Disposal of Spent Nuclear Fuel and High-level Radioactive Waste

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Executive Summary

The characteristics of spent nuclear fuel and high-level waste are described, and options for permanent disposal that have been considered are described. These include:

- disposal in a mined geological formation,
- disposal in a multinational repository, perhaps on an unoccupied island,
- by *in situ* melting, perhaps in underground nuclear test cavities,
- sub-seabed disposal,
- disposal in deep boreholes,
- disposal by melting through ice sheets or permafrost,
- disposal by sending the wastes into space, and
- reprocessing, separation, and transmutation of wastes.

Introduction

This paper was written as a follow-up to a presentation made to the Disposal Subcommittee of the Blue Ribbon Commission on America's Nuclear Future on July 7, 2010. Speakers at that meeting[2] were asked to address three questions:

- Is a disposal facility (or facilities) needed under all foreseeable scenarios?
- If so, what are our alternative approaches for disposal?
- What should the process to develop a US disposal system look like?

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[1] **Disclaimer:** This material was prepared at the request of the Blue Ribbon Commission on America's Nuclear Future ("the BRC"). The contents herein do not necessarily reflect the views or position of the BRC, its Commissioners, staff, consultants, or agents. This report reflects my views and I am solely responsible for the text and its conclusions as well as for the accuracy of any data used. The BRC makes no warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information disclosed, or represents that the use of any information would not infringe privately owned rights. Any reference to a specific commercial product, process or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement, recommendation, or preference by the BRC.

[2] http://brc.gov/Disposal_SC/Disposal_Subcommittee_July_7_Meeting_info.html

Following the meeting, I was invited to write this paper[3] that describes the options that have been considered for spent nuclear fuel and high-level waste.

A few definitions:[4]

- Spent nuclear fuel is fuel that has been irradiated in a reactor; such irradiation creates fission products such as cesium and strontium and actinides such as plutonium, americium, and neptunium; and
- High-level radioactive waste is created by the reprocessing of spent fuel. Fission products and actinides are the main wastes when uranium and plutonium are recovered during reprocessing.

Retrievability

The extent to which radioactive wastes are retrievable once they have been disposed of is an important characteristic of each disposal method. Whether retrievability is a good or bad feature depends on why wastes would be retrieved. Retrieval could be beneficial if:

- Our understanding of repository performance changes and weaknesses are identified. For example, monitoring may indicate that the waste disposal system is not working as anticipated, or innovations in repository performance assessments reveal previously unrecognized weaknesses;
- Advances occur that would permit disposal via improved processes for waste treatment, packaging, or repository design; or if
- Reprocessing becomes desirable, for example to reclaim the energy available from spent nuclear fuel.

Disposal is as much a policy decision as a technical decision, so one may also want to preserve retrievability for policy reasons The 1982 Nuclear Waste Policy Act[4] included the following requirement: "The Secretary shall specify the appropriate period of retrievability with respect to any repository at the time of design of such repository, and such aspect of such repository shall be subject to approval or disapproval by the Commission as part of the construction authorization process …"

Conversely, the goal may be to reduce the possibility that any constituents of spent fuel or high-level wastes can be retrieved (e.g., to meet nonproliferation concerns).

[3] I thank Tom Cotton, Allen Croff, Kevin Crowley and Glenn Paulson for comments on an earlier draft.

[4] High-level radioactive waste and spent nuclear fuel are defined in the 1982 Nuclear Waste Policy Act, available at http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr0980/v2/sr0980v2.pdf#pagemode=bookmarks&page=141. The definitions above are consistent with those in the NWPA, but not identical.

The waste disposal concepts discussed in the remainder of this paper vary in the extent to which they allow waste retrieval and the likely difficulty associated with retrieval. If the ability to retrieve spent fuel or high-level waste is considered highly important, a monitored retrievable storage facility or mined repository that has not been closed (such as the Yucca Mountain design) would facilitate retrieval. Retrieval would be possible but more difficult where a site has been sealed or a deep borehole.

