dynamics and climatic variations affecting glaciation might be altered by waste disposal activities. Regardless of whether meltdown, anchored emplacement, or surface storage were used, potentially major modifications in the delicately balanced glacial environment could occur.
>
> One of the major areas of uncertainty stems from our

62 DOE 1980, p. 8.87.

63 DOE 1980, p. 6.84. This applies to fuel burnup levels prevailing at the time of the preparation of the EIS.

64 DOE 1980, p. 6.95

> limited understanding of ice sheet conditions. Little is known of the motion of the continental ice sheets except for surface measurements made close to the coast....Three general types of flow have been defined—sheet flow, stream flow, and ice-shelf movement....Each type of flow appears to possess a characteristic velocity. It is also believed that ice sheets where bottom melting conditions exist may move almost as a rigid block, by sliding over the bedrock.
>
> Where there is no water at the ice-bedrock interface, it is believed that the ice sheet moves by shear displacement in a relative thin basal layer. The formation of large bodies of water from the waste heat could affect the equilibrium of such ice sheets.
>
> In addition, two potential problems concerning the movement of the waste are unique to an ice sheet repository. First, the waste container would probably be crushed and breached once it reached the ice/ground interface as a result of ice/ground interaction. Second, the waste might be transported to the sea by ice movement.

The Final EIS discusses the potential for release of wastes into the oceans at the rate of 0.3 percent per year and mixing of radionuclides in the oceans. It also discusses the fact that an international treaty would be a legal bar to disposal in the Antarctic ice sheet. There would be territorial issues in relation to the Greenland ice sheets, since Greenland is part of the territorial system of Denmark.

Two retrievable ice-sheet systems are also discussed in the Final EIS. In one, the waste would penetrate the ice sheet to a limited extent because it would be anchored to surface facilities. The other approach is surface storage, which is not a disposal method.

Finally, the EIS notes that transuranic wastes from reprocessing would have to be disposed of in a geologic repository since they do not have sufficient thermal output for ice-sheet disposal. The Final EIS does not discuss rapid climate change impacts on the ice-sheet disposal concept.

iv. Sub-seabed disposal[65]

Sub-seabed disposal consists of disposal in sedimentary deposits under the seabed. It involves sending the wastes through the oceans to the bottom, where they would penetrate into seabed sediments. A specially designed "penetrometer," with a pointed tip and fins for guidance, would be used to ensure penetration into the sub-seabed sediments. The disposal zone would avoid subduction zones. Evidently, the waste containers would have to be designed to withstand the high pressures of the deep ocean.

The basic concept is similar to a geologic repository except that the disposal location would not be engineered. The main

65 Based on Section 6.1.4 of DOE 1980 unless otherwise stated.

barrier to dispersal would be the capacity of the subsea sediments to sorb the long-lived radionuclides that would leak out of the disposal canisters. The Final EIS postulates that sub-seabed disposal could be used for high-level waste, spent fuel, transuranic waste, and cladding hulls. In this respect, it would be similar to geologic repositories, where all these classes of waste could be disposed of—though not necessarily in the same repository.

Among other things, the Final EIS considers the impacts of possible loss of a vessel carrying the waste to the disposal location[66]:

> The maximum risk would be posed by the sinking of the seagoing vessel or by loss of waste canisters overboard. Except for accidents in coastal waters where mitigation actions could be taken, the radioactive materials released into the sea following such an event would disperse into a large volume of the ocean. Some radionuclides might be reconcentrated through the food chain to fish and invertebrates, which could be eaten by man.

Radiation doses from loss of waste at sea would depend on where the waste was lost, with the largest impact occurring if damaged spent fuel were lost within the continental shelf region—100,000 person-rem population dose and 0.11 rem

66 DOE 1980, p. 6.73.

maximum individual dose.[67]

Population doses in the long term from consumption were estimated to be the same order of magnitude: 100,000 person-rem with consumption of fish being the main pathway.[68] Impacts on benthic organisms and ecosystems were not estimated.

The Final EIS discusses both domestic legal barriers to sub-seabed waste disposal (the 1972 Ocean Dumping Act) in the oceans as well as the barriers, difficulties, and uncertainties posed by international treaties such as the 1972 London Convention, which prohibits dumping of low-level and transuranic radioactive waste at sea.

Despite the difficulties and uncertainties, sub-seabed disposal was part of the Record of Decision as one of the two backup approaches to geologic disposal, the other being vertical, very deep borehole disposal. The Record of Decision stressed the DOE's "commitment to the early and successful solution to the Nation's nuclear waste disposal problem so that the viability of nuclear energy as a future energy source for America can be maintained."[69]

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67 DOE 1980, Table 6.1.2, p. 6.74. The dose estimates are based on each vessel carrying 1,275 spent-fuel canisters (DOE 1980 p. 6.67). The spent-fuel content per canister is not specified in the sub-seabed disposal section of the Final EIS. The section on mined disposal describes each canister as having spent fuel with two metric tons of heavy-metal content (DOE 1980, p. 5.66).

68 DOE 1980, p. 6.78

69 DOE 1981. This Record of Decision was made in the context of an earlier Nuclear Regulatory Commission MRC rule, known as the "Waste Confidence" rule. In this rule, the NRC declared it was confident that the development of a geologic disposal system was feasible and could be done within a specified time frame and that spent fuel (or high-level waste) could be safely stored during the limited period until disposal in a repository. See 10 CFR 51 and Makhijani 2013.

v. Island disposal[70]

This is essentially a variant of geologic disposal. The island chosen would provide "a remote repository location with possibly advantageous hydrogeological conditions."[71] The main difference, other than legal and political issues, was that ship transport would be required, in addition to any overland transport. Since it would be a geologic repository, the same range of wastes could, in theory, be disposed of in it. No detailed investigations of the concept had been done at the time of publication of the Final EIS.

It would be expected to have similar long-term impacts as a geologic repository except that contamination of ocean waters was also possible. Volcanism and seismic issues would in some situations pose greater challenges. It was considered that the risk of diversion of sensitive materials would be mainly in the short term due to the remoteness of the location and the major facilities that would be required to access the materials.

vi. Well injection[72]

Two varieties of well injection of wastes were considered in the Final EIS:

70 Based on DOE 1980, Section 6.1.3.

71 DOE 1980, p. 6.48.

72 Based on DOE 1980, Section 6.1.6. Deep-well injection of wastes was developed by the oil industry for injection of brines that are often produced along with oil.

1. Injection of acidic liquid wastes “into porous or fractured strata” at depths of 1,000 meters to 5,000 meters;

2. Liquid waste would be mixed with cement and clays; this grouted waste would be injected at depths of 300 meters to 500 meters into shale formations that had been hydraulically fractured prior to waste injection.

The second of these approaches had been developed by Oak Ridge National Laboratory; it was being used for disposal of low-level and transuranic radioactive waste.

In theory, the approach could be used for spent fuel or reprocessing high-level wastes. However, for spent fuel, dissolution in acid would first be necessary; this is the normal first step in reprocessing using the PUREX process. Thus, the reference approach chosen for investigation was disposal of high-level waste, under the assumption that commercial spent fuel would first be reprocessed if this approach was used.

Mobility of radionuclides was considered to be a greater issue in case of liquid high-level waste injection. For grouted waste of the type used by Oak Ridge, the Final EIS estimated that:

> Isolation from the biosphere is achieved by low leach rates of radionuclides from the hardened grout sheet, negligible ground-water flow particularly up through the shale strata, retardation of nuclide movement by miner-

> als within the shale strata, and low probability of breeching by natural or man-made events.[73]

The selection of the site was considered important to waste isolation. In particular, the structure of the shale formation and the propagation of the fractures in it were critical:

> The principal requirement for shale grout injection is that the hydrofracture, and hence the grout sheet, develops and propagates horizontally. Vertical or inclined hydrofractures could result in the waste gaining access to geologic strata near the surface, and even breaking out of grout at the bedrock surface itself. Theoretical analyses indicate that, in a homogeneous isotropic medium, the plane of hydrofracture develops perpendicularly to the minor principal stress....Thus, a requirement for horizontal hydrofracturing is that the horizontal stresses exceed the vertical stresses.[74]

The Final EIS notes that deep-well injection of liquid wastes could induce seismicity; it noted research that concluded that deep-well waste injection at the Rocky Mountain Arsenal in Colorado had "been instrumental in producing seismic events."[75] Such concerns would have to be investigated.

73 DOE 1980, p. 6.101.
74 DOE 1980, p. 6.106.
75 DOE 1980, p. 6.116.

vii. Rock melt[76]

The rock-melt concept is a variant of geologic disposal. In this approach, the liquid high-level radioactive waste resulting from reprocessing would be put into an underground cavity. The thermal output of the waste would gradually melt the rock. After the water has evaporated from the waste, it would mix with the molten rock and form a solid matrix containing the waste. Rock melting as a disposal approach would essentially fabricate a waste form in situ at the location of disposal. The process of melting, mixing, and resolidification would take about 1,000 years. This approach would not be suitable for spent fuel disposal; it could be suitable for disposal of transuranic waste with a sufficient thermal source term. This approach assumed repeated reuse of recovered plutonium and uranium. The reference cycle assumes the use of light-water reactors for this purpose. The rock cavities were assumed to be 2,000 meters deep. Two cavities at a single site would accommodate high-level waste from 5,000 metric tons of spent fuel (in terms of heavy-metal content) per year for 25 years.[77]

The preferred rock type would be silicates, which consist of minerals with different melting characteristics. The Final EIS noted that the problems posed by the concept were significant since little development had taken place[78]:

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76 Based on DOE 1980, Section 6.1.2.

77 DOE 1980, p. 6.31. The amount of spent fuel corresponds roughly to a system about two-and-a-half times the one that was eventually built in the twentieth century.

78 DOE 1980, p. 6.37.

> The technological issues that would require resolution before initiation of the rock-melting concept can be summarized as follows:
>
> - The necessary geological information cannot be predicted with present knowledge;
> - Empirical data on the waste/rock interaction and characteristics are lacking;
> - No technical or engineering work design of the required facilities has been attempted.

A large number of problems in developing the approach were discussed in the Final EIS. For instance, how would workers be lowered through a relatively narrow two-meter-diameter shaft into the area to be mined out? Systems to capture volatile fission products and return them to the cavity needed to be developed as well as methods to line the cavity (should that be needed). The steam from evaporation of the water in the waste would have to be captured and condensed. The steam may contain tritium, posing handling and disposal issues. Sealing the shafts after waste emplacement would also pose challenges.

The post-emplacement challenges would also be considerable. The rock would expand during melting, during which time the high-level waste would be incorporated into it. The combined mass would contract during the solidification phase. Would the waste matrix fracture during contraction? Would induced fractures compromise containment? How would the chemical composition of the rock change when the high-level waste combined with it?

The Final EIS's conclusion about the approach was as follows[79]:

> In view of the significant technical uncertainties remaining, it is not possible to predict a cost estimate of the required R&D to implement this concept, nor the amount of time it would take.

If it worked as designed, the Final EIS opined that it might provide better containment than a mined geologic repository. But the impacts were expected to be highly site specific.

viii. Disposal in very deep holes

The Final EIS describes very-deep-hole disposal as follows:

> The very deep hole (VDH) concept involves the placement of nuclear waste as much as 10,000 m (32,800 ft) underground, in rock formations of high strength and low permeability. In this environment, the wastes might be effectively contained by the distance from the biosphere and the location below circulating groundwater...[80]

This concept was distinguished from a mined repository in that the waste canisters would be placed in a vertical hole; no

79 DOE 1980, p. 6.41.

80 DOE 1980, p. 6.6. Section 6.1.1 of the Final EIS discusses the various aspects of very deep hole disposal. Figure 6.1.1 shows a schematic diagram of the process of waste disposal.

actual underground work by miners for preparing the location for receiving waste would be involved. Each hole would not contain as much waste as a mined repository but could be much deeper. The central isolation concept was that the waste would be placed

> …far enough below circulating ground waters that, even if a connection develops, transport of materials from the repository to the surface would take long enough to ensure that little or no radioactive material reaches the biosphere…[81]

These criteria meant that the waste would be placed considerably below the water table; the actual depth would be site specific. Each hole would contain many canisters separated from one another by seals. Once sealed, the canister below the seal would not be retrievable. In the reference deep-borehole-disposal design, each borehole would contain 150 canisters of spent fuel.

The EIS stated that pathways to the biosphere might be created during construction:

> Microfractures and other openings might develop in the vicinity of the hole because of the stress relief created by drilling or excavation. In addition, small openings might develop within the cement plug and between the plug and the hole wall if the bonding between the two were

81 DOE 1980, p. 6.6.

> not adequate. Such channels would provide pathways for contaminated waters to migrate to the biosphere. If the hole were sited below circulating ground water, the primary driving force for migration would likely come from the thermal energy released by the radioactive waste. The travel time to the biosphere would therefore depend on the availability of water, the continuity and apertures of the existing and induced fractures, the time and magnitude of the energy released, geochemical reactions, and the volume and the geometry at the opening over which the energy persists. The lack of data on the presence of water and the properties of fractures in deep rock environments prevents making any estimate of the consequences to the ecosystem.[82]

Failure of the seals could also provide pathways for radionuclides to the biosphere. The EIS concluded that the impacts of such failures "could be evaluated only on the basis of site-specific parameters."[83] The EIS also notes the "susceptibility of the ground-water system to tectonic changes and groundwater action."[84]

Despite these reservations, the Final EIS provides an estimate of the dose to the maximally exposed individual in the long term due to an "abnormal event" as being only 0.5 microrem per year to the whole body and 0.5 microrem per year

82 DOE 1980, p. 6.21.
83 DOE 1980, pp. 6.24-6.25.
84 DOE 1980, p. 6.25.

to the bone from either spent fuel or high-level waste disposal in boreholes.[85]

It also concluded that, despite the lack of information, “it is not expected that the impact on the ecosystem would be any greater than that for a mined geologic repository and maybe less since the radionuclides would be expected to take longer to reach the biosphere.”[86]

More recent developments in borehole disposal are discussed in Chapter IV, Sections iv and v.

ix. Disposal in a mined geologic repository[87]

This was the preferred option selected for disposal of high-level waste, spent fuel, and transuranic waste. We cite the analysis and findings in the Final EIS more in detail because this was the chosen option. According to the Final EIS, disposal in a mined repository would consist of

- Engineered barriers preventing leakage of the waste for long periods of time into the geologic medium;
- A deep mine constructed in a geologic formation selected, among other things, to retard the wastes and contain them for long periods should the engineered barriers fail;
- A system to seal the mine once waste emplacement and engineered barrier construction was complete.

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85 DOE 1980, Table 6.1.6, p. 6.24.

86 DOE 1980. p. 6.25.

87 Based on DOE 1980, Chapter 5, unless otherwise noted.

The Final EIS's criterion for the engineered barriers was that they should ensure "total containment for an initial period," which might be "as long as 1000 years."[88] This initial period was chosen so that the intermediate half-life radionuclides, like cesium-137 and strontium-90, would have decayed away essentially completely by the end of that period. The geologic setting of the repository would be "expected to provide isolation of the waste for at least 10,000 years after the waste is emplaced in a repository and probably will provide isolation for millennia thereafter."[89]

As an aside, we note that the proposed Yucca Mountain repository would not have met the 600-to-1,000-meter depth criterion in the Final EIS, as can be seen from Figure III-4.

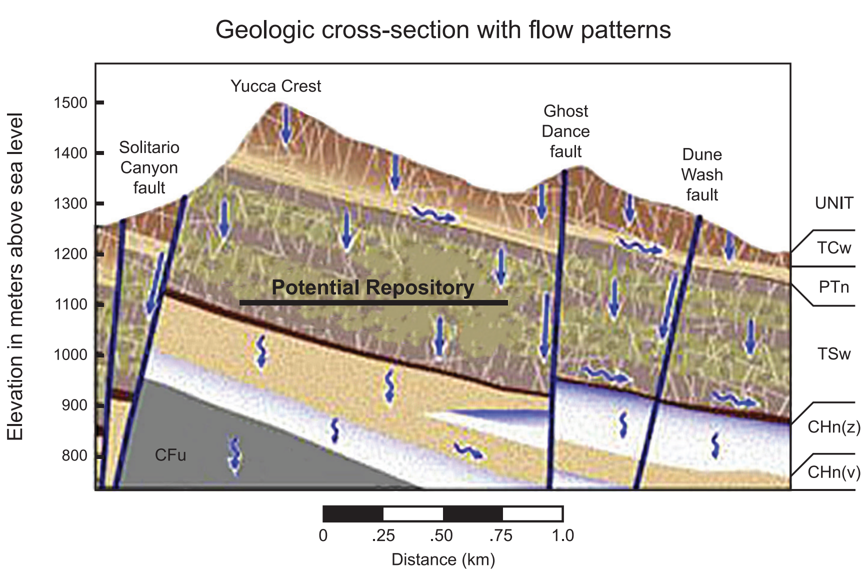

Figure III-4: Potential Yucca Mountain disposal location in its hydrogeologic context
Source: Krotz 2002.

The Nuclear Regulatory Commission's (NRC) rule for licensing geologic repositories, 10 CFR Part 60, issued in

88 DOE 1980, p. 5.1.
89 DOE 1980, p. 5.1.

1981 and amended thereafter, incorporated these criteria in modified form. The 10 CFR 60 requirements for performance of the engineered barriers are that containment should be "substantially complete during the period when radiation and thermal conditions in the engineered barrier system are dominated by fission product decay"; this period was specified as being "not less than 300 years nor more than 1,000 years after permanent closure of the geologic repository." Releases from the engineered barrier system after that time were required to be gradual and were required "not [to] exceed one part in 100,000 per year of the inventory of that radionuclide calculated to be present at 1,000 years following permanent closure, or such other fraction of the inventory as may be approved or specified by the Commission."[90]

In effect, 10 CFR 60 required that the long-lived radionuclide inventory should (1) leak out very slowly and (2) not leak out completely before 101,000 years after permanent closure of the repository. The 10,000-year EPA requirement was not explicitly included in 10 CFR 60. Rather, a limitation of the fastest groundwater travel time prior to waste emplacement of at least 1,000 years "from the disturbed zone to the accessible environment" was imposed; the travel time could be changed at the discretion of the NRC.[91]

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90 Quotes are from the clauses in 10 CFR 60 at 60.113(a)(1)(ii)(A) and 60.113(a)(1)(ii)(B). Note that the NRC later issued a different rule, 10 CFR 63, specifically for licensing Yucca Mountain after that site became the only one to be investigated. See Chapter V.

91 10 CFR 60.113(a)(2).

A 10,000-year containment requirement was incorporated by the Environmental Protection Agency into its high-level waste disposal rule. This rule, as amended, required the demonstration of a "reasonable expectation" that the annual dose to "any member of the public" would not exceed 15 millirem over a 10,000-year period.[92] It also required that disposal systems should similarly provide a reasonable expectation that groundwater contamination would not exceed the limits in the drinking water standard, which applies to public water systems.[93] Given the long period of time, a strict demonstration of compliance was not required; hence the phrase "reasonable expectation."