Forms of waste to be disposed

- Spent fuel, as part of a once-through fuel cycle, is the current U.S. waste form from commercial nuclear power. The "burnup"[5] of the fuel and the time since its removal affect the heat output of the spent fuel, which in turn affects how a repository may perform;
- Almost all commercial spent fuel from U.S. nuclear power production remains stored as spent fuel; it has not been reprocessed. A small amount of commercial spent fuel was processed at the West Valley, NY site about 40 years ago. High-level wastes from this operation have been vitrified and, along with other wastes, remain at the West Valley site.
- Spent fuel from U.S. naval reactors was reprocessed until 1992. Since that time, it has been stored without being reprocessed.
- Much of DOE's high-level wastes are the byproduct of plutonium production for the nuclear weapons program. After irradiation in a production reactor, the fuel rods were chemically digested to separate and recover plutonium and uranium; the residual fission products and actinides were stored in large underground tanks. DOE also has a variety of spent fuel from production reactors, and research reactor spent fuel stored at the Savannah River Site and at the Idaho National Engineering and Environmental Laboratory. DOE also has other wastes such as strontium and cesium capsules stored at Hanford.
- Programs are underway at the Savannah River Site and at Hanford to convert reprocessing wastes into a stable solid form by vitrification into glass logs. Some DOE high-level wastes at the Idaho site have been solidified by calcination (a thermal process in which liquids are driven off and wastes are converted to a granular form). The plan is to convert these wastes to a solid form prior to disposal. Several other materials for immobilizing radioactive waste (e.g., crystalline ceramic waste forms such as synrock) have been experimentally investigated but have not offered sufficient advantages to warrant their use.[6]

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[5] Burnup is a measure of how much energy has been extracted from the fuel, and corresponds to the number of atoms that have fissioned.

[6] A study of Waste Form Technology and Performance is underway at the National Research Council and the report should be available in late summer or early fall 2010. Details are available at

Relevant characteristics of the waste

- For both spent fuel and high-level wastes that are a few years old, the radioactivity and heat produced by the waste tends to be dominated by cesium-137 and strontium-90 and their immediate decay products. These cesium and strontium isotopes both have half-lives of about 30 years. It takes on the order of hundreds of years for the heat-generating fission products to decay. In 700 years, the activity of these short-lived isotopes is less than one ten-millionth of the initial activity.[7]
- After about 70 years, the fission products have decayed to the point that their heat output is about equal to that from actinides. At longer times, the activity is dominated by actinides such as americium-241 (half-life of 432 years) which decays to neptunium-237 (2.1 million year half-life) and by several isotopes of plutonium. Figure 1[8] shows the decay heat versus time for spent fuel.
- There are several long-lived fission products, notably technetium-99 and iodine-129, that are also important components of spent fuel thousands of years into the future. In addition to their long half-lives, technetium-99 and iodine-129 tend to be comparatively mobile when transported in groundwater; that is, they do not tend to sorb to the rock but rather move with the water.[9]
- While reprocessing spent fuel can potentially provide for significant reductions in waste volume for disposal, the reprocessing waste stream contains the fission products so the heat generation rate initially is almost as high as that of the spent fuel. At later times, the heat output of high-level waste with plutonium removed would be significantly lower than that of the spent fuel from which the waste was derived.

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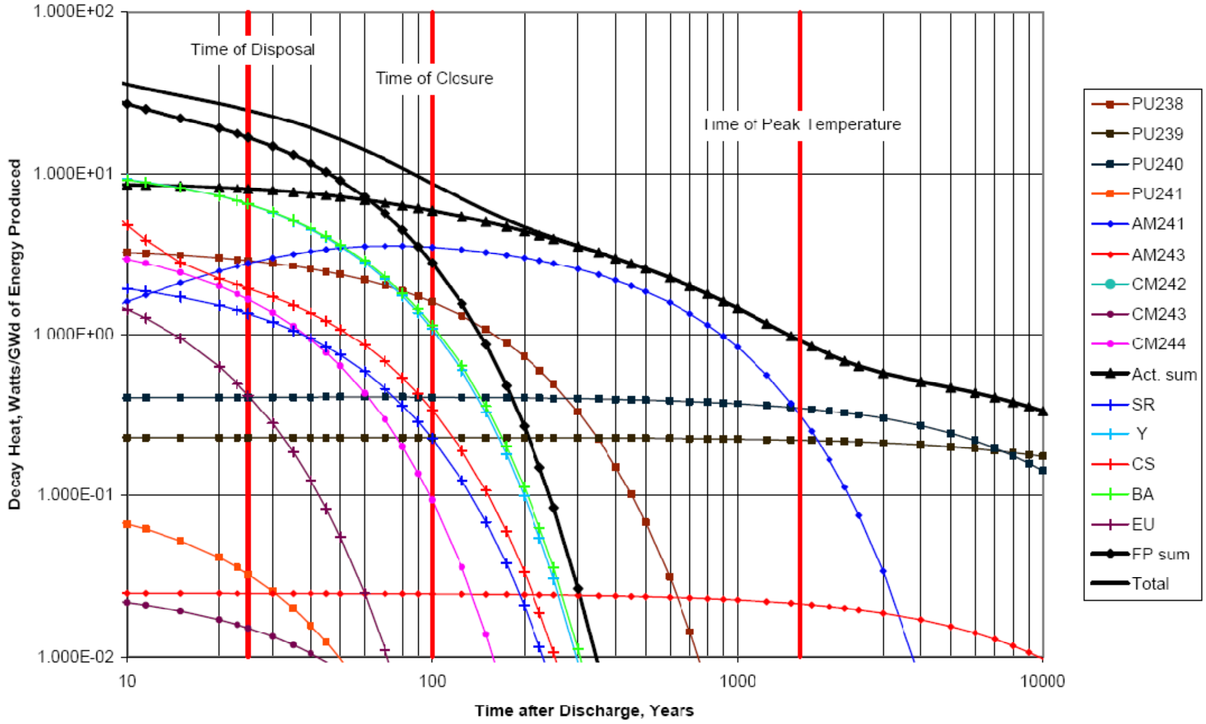
http://dels.nas.edu/Study-In-Progress/Waste-Form-Technology-Performance/NRSB-O-08-02-A. An interim report is available at http://www.nap.edu/catalog.php?record_id=12937.