Evidently, the host rock, the engineered barriers, and the hydrogeologic system would have to meet these criteria. The Final EIS described six features that would be important:

1. *Depth of the disposal location below the land surface*: this distance was assumed to be between 600 and 1,000 meters. Depth was important both to serve as a barrier separating the waste from the biosphere and also to reduce the risk of post-closure human intrusion. The disposal area would also have to be sufficient to accommodate the waste planned to be disposed of in the location;
2. *"Properties of the host rock"*: The rock's strength, thermal conductivity (to limit post-disposal temperature increases); chemical properties to avoid adverse chemical

92 40 CFR 191.15
93 40 CFR 191(a)(1). The EPA's drinking water standards for radionuclides are at 40 CFR 141.66.

reactions and promote sorption of radionuclides should they leak, and a limited permeability were among the important properties of the geologic medium for meeting performance and radiation protection goals;

3. *Tectonic stability*;
4. *Hydrologic properties*: A suitable hydrogeologic regime would be needed to meet the water travel time criteria, among other things;
5. *Resource potential*: A low potential for usable resources would reduce the risk of human intrusion in the long term;
6. *Multi-barrier approach to performance* (as discussed above).

Retrievability of the waste "for some initial period of time" was considered a "technically conservative basis" for planning a repository.[94] Two periods were considered in the Final EIS—25 years and 50 years. The longer period would imply lower thermal loading. Some retrievability issues would be specific to the medium; for instance, creep deformation of salt after waste emplacement but during the retrievability period would be a concern that would have to be addressed in repository design.[95]

An initial five-year period of retrievability was considered important "for observation of waste-rock interactions when waste and local rock temperatures reach their maximum."[96]

94 DOE 1980, p. 1.7.
95 DOE 1980, p. 5.36.
96 DOE 1980, p. 5.36.

The retrievability principle was incorporated into the NRC licensing regulation, 10 CFR 60:

> The geologic repository operations area shall be designed to preserve the option of waste retrieval throughout the period during which wastes are being emplaced and, thereafter, until the completion of a performance confirmation program and Commission review of the information obtained from such a program. To satisfy this objective, the geologic repository operations area shall be designed so that any or all of the emplaced waste could be retrieved on a reasonable schedule starting at any time up to 50 years after the waste emplacement operations are initiated, unless a different time period is approved or specified by the Commission. This different time period may be established on a case-by-case basis consistent with the emplacement schedule and the planned performance confirmation program.[97]

The Final EIS considered four host rock types for its impact assessment (the numbers in parentheses are the metric tons of heavy metal assumed to be disposed of in each type): salt (51,000), granite (122,000), shale (64,000), and basalt (122,000).

The Final EIS made a rather sweeping, simplifying assumption about long-term radiological impact:

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97 10 CFR 60.111(b)(1).

> If the amount of disposed waste, rather than the size of the repository, were held constant, the radiological consequences would be the same for each geologic medium. In other words, once the radionuclides are outside the repository proper, their movement away from the repository is governed by the same set of assumptions regardless of repository media. (This limitation of the analysis would be improved upon in site-specific analyses when site specific data or sorptive properties of adjacent rock become available.)[98]

Several different types of release scenarios were considered for assessing long-term radiological impacts after repository closure:

- A meteorite impact large enough to breach the repository, with an assumption that 1 percent of the radionuclide inventory would be released: Maximum individual dose would be in the thousands of rem (i.e., at levels implying certain or near-certain death) if the impact is in the year of closure, declining to between 6 and 16 rem 1,000 years after closure. Population dose, between 4 million and 10 million rem at closure, declining to between 360 rem and 970 rem 1,000 years after closure. Most people within a few kilometers would be expected to die from the non-radiological consequences of the impact: the initial blast and heat. The reference scenario was a repository in the

98 DOE 1980, p. 5.74.

Midwest with 150 people living within a radius of two miles of the repository location.[99]

- "Breach of Repository by Fault, Fracture and Flooding": Various scenarios were explored. The 70-year committed doses would vary between a few tenths of a rem in salt to a few rem in other media, except in the case of groundwater intrusion into the repository caused by faulting. In that case, the highest whole body committed dose would be 440 rem from neptunium-237; the highest organ dose, from iodine-129 would be to the thyroid: 990 rem. The probability of such an event over 10,000 years was considered low: between $4x10^{-7}$ and $2x10^{-9}$. Thus, the risk, computed according to convention as the product of probability and consequence, was "believed to be insignificant" according to the Final EIS.[100]

The Final EIS also considered doses from inadvertent drilling into spent fuel or high-level waste canisters 1,000 years after repository closure. It estimated maximum first-year doses to be 13 rem (in the case of spent fuel) and 19 rem (in the case of high-level reprocessing waste).[101]

So far as safeguards are concerned, the Final EIS assessed it not to be an issue during the pre-closure period. Its conclusion after closure was as follows:

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99 DOE 1980, pp. 5.75-5.76.

100 DOE 1980, pp. 5.80-5.87.

101 DOE 1980, p. 5.88.

> After emplacement and closure in the geologic repository, the spent fuel would be essentially inaccessible for sabotage or theft. A successful intrusion and theft of HLW containers or sabotage in place would be unlikely because of the limited access to the containers, the operational control over entry, and the physical security provided at the access points in the surface facility. After repository closure the waste would be available only through re-excavation or mining. Theft or sabotage after closure and decommissioning does not appear credible because the effort would be readily detectable.[102]

The last conclusion about theft or sabotage being "readily detectable" after closure implies long-term institutional controls of some kind being operational for tens of thousands of years since the half-life of plutonium-239 is in excess of 24,000 years.

102 DOE 1980, p. 5.101.

IV. Retrospective on disposal options

The Final EIS was completed nearly four decades prior to the present review. It is therefore worthwhile to briefly survey whether developments since that time would change the fundamental conclusion that the preferred approach should be geologic disposal of spent fuel, high-level reprocessing waste, and transuranic waste. There is admittedly some judgment involved in assessing the present status of the various options and their prospects. However, these judgments are based on the author's intensive involvement in and assessment of the technical, environmental, and regulatory aspects of high-level waste and spent-fuel management in the United States since the early 1980s and, to a lesser extent, in France in 2004–2005 and 2010–2011.

The options for disposal discussed in the previous chapter can be grouped into three sets:

1. Those that necessarily involve reprocessing;
2. Those that likely or preferably involve reprocessing;
3. Those that could be used to dispose of spent fuel, high-level reprocessing wastes, and transuranic wastes.

The relative feasibility and practicality of the reprocessing-related options has declined considerably since the Final EIS was published in 1980. The fortunes of reprocessing have declined considerably because of the costs and risks of the approach and because decades of efforts and tens of billions of dollars of investment worldwide failed to commercialize breeder reactors.

i. Breeder reactors and reprocessing[103]

The commercial success of reprocessing depended essentially on the development of breeder reactors. These reactors would not only use the separated plutonium as fuel but, equally important, they could also convert uranium-238, by far the most abundant uranium isotope, into fissile plutonium-239. But the development of breeders, focused on sodium-cooled reactors, stalled in the 1990s and then, for practical purposes relevant to this review, failed.

In the United States, the Clinch River Breeder Reactor, meant to demonstrate commercialization of breeders, was cancelled. In France, the commercial-scale breeder at 1,200 megawatts-electrical output, Superphénix, went critical in 1985; it produced electricity until 1996 with an average lifetime capacity factor of less than seven percent. Monju, Japan's commercial demonstration breeder went critical in 1994 and had a serious sodium leak in 1995, whereupon it was closed until 2010. It suffered another accident in the same year and is now permanently closed.

Sodium-cooled breeder reactors have proved technically nettlesome; some have operated reasonably well; others, including the most recent ones in France and Japan, have been failures. While development continues, there is essentially no prospect that breeder reactors would be able to use the enormous backlog of surplus plutonium and recovered uranium

103 The breeder reactor history in this section is based on IPFM 2010.

in the foreseeable future. Indeed, the surplus-accumulated separated plutonium in the commercial sector now exceeds the inventory in the military programs of all nuclear-weapon states put together.[104] This, of course, raises serious proliferation concerns. In this context, it should be noted that one of the aims of geologic disposal is to make plutonium much less accessible than it is with continued storage at or near the Earth's surface.

Instead of breeder reactors, recovered plutonium has been used mainly in light-water reactors, when it has been used at all. However, such use is necessarily very limited, as evidenced by the buildup of surplus civilian plutonium even in France, where the use of mixed plutonium-uranium oxide fuel has been more extensive than in any other country.

So far as resource use is concerned, even repeated reuse in light-water reactors cannot increase the fraction of underlying uranium resource used to more than one percent. This is mainly because each time uranium is enriched for use as light-water reactor fuel, the vast majority of it ends up in the depleted uranium stream.[105] Depleted uranium can only be converted into useful fissile material in quantity in a breeder reactor. Moreover, the isotopic composition of the ura-

104 IPFM 2015, p. 3 and p. 29. The total civilian and military stocks at the end of 2014 were estimated at 505 metric tons; of this, the civilian stock was estimated at 271 metric tons, or about 54 percent. Further references to civilian plutonium are based on IPFM 2015 unless otherwise specified.

105 See Makhijani 2010 for details of the uranium resource calculation. Once through uranium use in light-water reactors uses about 0.5 percent of the uranium resource. The rest of the light-water reactor reuse discussion is based on this publication unless otherwise specified.

nium is degraded when it is irradiated, since uranium-236, not present in natural uranium, is created in the course of reactor operation. Trace amounts of uranium-232, a particularly troublesome isotope, are also created during reactor operation. Finally, the recovered uranium is contaminated with traces of plutonium, neptunium, and fission products. Re-enrichment contaminates enrichment plants with these troublesome isotopes. When the recovered plutonium is used as a mixed oxide (MOX) fuel, its isotopic composition plutonium degrades with each reuse. As a result, the technical difficulties of reuse of both the uranium and plutonium material streams grow. The economics of recycling can be expected to degrade each time light-water-reactor mixed-oxide spent fuel is reprocessed for uranium and plutonium recovery.

Reprocessing has fared only marginally better than breeder reactors. France, Britain, Russia, and India have continued to operate commercial reprocessing plants. Japan's commercial scale plant at Rokkasho has yet to open after over 25 years of construction; in any case, Japan owns a vast surplus of separated plutonium because it has used only a negligible amount of its stock as fuel. The mounting global stockpile of surplus commercial separated plutonium is a central measure of the economic failure of reprocessing.

In the United States, the reprocessing plant that President Carter put on hold never operated despite President Reagan's announced intention to lift the reprocessing suspension.

Thus, the possibility of reprocessing as part of a waste-disposal scheme in the United States is much more remote at this writing than it was in 1980.

In sum, the failure to commercialize breeders and the poor economic and technical outlook for connecting reprocessing to light-water reactor programs together mean that reprocessing-dependent disposal options are far less practical in the United States than they were in 1980.

ii. Reprocessing-dependent disposal approaches

The following disposal concepts discussed in Chapter III are necessarily dependent on reprocessing:

- Transmutation;
- Well injection; and
- Rock melt.

The first is not a disposal option for high-level wastes but only for minor transuranic actinides, which would require their recovery numerous times, each time after irradiation in a reactor. Thus, a repository would be needed for high-level wastes in any case. The other two require wastes to be in liquid form, which limits them to high-level waste disposal. In addition, a large number of technical, safety, and environmental-impact issues associated with these two approaches remain since they have not been significantly developed since 1980. The well-injection method also had a grout-injection option, in which the waste would solidify in hydrofractured underground fissures. The utility of this waste form for containment is in serious question. Experiments on grout at Oak Ridge in 1982 and 1997 showed potentially high rates of leaching of strontium-90 from grout containing high-level waste within a few weeks or months.[106]

These three disposal options may therefore be ruled out as impractical in the United States for the foreseeable future.

In addition, volume, economic, and technical considerations limit the following options to disposal of high-level reprocessing wastes:

- Space disposal; and
- Ice-sheet disposal.

In the case of space disposal, the consideration was mainly the number of flights; the Final EIS's reference approach was use of the space shuttle, soon to be introduced. The space shuttle was introduced in the early 1980s; it operated for many years and was retired in 2011. Other options to launch waste into space, including reusable rockets, have since been developed. However, none of the other technologies, including the vehicles that would transfer the waste from earth orbit to solar orbit or out of the solar system altogether, have been developed (see Figure III-1 above).

106 Smith 2004, p. 3.

There is a central economic issue that was not considered in the Final EIS: opportunity cost. Space delivery of payloads will continue to be useful for high-value purposes, like commercial, military, and scientific-research satellites. There is also the increasing prospect of use of space flight for space tourism, including potentially for longer sojourns on the moon or Mars.

Opportunity cost can be assessed by the revenue per unit mass that delivery of payloads into space can command. These are typically tens of thousands of dollars per pound. *Business Insider* has reported that Space X claimed its *Dragon* spacecraft could deliver payloads for $9,100 per pound.[107] Assuming $5,000 per pound, the forgone revenues if space vehicles were used to deliver waste into space would be $11 million per metric ton—say $10 million in round numbers. There are ~80,000 metric tons of spent fuel in terms of initial heavy-metal content. But the spent fuel would have to be put into robust packages that would have to withstand reentry into the Earth's atmosphere in case of an accident, greatly increasing the mass of waste to be shot into space. Thus, the opportunity cost of delivering spent fuel into space would be well over a trillion dollars and perhaps trillions of dollars for waste already created. Future waste generation from existing reactors would increase the opportunity cost significantly.

The lost economic value of using space resources makes space disposal of high-level waste much more dubious than

107 Kramer and Mosher 2016.

in 1980, when the Final EIS was published. To reduce waste mass, reprocessing plants would have to be built. In that case, the problem of disposing of degraded reprocessed uranium, recovered plutonium, and transuranic waste arising from reprocessing would remain. These would require a deep geologic repository, similar to the one in New Mexico being used for military transuranic waste.

In addition, the risk of accidents from dispersing a large amount of radioactivity before the waste exits Earth's gravity (launch pad accidents, accidents during launch, accidents during transfer to the space launch vehicle, and accidents prior to escaping the Earth's gravitational pull) would remain. This poses ecological, legal, and political problems. Some idea of the problem may be gleaned from a single 1964 accident in which the plutonium-238 from one radioisotope thermoelectric generator (RTG) dispersed its cargo into the atmosphere.

In April 1964, a US Navy satellite did not get into orbit. The plutonium-238 in its RTG dispersed into the atmosphere. The total radioactivity so dispersed was 17,000 curies.[108] This is on the order of 50 times the radioactivity of the unfissioned plutonium-239 that was dispersed in the environment as a result of the first nuclear weapon test in New Mexico in July 1945 or the bomb of the same design dropped on Nagasaki, Japan, a few weeks later.

108 Sholtis et al. 2015.

There have been other accidents[109]:

- A reactor propulsion system was launched into space on April 3, 1965. A malfunction 43 days later “caused reactor permanent/irreversible shutdown in 3000+ year orbit.”
- An RTG was lost in 1968 during ascent of the launch vehicle. It was recovered from 100-meter depth intact and then used later.
- An RTG from the manned lunar mission launched on April 11, 1970 was lost on reentry over the South Pacific. The RTG reportedly survived and sank into the Tonga trench, where it presumably remains.[110]
- A Mars explorer launch failed in 1996; The RTG “fell near the coast of Chile/Bolivia. RTG designed to survive reentry; no radioactivity detected from reentry or impact.”

There have also been failures associated with Soviet RTGs.[111] We should note that, in some cases, the RTG was recovered. In other cases, it was lost, apparently irretrievably. In such cases, the fate of the plutonium-238 is unknown. Similar losses would be much more problematic in case of spent-fuel losses. Plutonium-238 has a half-life of 87.7 years. Thus, almost all of it (more than 99.95 percent) would decay into much less radioactive uranium-234 (half-life about 245,000 years) in

109 This list is from Sholtis et al. 2015, pdf pp. 6–7.

110 The author of the present report has not researched whether the RTG survived the descent into the Tonga trench intact, and, if so, whether it remains intact or its contents have been dispersed.

111 Sholtis et al. 2015, pdf p. 7.

1,000 years.[112] In the case of spent fuel, plutonium-239 has a half-life of over 24,000 years; iodine-129 clocks in at nearly 16 million years. Moreover, the amounts of radioactivity would be many orders of magnitude greater than with an RTG.

In sum, technology development, opportunity cost, and safety considerations indicate that space disposal is impractical and risky. In addition, there are complex international legal and political considerations and obstacles.

Ice-sheet disposal appears even more problematic in light of the accelerated melting of the ice sheets in Greenland and parts of the Antarctic. The heat from spent fuel or high-level waste disposal may well accelerate ice loss, aggravating what is already a severe problem.

iii. Non-reprocessing dependent disposal concepts

The remaining concepts examined in the 1980 Final EIS are:

- Sub-seabed disposal;
- Island disposal;
- Deep-borehole disposal; and
- Mined-geologic disposal.

These are all variants of the same basic disposal concept: deep geologic disposal of high-level waste, transuranic waste, or spent fuel. Reprocessing is not required. Indeed,

112 One curie of plutonium-238 decays into 0.00036 curies (0.36 millicuries) of uranium-234.

reprocessing increases the total volume of waste: the volume of high-level waste is smaller than that of spent fuel. However, reprocessing (and possible subsequent processing of plutonium into fuel) creates transuranic wastes as well. The total volume of transuranic waste plus spent fuel is considerably greater than the volume of spent fuel alone.[113] Thus, direct disposal of spent fuel minimizes the total volume of waste to be disposed of in a repository.

Sub-seabed disposal: The intervening decades since the Final EIS was published in 1980 have shown the critical role that deep-sea ecosystems play in the biosphere. These vast ecosystems are still not very well understood. Still, it is clear that they are being impacted by human activities, including discharge of pollutants and climate change. Characterization of benthic ecosystems and how they might be affected by the thermal and radiological pollution that would be introduced by disposal of spent-fuel and high-level reprocessing waste would be extremely difficult. Even land-based deep geologic systems have proved very difficult to characterize well enough to be confident of estimates of the radiological impacts on people far into the future. Ecosystem impacts have generally not had a comparable level of study under the rather simplistic assumption that protection of humans would result in sufficient protection of other species and their interactions. While this could at least be

113 Makhijani 2010, p. 19. This report cites a Department of Energy estimate that the volume of TRU waste, Greater than Class C waste (in principle also a repository-designated waste) and high-level waste would be about six times the volume of spent fuel to be disposed of.

studied in some depth for land-based repositories, understanding impacts on deep-ocean ecosystems and on the services they provide to other ecosystems and to human beings would likely be more complicated and costly.[114] In addition, there remain the legal and political issues associated with disposal in the global commons that does not belong to any country.