[7] Arthur Kubo and David Rose, "Disposal of Nuclear Wastes," *Science*, 21 Dec 1973, V. 182, No. 4118.

[8] Roald A. Wigeland, Criteria Derived for Geologic Disposal Concepts, presented at the OECD/NEA 9th Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation, September 28, 2006.

[9] *Nuclear Wastes: Technologies for Separations and Transmutation*, National Research Council, 1996. Appendix G notes that under reducing conditions with ferrous iron available, technetium-99 will form low-solubility compounds.

Figure 1



Disposal approaches

Many disposal options have been considered. All of those discussed below were addressed in some form in the Department of Energy's Final Environmental Impact Statement on the Management of Commercially Generated Radioactive Waste,[10] issued in 1980 before DOE selected disposal in mined geologic repositories as the preferred option.

- Disposal in a mined geological formation (e.g., salt, granite, tuff, basalt, clay.)

Disposal in a mined geological formation, typically a few hundred meters below the surface, has been the front-running disposal technology in the U.S. for over fifty years.[11]

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[10] *Final Environmental Impact Statement, Management of Commercially Generated Radioactive Waste, Volume 1*. DOE/EIS-0046F-V.1. Washington, DC: U.S. Department of Energy (October 1980). The EIS considered mined geologic disposal, very deep hole waste disposal, rock melt waste disposal, island-based geologic disposal, sub-seabed disposal, ice sheet disposal, well injection disposal, transmutation, and space disposal.

[11] In 1957, the NAS published *The Disposal of Radioactive Waste on Land.* This report suggested geological disposal and commented "Disposal in cavities mined in salt beds and salt domes is suggested as the possibility promising the most immediate solution to the problem." However, the report also observes that "The research to ascertain the feasibility of disposal has for the most part not yet been done." It also noted that "Disposal could be greatly simplified if waste could be gotten into solid form of relatively insoluble character."

Geologic disposal is also the approach being taken in other countries with spent fuel or high-level waste disposal programs. An overview of international high-level waste programs is available in a report from the Nuclear Waste Technical Review Board (NWTRB).[12] A table from that report (see Table 1 below) describes the geologic settings of the underground research laboratories associated with the waste program. As indicated in the table, these thirteen underground laboratories involve a number of different rock types.

The Waste Isolation Pilot Plant (WIPP) near Carlsbad New Mexico is the only geologic repository in the U.S.; the transuranic wastes[13] that go to WIPP are disposed of in rooms mined out of a salt bed. Regarding U.S. efforts to develop a repository for spent fuel and high-level waste, in the mid 1980's, before the 1987 Waste Act Amendments were passed, DOE was required to evaluate initially nine and then five candidate sites. Of the nine candidate sites, three were in salt domes (Vacherie dome, LA, Richton Dome, MS, and Cypress Creek dome, MS), four were in bedded salt (Deaf Smith, TX, Swisher County, TX, Davis Canyon, UT and Lavender Canyon, UT), one was in basalt (Hanford, WA) and one was in volcanic tuff (Yucca Mountain, NV). The plan at that time was to identify five of these nine sites for further evaluation,[14] and then select three for detailed characterization.[15] The plan was to construct the first U.S. repository for spent fuel and high-level waste at one of these three sites, and to plan for a second repository, probably constructed in granite, somewhere in the eastern U.S.