In addition to the legal obstacles discussed in the Final EIS, the United Nations Convention on the Law of the Sea would present a new one. It was opened for signature in 1982 and went into effect in 1994. The vast majority of countries are parties to the treaty. The United States is among the 15 non-signatories.[115]

Further, while sub-seabed disposal was a backup to geologic disposal in the 1981 Record of Decision, the focus has been on land-based geologic disposal, and since 1987, essentially entirely on the Yucca Mountain, Nevada, site (see next chapter). At present, sub-seabed disposal appears more complex, difficult, and challenging ecologically, technically, legally, and politically than it was in 1980.

Island disposal: Island disposal in a time of sea-level rise and large uncertainties about the speed and extent of such

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114 Sweetman et al. 2017.

115 The lists of parties, signatories without ratification, and non-parties can be found in a Wikipedia article at https://en.wikipedia.org/wiki/List_of_parties_to_the_United_Nations_Convention_on_the_Law_of_the_Sea. The text of the treaty can be found at https://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf

rise in the coming decades appears far more complex and riskier than in 1980.

Deep-borehole disposal and mined-geologic repositories: Of all the options that were considered in 1980 as potential approaches to disposal, these two remain. The focus of scientific and technical work up to the time of publication of the Final EIS in 1980 and the subsequent two decades or so was on geologic disposal in a mined repository. Considerable experience has been gained since that time as a result in considering and characterizing sites and in developing suitable engineered barriers and sealing systems. There is, of course, the extensive documentation and research relating to the Yucca Mountain, Nevada, site, which became essentially the sole focus of the program from 1987 onward (see Chapter V below). The 1983 report of the National Research Council considered a variety of specific sites as well as generic characteristics of other types. The Nuclear Waste Technical Review Board (NWTRB)[116] was created as an independent federal agency to do scientific and technical reviews of work relating to management and disposal of high-level waste, including spent fuel.

Considerable work has been done on vertical deep-borehole disposal in recent years, as exemplified by the 2009 and 2012 evaluations by Sandia National Laboratory and the 2016 report produced by the Nuclear Waste Technical Review Board.[117]

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116 The reports published by the NWTRB can be found on the Web at https://www.nwtrb.gov/our-work/reports

117 Sandia 2009, Sandia 2012, and NWTRB 2016.

Much of the recent technical interest in vertical deep-borehole disposal has been stimulated by developments in the petroleum industry, which has demonstrated the ability to drill vertical boreholes several kilometers deep. As a result, costs for drilling such boreholes have declined significantly:

> Petroleum drilling costs have decreased to the point where boreholes are now routinely drilled to multi-kilometer depths. Research boreholes in Russia and Germany have been drilled to 8–12 km.[118]

Similarly, horizontal-borehole drilling has been routinized by the oil and gas hydrofracturing industry. This has led to the concept of disposal in horizontal boreholes, around which a private company, Deep Isolation, Inc., has been formed. This is essentially a variation on the vertical-borehole disposal concept.

Since there have been new developments in the area of borehole disposal, we consider this approach in some more detail here. The vertical-borehole approach has been much more extensively studied, both in the United States and elsewhere.[119] We will also briefly describe the horizontal-borehole disposal approach, with the caveat that there is much less information given that it is a new concept. Further, the information has been developed mainly by the company itself.[120]

118 Sandia 2009, p. 11.

119 The presentations and transcript of an October 2015 NWTRB workshop on deep-borehole disposal can be found at https://www.nwtrb.gov/meetings/past-meetings/board-workshop-2015

120 For the horizontal borehole disposal concept, see the Deep Isolation website at https://www.deepisolation.com/ and Muller et al. 2019.

iv. Deep-vertical borehole disposal

The concept as developed by the Department of Energy is described, among other places, in the two Sandia National Laboratory reports noted above. The borehole would be on the order of 5,000 meters deep, which is five to ten times deeper than is typically considered for a mined repository. The disposal zone would start at a depth of 3,000 meters and extend 2,000 meters below that. The disposal concept is shown in Figure IV-1. The 2009 Sandia conceptual design envisages 950 boreholes for the disposal of 109,300 metric tons of spent fuel. Some borehole field designs may have a larger number of canisters per borehole. The boreholes would be about 0.2 km apart. The 2009 Sandia report estimates that the total land area of the borehole fields would be on the order of 30 square kilometers.[121]

121 Sandia 2009, pp. 9–11 and also p. 20. All spent fuel mass is in terms of initial heavy-metal content of the fuel. 109,300 metric tons was the mass of spent fuel projected to be created by US nuclear power plants at the time the Sandia report was prepared.

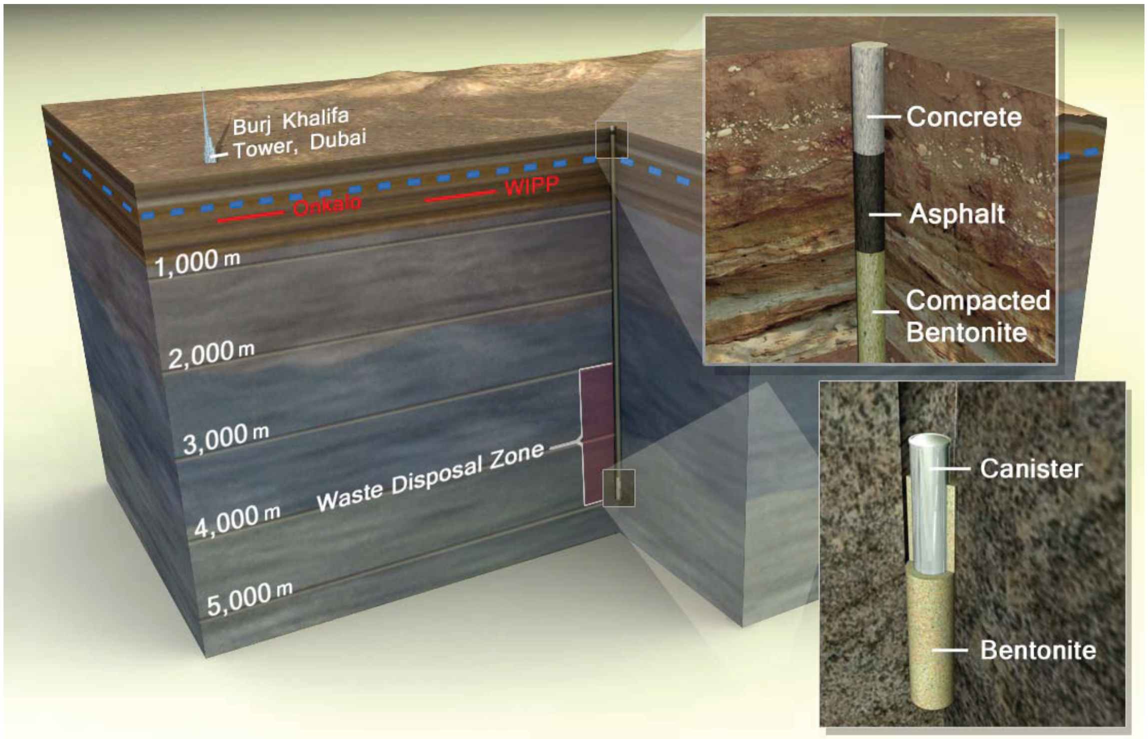

Figure IV-1: Deep Vertical-Borehole Disposal concept. The depths of the WIPP repository for nuclear weapons-derived transuranic waste in New Mexico and the Finnish repository, Onkalo, for spent fuel are indicated by the red lines near the top of the illustration.
Source: Sandia 2012, p. 8.

Borehole disposal is modular—only 100 to 200 canisters, possibly more, can be disposed of in one borehole; that means that there could be a large number of sites, each with a limited number of boreholes or, as with a mined repository, just one or a few sites, each with a large number of boreholes.

A generic safety case for deep-borehole disposal is described in a 2019 Sandia report. The report sets forth the merits and challenges of the approach:

> The robustness of the DBD [Deep Borehole Disposal] concept relies in large part on the subsurface hydrogeology and geochemistry, specifically: low permeability and porosity in the host rock; lack of significant

> vertical connectivity in the DRZ [Damaged Rock Zone]; chemically reducing, high salinity, and density-stratified groundwater at depth, and evidence of isolation of deep groundwater. The measurement and confirmation of these heterogeneous properties and conditions poses technical challenges.[122]

In sum, a significant amount of conceptual work to develop the deep-borehole disposal approach has been done since the Final EIS was completed in 1980. However, there is no actual site where a vertical borehole has been drilled to test its feasibility and develop the approach in the field. This is in contrast to mined geologic disposal, where a large amount of underground research has been carried out over several decades as a complement to theoretical, modeling, and laboratory studies in the United States and several other countries, including Sweden, Finland, France, Belgium, and Switzerland.

v. Horizontal-borehole disposal

The most recent approach to geologic isolation is disposal in a deep-horizontal borehole; it is being developed by a private company named Deep Isolation. Like the vertical-borehole disposal concept, this approach also derives from the oil and gas industry. Specifically, the hydraulic fracturing approach to oil and gas production involves drilling a horizontally deviated borehole at the depth that the oil and gas are expected to

122 Sandia 2019, p. 7.

be found. Of course, in the case of radioactive waste disposal, there would be no hydrofracturing.

The term “deep” in this approach means disposal at depths of more than 1,000 meters,[123] depending on the site and other factors. Many of the advantages and challenges facing horizontal-borehole disposal, such as characterizing sites sufficiently well to model performance with confidence, examining the role of a the damaged rock zone around the borehole, and developing sealing systems, are similar to those facing the deep-vertical borehole disposal. Each approach will face its own challenges as well.

Figure IV-2 shows the horizontal-borehole disposal concept. While the figure shows a borehole diameter of 14 inches for purposes of illustration, Deep Isolation has proposed boreholes of various sizes up to 50 centimeters (nearly 20 inches), depending on the type of waste being disposed of.[124]

123 Muller et al. 2019.
124 Muller et al. 2019, Abstract and Table 1, p. 3.

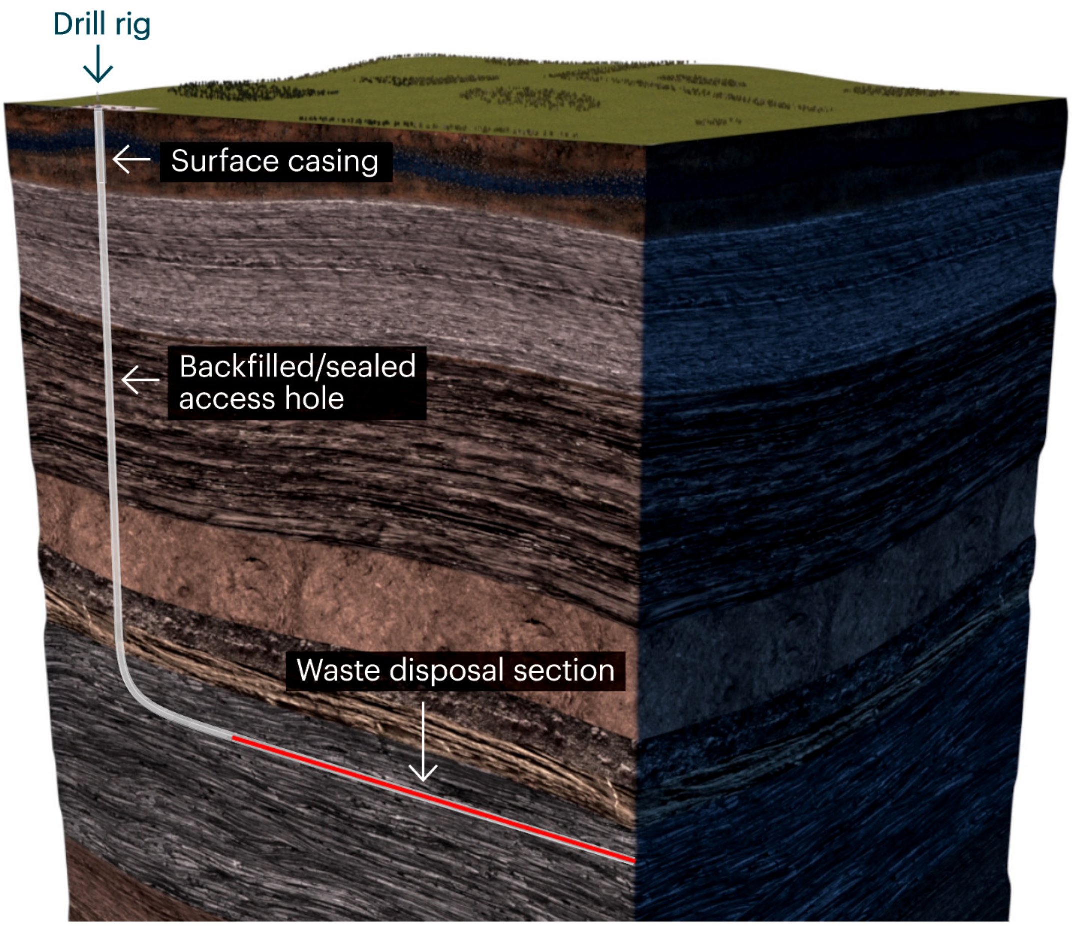

Figure IV-2: Deep Isolation's Horizontal-Borehole Disposal Concept.
Source: Deep Isolation website at https://www.deepisolation.com/technology/

We now turn to the 1982 Nuclear Waste Policy Act and its aftermath, followed by consideration of the Nuclear Regulatory Commission's Continued Storage Rule.

V.
The Nuclear Waste Policy Act

The Nuclear Waste Policy Act of 1982[125] (NWPA) codified in law the central part of the 1981 Record of Decision to dispose of spent-fuel and high-level waste in a deep geologic repository.

The NWPA as amended (in 1987) is still in effect. Site selection was suspended in 1987, and all efforts were focused on the Yucca Mountain, Nevada, site. Even so, the site selection and standard setting features of the NWPA as enacted in 1982 are worth noting:

- The DOE was required to promulgate guidelines for site selection within 180 days of the law going into effect. The guidelines were to take into account natural resources, national parks, water supplies, as well as geologic, hydrologic, and seismological factors. Highly populated areas were to be excluded; further, the repository could not be "adjacent to an area 1 mile by 1 mile having a population of not less than 1,000 individuals."[126]
- Within one year, the EPA was to promulgate "generally applicable standards for protection of the general environment from offsite releases from radioactive material in repositories standards."[127]
- The NRC was to promulgate licensing procedures and technical performance standards for repositories by January 1, 1984.[128] The NRC requirements were to be

125 NWPA 1982.
126 NWPA 1982, Sec. 112.(a).
127 NWPA 1982, Sec. 121.(a).
128 NWPA 1982, Sec. 121.(b).

compatible with the EPA standards for the protection of the environment.

- Nuclear utilities were to pay 0.1 cents per kilo-watt-hour to establish a Nuclear Waste Fund for disposal of spent fuel. The DOE was to set the procedures for collecting this fee.
- The DOE was authorized to take title to the waste[129] and was to begin disposal of high-level waste or spent fuel “not later than January 1, 1998.”[130]
- DOE was authorized to do research on alternative methods of disposal, but the funds for such activities would be separately appropriated by Congress. Thus, the Nuclear Waste Fund could not be used for such research.
- Within a year, the DOE was to identify three or more sites for characterization in at least two different geologic media, including at least one site that was not salt. The NWPA includes provisions for characterizing and comparing sites, including by placing limited amounts of high-level waste in them. The DOE was also authorized to select additional sites after the initial selection.

The DOE asked the National Academies to produce an assessment of geologic isolation, including consideration of a number of specific sites, like Hanford, Yucca Mountain, and

129 NWPA 1982, Sec. 214.(d).
130 NWPA 1982, Sec. 302(a)(5)(B).

salt sites, as well as generic sites in certain geologic settings. The National Academies formed a panel on geologic isolation and issued a comprehensive report in 1983.[131] The report included geologic assessments as well as consideration of radiological protection standards (EPA) and repository performance standards (NRC).

The EPA's approach to long-term health protection in its draft rule, published in late 1982, was to limit population doses. This was criticized by the 1983 National Academies panel, which preferred to limit the maximum individual radiation dose. The panel also criticized the EPA's limited time frame for compliance of 10,000 years.[132] The 1983 panel's recommendation was to limit the maximum dose to 10 millirem (lifetime average) per year, however far into the future it occurred. The draft EPA standard did not incorporate the drinking water standard (40 CFR 141.66) into its radiological protection framework.

Eventually (in the 1990s), the EPA issued a revised final standard (40 CFR 191) that was more along the lines suggested by the 1983 National Academies panel. It limited maximum individual dose in two ways. First, it limited total dose from all pathways (such as water, food, and external radiation) to a maximum of 15 millirem per year. Second, it included protection of groundwater that may be used for drinking by incorporating the drinking-water standard into the rule; this feature

131 National Research Council 1983.

132 National Research Council 1983, Section 8.5.

was not part of the recommendations of the 1983 National Academies panel. However, the EPA final rule still limited the compliance period to 10,000 years.

The NRC issued licensing and performance rules in 1982 (10 CFR 60), but the National Academies panel had significant criticisms of that regulation as well, including the fact that, in some cases, it was not compatible with the EPA draft rule.[133]

The NRC and EPA standards were eventually finalized and are still in effect for all repositories other than Yucca Mountain. As noted above, site selection and any activities relating to sites other than Yucca Mountain for spent-fuel and high-level waste were suspended in 1987. Thus, the issue of applying them to site investigations remains academic from a governmental point of view until the NWPA is again amended or a new nuclear waste law is passed.

The subsequent history of the proposed Yucca Mountain repository is rather tortured. The substance for purposes of this historical review is as follows:

- The DOE published a list of three sites it would characterize in detail in 1984: the Hanford Washington site, on the banks of the Columbia River where DOE nuclear facilities already existed; Yucca Mountain, Nevada; and a salt site in Deaf Smith County, Texas.

133 National Research Council 1983, Section 8.6. For instance, the report estimated that the NRC's waste package release limits of 1 part per 100,000 per year would result in releases that would vary from a small fraction of one percent of the allowable limits in EPA's rule to a few percent to hundreds of times the EPA limit, depending on the radionuclide. See Table 8-2, p. 236.