Of the thirteen underground laboratories listed in Table 1, only Yucca Mountain is in the unsaturated zone, that is, above the water table. From the perspective of the chemical aspects of long term waste isolation, a saturated site with reducing chemistry conditions is likely to be advantageous over a site with oxidizing conditions because many of the long-lived radionuclides have very low solubility and mobility in reducing conditions.

In addition, if intact spent fuel is to be disposed of, the chemical form of uranium in commercial spent fuel, UO_2, is much more stable in reducing environments than in oxidizing environments. For direct disposal of spent fuel, the stability of UO_2 is important because as long as the fuel elements remain as intact UO_2 pellets, the fuel acts as an important barrier to limit the release rate of fission products and actinides in the fuel.

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[12] *Survey of National Programs for Managing High-Level Radioactive Waste and Spent Nuclear Fuel,* A Report to Congress and the Secretary of Energy, October 2009, available from the Nuclear Waste Technical Review Board at http://www.nwtrb.gov/reports/reports.html.

[13] These wastes include material contaminated with plutonium and do not include spent fuel or high-level waste.

[14] The five sites selected were Deaf Smith, TX, Davis Canyon, UT, Richton Dome, MS, Hanford, WA, and Yucca Mountain, NV.

[15] The three selected were Deaf Smith, TX, Hanford, WA, and Yucca Mountain, NV.

Table 1 (Table 5 of the report referenced in footnote 3)

GEOLOGICAL INVESTIGATIONS		
COUNTRY	**GEOLOGIC ENVIRONMENTS CONSIDERED OR INVESTIGATED**	**INDIGENOUS UNDERGROUND RESEARCH LABORATORY ESTABLISHED**
United States	Salt, basalt, granite, tuff, clay, and shale	The Exploratory Studies Facility at Yucca Mountain served the function of an underground research laboratory (tuff).
Belgium	Clay and shale	Mol (clay)
Canada	Granite and sedimentary rock	Pinawa (granite)*
China	Granite	None
Finland	Granite, gneiss, grandiorite, and migmatite	Construction of ONKALO underground rock characterization facility in Eurajoki began in 2004 and is continuing (granite).
France	Argillite and granite	Bure (argillite)
Germany	Salt	Gorleben (salt)
Japan	Granite and sedimentary rock	Tono (granite) Mizunami (granite) Horonobe (sedimentary rock)
Republic of Korea	Granite	Korea Underground Research Tunnel (granite)**
Spain	Granite, clay, and salt	None
Sweden	Granite	Äspö (granite)
Switzerland	Clay and granite	Mont Terri (clay) and Grimsel (granite)
United Kingdom	No decision made.	None

*In the process of being decommissioned.

**At shallow depth only.

In an oxidizing environment (and assuming that barriers that protect the fuel have been breached), UO_2 will oxidize to U_3O_8. When UO_2 converts to U_3O_8, the volume increases and the fuel pellets fracture so that it does not retain fission products or actinides nearly as well as UO_2 does.

However, the trade-off between a saturated site and an unsaturated one is not as straightforward as simply looking at the effect of the local environment on UO_2. Technetium-99, iodine-129, and neptunium-237 can be highly mobile and soluble in either environment. The approach taken to restrict their release and migration in the Yucca Mountain design depended mainly on engineered barriers – a highly corrosion-resistant waste canister and a titanium drip shield to divert infiltrating water around the waste. Similar engineering features could be effective at a saturated site. For example, both the Finnish and Swedish repository designs include copper waste canisters surrounded by low-permeability clay. For the reducing chemical conditions of these repositories, the copper is predicted to be extremely durable – lasting for hundreds of thousands of years or longer.

The choice of an unsaturated versus saturated site also involves operational considerations. The plan at Yucca Mountain was to emplace the waste but keep the repository open and ventilated for an extended time, perhaps of the order of 100 years or longer. By selecting this operating mode, much of the decay heat in the waste would go into the atmosphere rather than into the surrounding rock, and the engineered barriers would experience lower operating temperatures than if the repository were closed soon after waste emplacement. Such a design also permits a straightforward method (relative to saturated sites) for waste retrieval if future conditions made it advantageous to do so.

- Disposal in a multinational repository, including consideration of the use of unoccupied islands

Consideration has been given to constructing an multinational repository or monitored retrievable storage facility,[16] including possible siting on an unoccupied island. There are many attractions to such a plan. First, and a major motivating factor in the support for this approach by the IAEA, is that many smaller countries with modest nuclear power programs lack suitable sites for a repository, and the cost of building a repository to accept wastes from just a few plants is likely to be very unattractive relative to the

[16] International Atomic Energy Agency, *Technical, Institutional and Economic Factors Important for Developing a Multinational Radioactive Waste Repository,* IAEA-TECDOC-1021, Vienna (1998) and *Developing multinational radioactive waste repositories: Infrastructural framework and scenarios of cooperation*, IAEA-TECDOC-1413, October 2004. These documents address multinational facilities and are not limited to island disposal. However, proposals involving the Marshall Islands and Wake Island are described.

economies of scale possible with an multinational repository. Second, such a program would likely have IAEA safeguards integrated into the operations, thereby reducing proliferation concerns. Finally, at an unoccupied island site, local opposition may be lower in comparison to sites with many neighbors. Conversely, there are ethical considerations involved in siting a repository in a country that does not have nuclear power, which would include most island sites.

The 2004 IAEA TECDOC included the following conclusions:

"This report allows one to come to a number of observations that are summarized below:

1. Multinational repositories can enhance global safety and security by making timely disposal options available to a wider range of countries. For some Member States, multinational repositories are a necessity, if safe and secure final disposal of long lived radioactive waste is to replace indefinite storage in surface facilities.

2. The global advantages of multinational repositories are clear and the benefits can be significant for all parties, if they are equitably shared. For individual countries, the balance of benefits and drawbacks resulting from participation as a host or as a partner must be weighed by the appropriate national decision making bodies.

3. Implementation of multinational repositories will be a challenging task. However, there are a number of conceivable scenarios under which their development might take place.

4. This report specifies some of the principal requirements to be fulfilled when implementing multinational repositories. In the future, both national and international repositories are expected to be implemented.

In addition, the current publication shares the conclusions of the earlier IAEA publication on this topic (Note – reference is to the 1998 IAEA report):

5. The multinational repository concept does not contradict ethical considerations.

6. The high ratio of fixed to variable costs for a repository ensures that considerable economies of scale will apply.

7. Transport of nuclear material is so safe that the distances resulting from a multinational repository will not have a significant impact on public health."

Despite the positive conclusions in the IAEA document, the idea of developing an international repository – on an uninhabited island or elsewhere – has not advanced since the IAEA report was published. The Association for Regional and International Underground Storage (ARIUS) is pursuing the multinational repository concept.[17]

Another option for waste disposal by small countries is an approach that involves international cooperation through fuel leasing and take-back, something that the Russians offer when they bid on new nuclear power plants outside of Russia.[18] Such an approach offers obvious proliferation benefits and provides a way for smaller countries that are beginning to add nuclear power to their energy supply systems to avoid ownership of spent fuel. As part of its nonproliferation efforts, the USDOE has been actively working to have foreign research reactor fuel that was fabricated in the U.S. returned to the U.S. However, this policy does not extend to commercial spent fuel.

- Disposal by *in situ* melting, perhaps in underground nuclear test cavities

One method suggested[7,19] for disposal of liquid wastes from reprocessing is to put them into an underground cavity such as those that were created by underground nuclear weapons testing. The idea is that the wastes would have sufficient heat to melt the rock surface and produce a glassy lining that would prevent migration. A rationale for this approach is that the cavities already contain radioactive material, so the operation would not contaminate an otherwise pristine setting. In addition to uncertainties in how such a system would perform and whether leakage could be detected, existing regulations lead to a preference for shipping and disposing of solids in comparison to liquids. In recognition of the difficulty in shipping liquid wastes, a variant of this proposal would co-locate an underground nuclear test with a reprocessing plant.

- Disposal in the seabed (in stable clay layers or subduction zones or faults)

The U.S. Sub-Seabed program was active in the 1970's and 1980's until it was stopped in 1986. The approach was to emplace waste canisters in areas of the ocean where thick layers of mud and clays make up the ocean floor. The design was to drop the wastes in packages designed to penetrate many meters into the mud, or, as an alternative, to emplace the wastes by drilling holes into the mud, as is done in offshore oil production. The idea was that the mud would close behind and around the packages and that there would be little migration of deep pore water back into the ocean. While many people in the technical community thought that the approach was workable and

[17] See http://www.arius-world.org/

[18] As far as I know, no countries other than Russia will accept commercial spent fuel back from a foreign country.