Opposition emerged at all three sites. All three states filed lawsuits challenging their inclusion in the list.[134]

- In January 1986, the DOE published a list of sites in the eastern and midwestern parts of the United States for possible investigation; the resistance to this list, including in New Hampshire, a politically sensitive state for presidential primaries, and in Maine was intense. The eastern site search was scrapped in mid-1986, sending implementation of the NWPA into a political crisis.[135]
- The NWPA was amended in 1987; site selection was essentially scrapped because Congress restricted characterization to a single site: Yucca Mountain, Nevada. Interestingly, this selection was made despite the preliminary calculations by the 1983 National Academies panel indicating that the Yucca Mountain site could have orders of magnitude of higher peak radiation doses than any reasonable health protection standard.[136]
- The late 1980s and early 1990s saw reservations emerge about the Yucca Mountain site's suitability for meeting the carbon-14 release limit in the EPA standard, 40 CFR 191. The EPA empaneled a special

134 Carter 1987, pp. 402-408.

135 Carter 1987, pp. 408-413.

136 National Research Council 1983. See Figure 9.6, p. 264. This estimate was for an unsaturated repository (i.e., above the water table). The high-dose estimate resulted largely from the fact that the water dilution volume in the single aquifer in the area is limited and the fact that there is no surface water in the area. Dose estimates made after 1987 were lower.

subcommittee of its Radiation Advisory Committee to review the matter. The subcommittee's report, published by the EPA's Science Advisory Board, concluded that travel times of carbon-14 from an unsaturated repository "are likely less than 10,000 years."[137] This put into question whether Yucca Mountain could meet the then-prevailing carbon-14 release limit of 100 curies per 1,000 metric tons of spent fuel. Instead of selecting a new site that might meet the EPA rule, Congress asked the National Academies to advise the EPA on setting a new standard specific to Yucca Mountain. The EPA subsequently issued a standard specific to Yucca Mountain;[138] the NRC also revised its performance rule and issued a rule specific to Yucca Mountain.[139]

- The licensing process for Yucca Mountain was terminated by the Obama administration in 2009.
- The Department of Energy has budgeted for a revival of the Yucca Mountain licensing process. There is some Congressional sentiment in favor of a revival as well as some to keep it terminated.

It is important to emphasize that, unless revised or scrapped by law, 10 CFR 60 and 40 CFR 191 would be applicable whenever Congress authorizes investigation of possible

137 EPA 1993, p. 19. The author of the present report was a member of the subcommittee that drafted the assessment, which was published by the EPA's Science Advisory Board.

138 40 CFR 197.

139 10 CFR 63.

sites other than Yucca Mountain. It is also important to note that 10 CFR 60 was criticized by the 1983 National Academies panel and that the EPA's revised 40 CFR 191 kept the compliance time limit of 10,000 years against the recommendation of that same panel that there be no time limit.[140]

Finally, it should be noted that the NWPA requires the NRC performance rules to be compatible with the EPA environmental protection standards. But the NRC's 10 CFR 60 was finalized before the final EPA rule (40 CFR 191). As a result, the compatibility of the NRC's performance standards with the EPA's final rule has not been legally or technically tested in any official way.

140 The EPA's Yucca Mountain rule 40 CFR 197 does not have the 10,000-year limit; rather, it relaxes the allowed radiation dose limit after 10,000 years.

VI. The NRC's Continued Storage Rule and geologic isolation

i. The Continued Storage Rule

The NRC issued a so-called "waste confidence" rule in 1979 affirming that it had "reasonable assurance" that it could dispose of high-level waste and spent fuel in a deep geologic repository and that such waste could be safely stored in the interim.[141] This rule was issued in view of the need, under the National Environmental Policy Act, of the NRC to evaluate the environmental impact of its nuclear power reactor licensing decisions.

The estimated dates for disposal of spent fuel in a repository kept slipping in the two decades that followed the 1987 amendments to the NWPA. As a corollary outcome, the NRC's assurances that interim storage was safe stretched for longer and longer periods. A lawsuit challenging the repeatedly revised waste confidence rule in federal court resulted in an order asking the NRC to assess the impact should a repository never be developed in the United States. In response, the NRC prepared a Generic Environmental Impact Statement and issued a final rule, the Continued Storage of Spent Nuclear Fuel rule (10 CFR 51). That rule asserts that continued storage of spent fuel and high-level waste, including onsite, could be safely done for an indefinitely long period.[142] The rule opines that a repository will likely become available; but, in case it does not, the rule assumes that the U.S. government will continue to ensure that the waste is safely stored

141 This section is based on Makhijani 2009 unless otherwise specified.
142 10 CFR 51.

for thousands of years and that the funds to do so will be routinely available. Also implicit in the rule is the idea that regulatory oversight would continue and ensure safety for an indefinitely long time.

The assumption of indefinitely long institutional control in the rule is at variance with some of the NRC's own standards as well other guidance, including from the National Academies. There is ample literature advising that an assumption of institutional control for an indefinitely long period should not be made when assessing safety and impact far into the future.[143] The rule was, nonetheless, finalized with the assumption that institutional control could endure indefinitely, for thousands or even tens of thousands of years.

ii. Comments on continued storage and geologic isolation

In effect, in the Continued Storage Rule, the NRC decided that the No-Action Alternative in the 1980 Final EIS was an acceptable alternative because it was safe enough. It is therefore worthwhile to consider what that 1980 Final EIS concluded about indefinite storage without disposal:

> The no-action alternative would leave spent fuel or reprocessing wastes at the sites generating the waste or possibly at other surface or near-surface storage facilities for an indefinite time. In this alternative, existing

143 See Makhijani 2013 for comments on the NRC's Generic Environmental Impact Statement and references to other parties' statements and conclusions on institutional control.

> storage is known to be temporary and no consideration has been given to the need for additional temporary storage when facilities in use have exceeded their design lifetime. There seems to be no question but that at some point in time wastes will require disposal and that considerable time and effort will be required to settle upon an adequate means of disposal. It seems clear that development of acceptable means of disposal of wastes is sufficiently complex and of sufficiently broad national importance that coordination of research and development, construction, operation, and regulation at the Federal level is required and that the no-action alternative is unacceptable. Indeed, adoption of a no-action alternative by the Department of Energy could be construed as not permissible under the responsibility mandated to the Department by law. Neither would a no-action alternative be in accord with the President's message of February 12, 1980, when he stated that "... resolving...civilian waste management problems shall not be deferred to future generations."[144]

There are more recent official expressions of the same conclusion as well as a more recent official assessment of the damage from the No-Action Alternative.[145] Specifically, essentially the same No-Action Alternative was consid-

144 DOE 1980, p. 1.21; emphasis added.

145 The rest of this section is based on Makhijani 2013, unless otherwise specified. The citations to the NRC and DOE materials are provided there. Citations are only provided for the parts quoted here.

ered in the context of the Final EIS for the Yucca Mountain repository. One principal issue is loss of institutional control and the damage that could occur in that context from continued storage of spent fuel. The Final Yucca Mountain EIS concluded that the No-Action Alternative would be "catastrophic," arising largely from the "unchecked deterioration and dissolution of the materials" in the spent fuel."[146]

The Yucca Mountain EIS omitted quantification of a number of serious impacts in the No-Action Alternative because it was only necessary to show that even seriously underestimated impacts would be worse than the recommended alternative of geologic disposal. In other words, if only a partial sum of the impacts of indefinitely long storage without disposal was clearly worse than the total impacts of geologic disposal, then the No-Action Alternative should be rejected in favor of geologic disposal. Among the impacts that were not quantified in the No-Action Alternative was loss of large amounts of radionuclides into "more than 20 major waterways," including the Mississippi River system, the Great Lakes, and the Columbia River, affecting 30.5 million people. "The shorelines of these waterways would be contaminated with long-lived radioactive materials (plutonium, uranium, americium, etc.) that would result in exposures to individuals who came into contact with the sediments, potentially increasing the number of latent cancer fatalities."[147]

146 As quoted in Makhijani 2013.

147 Yucca Mountain Final EIS as quoted in Makhijani 2013, p. 37.

Yet the large number of latent cancer fatalities, though devastating, would likely pale in comparison to some other catastrophic impacts, which could include losses of homes and businesses of tens of millions of people and economic devastation or collapse in large parts of the United States.

The events of September 11, 2001 (or 9/11 in common parlance) brought the possible impacts of malevolent acts far more to the fore than they had been previously. Each power plant site with spent fuel storage has a vast inventory of radionuclides that, if dispersed, could render large areas uninhabitable for centuries or longer. Cesium-137, being volatile in the context of fires and explosions, has been a problem radionuclide in this regard, as the Chernobyl and Fukushima accidents have shown. The latter accident has also shown that nonvolatile strontium-90 also poses severe risks if dispersed by contact with water. Curie-for-curie, strontium-90 is far more dangerous in ecosystems since it bio-concentrates in bone and affects the bone marrow, where red and white blood cells are made.

The safety and security of spent-fuel storage was considered, at the request of the U.S. Congress, by a panel of the National Research Council of the National Academies. The panel was constituted in the wake of 9/11 and widespread concerns about the vulnerability of nuclear facilities, including nuclear power plants and spent-fuel pools. The panel published its work in 2006, when on-site storage for an indefinite period of time was not considered a reasonable option—that is, before the publication of the Continued Storage rule by the Nuclear Regulatory Commission. Its findings regarding attacks on spent- fuel pools, necessary to store newly discharged spent fuel for several years, were as follows:

> Terrorists view nuclear power plant facilities as desirable targets because of the large inventories of radionuclides they contain. The committee believes that knowledgeable terrorists might choose to attack spent fuel pools because (1) at U.S. commercial power plants, these pools are less well protected structurally than reactor cores; and (2) they typically contain inventories of medium- and long-lived radionuclides that are several times greater than those contained in individual reactor cores.[148]

A severe attack on a spent-fuel pool could cause a draining of the spent-fuel pool and, potentially, a zirconium-cladding fire. The panel found that such fires "would create thermal plumes that could potentially transport radioactive aerosols hundreds of miles downwind under appropriate atmospheric conditions."[149] Many U.S. nuclear power plants are located at distances less than 50 miles from major metropolitan areas, including New York City, Philadelphia, Miami, and Los Angeles, where impacts could be very severe, especially in case of adverse weather conditions. These risks will exist as long as there are spent-fuel pools, which, in turn, are needed as long as nuclear power plants are oper-

148 National Research Council 2006, p 36.
149 National Research Council 2006, p. 50.

ating (and for a few years thereafter). The National Research Council panel concluded there are also risks of malevolent acts relating to dry-cask storage but that they would have far smaller consequences.[150]

The risks from dispersal of radionuclides decrease with time due to the decay of the two most dangerous long-lived fission products in spent fuel—strontium-90 and cesium-137, which have half-lives of about 28 years and 30 years, respectively; therefore, these risks would greatly diminish over two or three hundred years. In stark contrast, security risks increase greatly with time.