[19] Disposal of Nuclear Waste by *In Situ* Incorporation in Deep Molten Silicate Rock," J. J. Cohen, A. E. Lewis, R. L. Bra, *American Association of Petroleum Geologists Bulletin*, Volume 55 (1971), at http://search.datapages.com/data/doi/10.1306/819A3DEA-16C5-11D7-8645000102C1865D

had advantages over land-based disposal, the concept was very unpopular with most environmental groups, especially those associated with ocean issues. The sub-seabed program's popularity was not helped by past instances of ocean dumping, and those opposed to the method equated sub-seabed disposal as equivalent to ocean dumping. A variant on the approach was to dispose of wastes in ocean subduction zones (zones where one tectonic plate moves beneath another, such that the wastes placed in sediments in the lower plate would eventually migrate down into the earth's mantle. Sub-seabed disposal is prohibited under the UN Convention on Law of the Sea and the London Convention and Protocol.

- Disposal in deep boreholes

Several deep borehole disposal concepts are described in an article published in March of this year.[20] The basic idea is that a cased hole is drilled to a depth of perhaps 4-5 km, that the bottom 1-2 km is filled with either vitrified high-level waste or spent fuel, and then some backfill or sealant (such as grout or cement) is added to fill in the gaps between the wastes and the well casing. A variety of materials are proposed for various wastes, including one concept in which lead shot is added as backfill. The Gibb article describes how "decay heat from the spent fuel will generate temperatures 100-200ºC above ambient and melt the shot to create a dense liquid that will displace the aqueous fluid upwards and fill any remaining voids between the containers and wall rock. Within a few decades, as the decay heat diminishes, this molten alloy will cool and solidify, effectively soldering the containers into the borehole."

The Gibb article indicates that the concept was introduced by SKB (the Swedish Nuclear Fuel and Waste Management Company) in 1989 and that more recently, work on the concept has been done by a collaboration of researchers at Sandia National Laboratory and MIT. This timeline is contradicted in a presentation[21] on the concept by Peter Swift of Sandia, which indicates that U.S. work on deep boreholes began in the 1950's and that extensive work was done in the 1970's and again in the 1990's. A detailed evaluation by Sandia was published in 2009.[22] The abstract of the Sandia report begins "Preliminary evaluation of deep borehole disposal of high-level radioactive waste and spent nuclear fuel indicates the potential for excellent long-term safety

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[20] Fergus Gibb, "Deep borehole disposal (DBD) methods," *Nuclear Engineering International*, March 25, 2010, at http://www.neimagazine.com/story.asp?storyCode=2055862.

[21] http://www.mkg.se/uploads/Presentation_-_Introduction_-_Peter_Swift_-_Goals_for_a_Deep_Borehole_Disposal_Workshop_100315.pdf

[22] Patrick V. Brady, Bill W. Arnold, Geoff A. Freeze, Peter N. Swift, Stephen J. Bauer, Joseph L. Kanney, Robert P. Rechard, Joshua S. Stein, *Deep Borehole Disposal of High-Level Radioactive Waste*, SAND2009-4401, August 2009, at http://www.mkg.se/uploads/Bil_2_Deep_Borehole_Disposal_High-Level_Radioactive_Waste_-_Sandia_Report_2009-4401_August_2009.pdf

performance at costs competitive with mined repositories." This report estimates that about 950 boreholes (filled in the bottom 1-2 km of a 3-5 km depth, with a 45 cm diameter) would be required to dispose of all U.S. spent fuel and high-level waste, projected to be about 110,000 metric tons. It also observes that "Deep borehole disposal of radioactive waste has the added advantage of not producing as large a "thermal footprint" as a mined geologic repository, because boreholes placed more than ~200 m apart are unlikely to thermally affect one another."

- Disposal by melting through ice sheets or permafrost

Kubo and Rose[7] discuss the concept of disposing of radioactive wastes in Antarctic rocks and "Permanent" ice in some detail, including both the favorable point of view and a view focused on the drawbacks. In the defense of the proposed approach, they write:

> "Two difficulties that exist with conventional hard rock disposal are the possibility that groundwater might leach out the wastes, and the possibility that people might come across the material in some future age when markings have vanished. These difficulties can be circumvented, at least in large part, by disposal at great depths. But both would be overcome by burial at modest depth in Antarctic rocks. To a depth of about 1 km, all groundwater is frozen in the Antarctic; thus, insertion of the wastes might be arranged to cause only warm inclusions in the totally frozen surround. Also, none but scientifically well-prepared civilizations are likely to come upon the area."

They then describe the negatives:

> "Ice-cap disposal has several drawbacks. First, wastes still containing actinides require extremely long periods of storage; for example, if the original concentration of ^{239}Pu is 10^6 times the permissible concentration in drinking water and no credit is allowed for insolubility, dilution, or adsorption, the required period of isolation is 500,000 years, and the ice may not be that permanent. Even if the actinides were removed, an area problem remains: to preclude appreciable heating at the ground-ice interface (and hence increased ice flow), the heat generated from the wastes must be a small fraction of that appearing via the geothermal gradient-1 percent would be 63 kw/km^2. Wastes from the United States aged 10 years before burial, if accumulated and spread out in Antarctica to give that heat load, would cover 10^6 km^2 by A.D. 2025, that is, 25 percent of the area that has ice with an anticipated lifetime exceeding 10,000 years."
>
> "Finally, transportation and working conditions in the Antarctic are difficult and hazardous, and at present the Antarctic is kept free of nuclear wastes by international treaty."

The idea of disposing of radioactive wastes in sheet ice or permafrost has also been adversely affected by global climate change. The confidence that Kubo and Rose exhibit in referring to “ice with an anticipated lifetime exceeding 10,000 years” has been overtaken by loss of large areas of ice cover in the arctic. As the Polar Regions are increasingly seen as ecologically fragile, the likelihood diminishes that radioactive waste disposal would be proposed or accepted in these regions.

- Disposal by shooting the wastes into deep space or the sun

Cost and the risk of an accident during launch has kept space disposal from being taken seriously. With the current cost of putting objects in orbit at around $10,000 per pound, and given that the U.S. inventory of spent fuel and high-level waste is of the order of 100,000 metric tons, not including the heavy shielding that would be required, the costs with present technology would be prohibitive, even if the risks of radioactive wastes crashing back to earth could be managed somehow.

But if one wanted to dispose of only the very long-lived waste, e.g., technetium-99, cesium-135, iodine-129, and the long-lived actinides, then the amounts are much more manageable, of the order of a few million kilograms for all current U.S. wastes. This is still very expensive at $10,000 to put a pound in orbit, and does not include the costs to separate out these long lived wastes from the other components. Proposals to launch wastes into space using earth-based lifting devices[23] (lasers, microwaves, and high speed rail guns) offer the advantage that not all that fuel needs to be lifted, but the capability of these technologies to put materials into space has not been demonstrated.

It appears that in order to make space disposal feasible, significant advances are needed in the technologies for separating nuclear wastes and in the cost of moving materials into space.

- Spent fuel reprocessing, partitioning and transmutation

Unlike the once-through fuel cycle used in the U.S., the French, British, Japanese, and Russians have built reprocessing plants where spent fuel is dissolved so that the uranium and plutonium can be recovered and reused in new fuel. For present operations, most of the plutonium is stored rather than used to fabricate mixed oxide fuel. While reprocessing is not a disposal technology, the significant volume reduction that is obtained when uranium and plutonium are recovered could reduce the amount of repository volume needed for disposal, relative to that for a once-through fuel cycle.

One consideration is timing. If reprocessing of spent fuel is delayed for several decades after fuel is removed from reactors, the plutonium-241 (14 year half-life) will decay to

[23] Jonathan Coopersmith, “Nuclear waste in space?” in The Space Review: essays and commentary about the final frontier, August 22, 2005, at http://www.thespacereview.com/article/437/1

americium-241, which is problematic for fabricating new fuel because it is a gamma emitter.

While a detailed analysis of alternatives for closing the back end of the fuel cycle is beyond the scope of this paper, a simplified description of several options is provided. If the U.S. were to decide to reprocess spent nuclear fuel, one option would be to recycle the recovered uranium and plutonium as a mixed oxide fuel using conventional water reactors. Depending on the reprocessing technology used, some of the actinides and almost all of the fission products would become a waste stream that is similar to those undergoing treatment at the Savannah River Site and Hanford. At each of these sites, the high-level waste residuals from reprocessing are being vitrified into borosilicate glass.

The choice between the once-through fuel cycle and reprocessing is largely about cost, since both systems have been demonstrated. One can identify analyses of the cost of reprocessing versus a once-through fuel cycle that come to opposite conclusions. A 2003 report[24] that compared the economics of a once-through fuel cycle with those of reprocessing concluded:

> "At a reprocessing price of $1000 per kilogram of heavy metal (kgHM), and with our other central estimates for the key fuel cycle parameters, reprocessing and recycling plutonium in existing light-water reactors (LWRs) will be more expensive than direct disposal of spent fuel until the uranium price reaches over $360 per kilogram of uranium (kgU)—a price that is not likely to be seen for many decades, if then."