Spent fuel contains a large amount of plutonium, which, if separated, could be used to make nuclear weapons. Depending on what one assumes about the level of sophistication of those who might divert the material, each metric ton of spent fuel contains one to two nuclear bombs' worth of plutonium.[151] Strong external gamma radiation provides the main physical barrier to theft of spent fuel and to the subsequent extraction of plutonium from it. Unfortunately, only one fairly long-lived radionuclide—cesium-137—presents such a radiation barrier. But since it has a half-life of only about 30 years, the radiation barrier is sufficiently lowered after roughly 200 to 300 years to significantly affect proliferation risk. After such a period, the main difficulty for

150 National Research Council 2006, Chapter 4.

151 IPFM 2015 assumes 5 kilograms per bomb for reactor grade plutonium—see p. 24. There are typically nine or ten kilograms of plutonium in a metric ton of light-water-reactor spent fuel. This is by far the most common kind of nuclear power reactor in the world.

diversion and proliferation would be the physical mass of the spent fuel and the container in which it is stored.

Once diverted, the plutonium in spent fuel could be extracted by well-known techniques with much less danger from the gamma radiation emanating from cesium-137. In sum, proliferation and security threats from continued storage rise dramatically at times that are only about one percent of the half-life of plutonium-239. Loss of institutional control over hundreds of years is a distinct possibility, increasing the potential for diversion. Historically speaking, the United States has been a relatively stable country. Yet it has seen, among other major events, a revolution, a Civil War, a huge aerial attack on a port (Pearl Harbor, 1941), and a terrorist attack on two major cities causing thousands of deaths (9/11)—all in less than 250 years. A major diversion of spent fuel and subsequent extraction of plutonium from it could, of course, be utterly catastrophic.

The central conclusion from these facts is that geologic disposal of spent fuel without reprocessing is the least risky long-term management approach by far, even though it comes with its own uncertainties and risks.

VII. Conclusions

The policy sanctioned by the NRC—that continued storage of spent fuel for indefinite periods of time is safe—relies on the assumptions that (1) institutions like those we have today will continue for thousands or even tens of thousands of years and (2) Congress will regularly appropriate money for an indefinite number of years to ensure safe storage, including from malevolent acts and a deteriorating climate. The only saving grace in the rule is that the NRC believes that geologic disposal will be realized within 60 years after a reactor's operating license expires or, at most, an additional 100 years after that.

For the spent fuel already in existence, geologic disposal is the only credible, if admittedly imperfect, way of protecting the public and ecosystems from what could be catastrophic outcomes arising from indefinite storage. We make a brief comparison of the three geologic disposal options that could be deployed in the United States.

Given the long periods of time involved, the problem of demonstrating with confidence that future generations will be protected in conformity with standards is very difficult. Routine loss of containment and hydrological dispersion over long periods, dispersion of radionuclides due to severe seismic events, and human intrusion, inadvertent or not, pose considerable hurdles to confident demonstration of safety over, literally, eons. Geologic disposal is by far the least problematic of the approaches to manage the problem of spent fuel and high-level waste. Within that approach, the ability to estimate a variety of consequences over a long period of time with some confidence is a key attribute in comparing approaches, engineered barriers, sealing systems, and sites. In other words, it is not only the technical merits of the site and the isolation system associated with it that matter; it is also the ability to be confident that the estimated long-term performance is robust.

The table below compares the three options and some of the questions that each would have to address for 100,000 metric tons of spent fuel. This table represents initial judgments of this author about deep-borehole disposal and horizontal-borehole disposal.

	Mined repository (Note 1)	**Very deep boreholes (Note 2)**	**Deep horizontal boreholes (Note 3)**
Number required	1 or 2?	500 to 1,000 boreholes. Number of sites would depend on the number of boreholes per site. Total area required would be in the tens of square kilometers.	Several hundred to 1,000 boreholes, depending on amount of spent fuel per borehole (100 to 300 metric tons). Number of sites would depend on the number of boreholes per site.
Rock type	Various	"crystalline basement rock—typically granites" (Note 4)	Sedimentary, igneous, or metamorphic.
Depth of disposal below surface	A few hundred meters, generally less than 1,000 meters.	Disposal zone in the 3,000- to 5,000-meter depth range.	>1,000 meters

	Mined repository (Note 1)	**Very deep boreholes (Note 2)**	**Deep horizontal boreholes (Note 3)**
Characterization issues	A few sites would be characterized.	The zone to be characterized for each borehole is far more limited, but hundreds would need to be characterized. The number of sites would depend on number of boreholes per site.	The zone to be characterized for each borehole is far more limited, but hundreds of boreholes would need to be characterized. The number of sites would depend on number of boreholes per site.
Excavation damaged zone (or damaged rock zone)	Around the entire mine, extent depending on rock type and mining method. Anisotropic stresses may prevent safe construction of mined repository (Note 5).	An annular volume around each borehole. Minimizing damaged rock zone is important because this could be the pathway for radionuclides to the human environment. Excavation damage would depend on in situ stress regimes, for instance where they are anisotropic.	An annular volume around each borehole. Minimizing damaged rock zone is important because this could be the pathway for radionuclides to the human environment. Excavation damage would depend on in situ stress regimes, for instance where they are anisotropic.
Sealing requirements and performance assessment	Complex and extensive. Sealing demonstration projects have been done in several countries. While difficult, a mine provides physical access to the seals.	Sealing of vertical boreholes has been done but not in the context of large-diameter very deep boreholes for spent-fuel disposal. Thorough sealing is critical for waste isolation. Lack of access to the seals is a complicating factor.	Sealing of large-diameter very deep boreholes for spent-fuel disposal may be difficult and complex. Thorough sealing is critical for waste isolation. Lack of direct access to the seals is a complicating factor.

	Mined repository (Note 1)	Very deep boreholes (Note 2)	Deep horizontal boreholes (Note 3)
Accessibility to human environment	Site dependent; relatively small depth implies more accessibility relative to the other two, all other things being equal.	Site dependent; greater depth than a mined repository (and horizontal boreholes as presently proposed) implies lower accessibility, all other things being equal.	Site dependent; greater depth than a mined repository implies lower accessibility, all other things being equal.
Faults, fractures, and "flooding" impacts (Note 6)	Site dependent; performance assessment is complex.	Site dependent; large number of boreholes would need to be evaluated. Performance assessment for long time periods will likely remain a challenge.	Site dependent; large number of boreholes would need to be evaluated. Performance assessment for long time periods will likely remain a challenge.
25-meter diameter meteorite impact	Potential severe dispersion of radioactivity for repository 600 m or less deep.	Greater depth may mean lower probability of radioactivity dispersal relative to a mined repository depending on hydrogeological driving forces. Amount of waste affected would depend on areal configuration of boreholes.	Greater depth may mean lower probability of radioactivity dispersal relative to a mined repository, depending on hydrogeological driving forces. Amount of waste affected would depend on areal configuration of boreholes.

	Mined repository (Note 1)	Very deep boreholes (Note 2)	Deep horizontal boreholes (Note 3)
Inadvertent criticality	Risk depends on considerations such as spent-fuel disposal configuration, engineered barrier composition, and site-specific issues such as potential ingress of water.	Risk would likely be reduced relative to mined repository.	Risk would likely be reduced relative to mined repository and possibly relative to vertical boreholes, given appropriate design.
Human intrusion	Difficult. Large amount of fissile material in one location.	Difficult. Smaller amount of fissile material in one location if there are several sites.	Possibly more difficult than vertical boreholes. Potentially small areal density of fissile material and smaller cross section to vertical penetration
State of development	Many countries have studied it; many experimental and study locations; two repositories—in Sweden and Finland—are in an advanced stage of development. The U.S. has faced a large set of problems in siting and licensing a mined repository.	Academic and official studies have been done; extent of evaluation is far less than with mined repositories.	A relatively new concept; it has been examined mainly by the company. A demonstration of lowering an empty canister into a borehole and retrieving it has been completed.

Notes:

1. For mined repository impacts see DOE 1980, Chapter 5; and National Research Council 1983, Chapter 9.
2. Assessments of deep boreholes can be found in Section 6.1.1 of DOE 1980, Sandia 2009, and Sandia 2012.
3. Information about the approach of Deep Isolation, Inc., can be found on the company's website: https://www.deepisolation.com/. For this table, that information was supplemented in a personal email communication from Rich Muller to Arjun Makhijani on June 23, 2019, and from Muller et al. 2019.
4. Sandia 2009 pdf p. 9. The term "crystalline" is used here because that is the usual way in which preferred deep-borehole disposal geology is described in the official literature, such as the Sandia reports. The terms "metamorphic" or "igneous" rocks would be preferable.
5. This was an issue at the Hanford site in Washington State. See the supplement by Donald E. White in Makhijani and Tucker 1985. The paper in the supplement was originally prepared for the National Research Council's 1983 panel on geologic isolation (National Research Council 1983) but not published by it. Dr. White was a member of the panel that authored the 1983 report. Core discing at Hanford is discussed in that report, which includes photographic evidence of it—see Figure 6-7, p. 117 of National Research Council 1983.
6. The term "flooding" in a mined repository context was used in the 1980 Final EIS DOE 1980, Section 5.5.2.

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