As a point of reference, uranium prices have ranged between $40 to $54 per pound ($88 to $120 per Kg) over the past year.[25] The Bunn et al report also comments that

> "In principle, both the uranium and plutonium separated from spent fuel during reprocessing can be made into new reactor fuel and recycled. In practice, this is done for only a small fraction of the uranium recovered from reprocessing today, because freshly mined uranium is cheap enough that the uranium recovered from reprocessing (which is less desirable because of various isotopes created during irradiation in the reactor, including U-234 and U-236) is not competitive for use in fresh fuel. So

[24] Bunn, Matthew, Steve Fetter, John Holdren, and Bob van der Zwaan. *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel.* Cambridge, Mass.: Report for Project on Managing the Atom, Belfer Center for Science and International Affairs, Harvard Kennedy School, December 2003, at http://belfercenter.ksg.harvard.edu/files/repro-report.pdf.

[25] http://www.uxc.com/review/uxc_Prices.aspx

nearly all of the uranium recovered from reprocessing every year simply remains in storage."

An opposing view comes from an analysis[26] that finds the costs of the two systems comparable, but when uncertainties regarding the costs of disposal for the once-through cycle after Yucca Mountain is filled (the report was written in 2006 and assumes that Yucca Mountain would be used) are taken into account, reprocessing is seen as potentially cheaper.

These two perspectives may not be as far apart as they seem. There seems to be little doubt that new uranium fuel is currently cheaper and easier to use than mixed oxide fuel made from recycled spent fuel, if the full cost of reprocessing and management of the reprocessing waste streams and mixed oxide fuel fabrication are considered. But the extent to which the full life cycle costs, including the fees that utilities pay for future disposal costs, are representative of future disposal costs is not clear.

Another alternative would be to reprocess spent nuclear fuel and to recycle the new mixed oxide or plutonium fuel through fast reactors.[27] Fast reactors, typically based on a liquid metal coolant such as sodium, are capable of producing more fuel than they consume by converting depleted uranium (i.e., uranium-238) into plutonium-239. Such reactors are also called fast breeder reactors.

Fast neutrons can also convert long-lived actinides into shorted-lived fission products, a process referred to as transmutation. Transmutation concepts were explored in the NAS study (reference 9); the three approaches that were evaluated were the use of a light-water reactor, a liquid metal reactor with a fast neutron spectrum, and an accelerator-driven subcritical reactor concept. This report notes that technetium-99 and iodine-129 can be transmuted, but that thermal neutrons were more effective than fast neutrons for this purpose.

In the previous administration, the Department of Energy's Global Nuclear Energy Partnership (GNEP) was proposing that reprocessing and actinide burning in fast reactors be brought into commercial application on an ambitious schedule. In contrast to a plan to use fast breeder reactors, the GNEP plan was to use fast reactors as

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[26] Economic Assessment of Used Nuclear Fuel Management in the United States, Prepared by the Boston Consulting Group for AREVA, July 2006, available at http://209.83.147.85/impact_expertise/publications/files/Economic_Assessment_Used_Nuclear_Fuel_Mgmt_US_Jul2006.pdf.

[27] The term "fast" refers to the neutron energies in the reactor, and is in contrast to the slow or thermal neutron energies in current water reactors.

"burners", that is, reactors with a primary mission to transmute actinides rather than to produce plutonium. A review by NAS[28] was highly critical of this plan.

If and when separation and transmutation technologies become competitive with a once-through fuel cycle, it is likely that uranium will be significantly more expensive than it is now. If that is the case, the plan to operate fast reactor burners (as in the GNEP plan) may be less attractive than operating fast reactors as breeders. It is difficult to see how the economics of disposing of actinides and long-lived fission products by reprocessing, separation, and transmutation can be competitive, given that these long-lived radionuclides consist of relatively small volumes that can easily be stored.

Concluding comments

Geologic disposal is the approach that all countries with waste disposal programs have emphasized. However, there are interesting variations on that idea such as the use of deep boreholes that may offer advantages in comparison to mined repositories. The IAEA proposals to consider multinational repositories also have merit, especially for countries without an appropriate site for a repository and for countries with comparatively small nuclear power programs. It appears that reluctance to allow radioactive waste imports has been and remains an obstacle to such an approach. Whether a multinational program could be successful in building on an unoccupied island is not known, but seems worth pursuing. What all of these options have in common is the use of a geologic setting for waste disposal. Regarding the question of the form of waste to be disposed, perhaps the most relevant question regarding reprocessing is when to do it rather than whether to reprocess. If, as many projections suggest, nuclear power use expands globally throughout this century, then spent nuclear fuel may come to be regarded as a resource rather than as a waste. If so, then the retrievability of any disposal system will be an important attribute.

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[28] *Review of DOE's Nuclear Energy Research and Development Program*, Committee on Review of DOE's Nuclear Energy, Research and Development Program, National Research Council, 2008 at http://www.nap.edu/catalog/11998.html.