Chapter 5 — Waste Management

It has been three decades and five presidents since the determination to deal with civilian radioactive waste was first proclaimed. One generation later, the United States still lacks an integrated nuclear waste management strategy, contributing to a public perception that the radioactive waste problem cannot be readily solved.

The United States has shown that it can effectively manage waste storage facilities for low-level and transuranic waste. It is the only country in the world that has successfully licensed, constructed and now operates a deep geological repository for defense-generated radioactive waste, the Waste Isolation Pilot Plant (WIPP). This chapter discusses the issues and obstacles that have prevented similar progress on SNF from power reactors and presents recommendations to move forward.

Our analysis centers on the following observations and findings.

1. All fuel cycles generate long-lived radioactive wastes that can not be practically destroyed; thus, all fuel cycles require a geological repository to support the disposal of radioactive wastes.
2. Spent nuclear fuel from LWRs has a high residual energy content, is stable for a long time when isolated from the environment, and can be processed to recover the fissile and fertile materials for reuse in the future.
3. Historically, fuel cycles in the United States have been developed independently of waste management although there are large economic and risk-reduction benefits for treating waste management as an integral part of the fuel cycle.
4. The United States does not have an integrated waste management system but rather an ad hoc system to address specific wastes. This has resulted in orphan wastes with no disposition pathways, high costs, and a system that will have increasing difficulties if an alternative fuel cycle was adopted.
5. There have been technical and institutional failures in waste management in the U.S.

This analysis leads to several recommendations.

1. A risk-based waste management strategy should be adopted with (1) a waste classification system based on the radionuclide, chemical, and physical characteristics of each waste stream with (2) corresponding disposal facilities for each category of wastes. This is needed to manage existing wastes and required to establish a rational basis for the future management of wastes that could be generated by future fuel cycles. Implementation will require both regulatory and statutory actions.
2. The United States should create an independent organization (with no additional responsibilities) for the management of all long-lived radioactive wastes—including high-level waste (HLW) and spent nuclear fuel (SNF). This includes long-term storage of HLW and SNF, siting of repositories, and operation of such facilities.

3. Waste management (including SNF storage) must become an integral part of the development of any fuel cycle, including an open fuel cycle. The impact of waste management must be assessed and properly reflected in cost and risk evaluations of alternative fuel cycles.

**RADIOACTIVE WASTE SOURCES, CATEGORIES, AND DISPOSAL FACILITIES**

**Origins of Radioactive Waste**

There are three main sources of radioactive waste. Defense operations have generated large quantities of wastes. These wastes are primarily the byproduct of nuclear weapons production. Smaller quantities of wastes are generated by nuclear navy operations—including SNF. Commercial nuclear power generates wastes from the fuel cycle and reactors. The primary waste form is SNF, which consists of highly radioactive fission products and actinide elements, and is classified as high-level waste. A 1000 MWe LWR generates ~20 tons of SNF and 250-350 m$^3$ of other radioactive wastes (primarily low-level wastes (LLW)) per year. Other wastes result from research and development; accelerators, medical, industrial operations; and natural occurring materials.

There are significant differences between historical defense wastes and those from the nuclear power fuel cycle. The operations of defense facilities resulted in the radioactivity being in dilute forms not suitable for direct disposal. Large-scale waste processing operations are required to convert these wastes into forms suitable for disposal. In contrast, SNF from electricity production is highly concentrated and generally in chemically stable forms. Most of these wastes, including SNF, can be packaged and disposed of directly.

**Waste Categories***

Radioactive wastes are divided into categories. How a waste is categorized is central to how it is managed. Wastes classified as municipal garbage, construction debris, and chemical waste are treated differently because they have different characteristics and create different risks to the public. Similarly, different classes of radioactive wastes are treated differently.

Radioactive nuclides decay to nonradioactive nuclides. Different radioactive wastes require different lengths of time before they become nonhazardous. The waste classification system divides radioactive wastes into categories primary based on the time the wastes remain hazardous. Different types of disposal facilities are required for a waste that remains hazardous for years versus a waste that is hazardous for thousands of years. The process of radioactive decay generates heat. If a waste is highly radioactive it will generate significant decay heat that requires special engineering features in the disposal facility to prevent excessive temperatures. Radioactive waste classification systems also categorize waste by its heat generation rate because it defines what type of disposal facility is required.

Different countries have different waste classification systems that fall into two major categories: those that are based on “where” the waste was generated (point of origin) and those that
are based on the “intrinsic qualities” of the material (risk based). The United States adopted a point of origin system whereas the international community today uses a risk-based system.

For example, in the United States HLW is defined by the Atomic Energy Act of 1954 as the “first cycle rafinate” from a nuclear fuel reprocessing plant—the original source of HLW. Such a technology-based definition assumes (1) a specific reprocessing technology that generates a “first cycle rafinate” and (2) only reprocessing plants with “first cycle rafinates” will generate highly-radioactive materials that should be defined as high-level wastes. This was a reasonable approach for what was known in 1954; but, the assumptions it was built upon are no longer true. SNF is now defined as HLW.²

Because the U.S. has not updated its waste classification system, the United States today has an inconsistent, unstructured, and ad hoc waste classification system. Table 5.1 shows the U.S. classification system for radioactive wastes with different categories for defense wastes and civilian wastes. Various regulatory patches have been used to protect public health and safety, but with several consequences:

- **Unknown requirements and costs to treat new types of wastes.** Many proposed fuel cycles would create new types of waste but the regulatory structure for disposal of many such wastes does not fully exist in the U.S.³ Without a comprehensive waste classification system it is not possible to compare the waste management costs and risks of different fuel cycles without making arbitrary assumptions.

- **Orphan wastes.** The U.S. has some types of waste that do not have an agreed upon disposition path. An example is the disposition of depleted uranium that is classified by default as Class A low level waste (LLW) although its radiological characteristics are very different from other wastes classified as Class A LLW.⁴ There is an ongoing multi-decade regulatory effort to categorize this waste and thus define disposal requirements.

In most major nuclear countries wastes are categorized by their content, not the source of the waste. These waste classification systems are similar to that recommended by the International Atomic Energy Agency. The IAEA recommends a risk-based system that accounts for the intensity of the radiation and the time needed for it to decay to an acceptable level. The intensity of radiation is given by a range of radioactivity per unit of weight. Decay time is split into short lived (< 30 years) and long lived (>30 years). There is no distinction in either categorization or disposition options based on the sources of nuclear waste.

Disposal facilities

The U.S. has built disposal facilities for various defense and commercial radioactive wastes. The combination of the proposed YM repository, the Waste Isolation Pilot Plant (WIPP), and other waste facilities have the capability to dispose of all defense- and civilian-generated wastes; however, each facility is limited to specific wastes from specific sources rather than being disposal facilities for all wastes in a particular category. The WIPP repository is designed to isolate long-lived low-heat radioactive wastes but is legally restricted to defense transuranic wastes—the largest category of such wastes. The proposed YM repository or an equivalent facility would be technically capable of disposing of all long-lived wastes from any fuel cycle. However, the license application for the proposed YM repository was only for the disposal of SNF and HLW—it did not address the disposal of small quantities of orphan wastes generated by today’s once-through fuel cycle requiring geological disposal. A
closed fuel cycle would generate many more orphan wastes with no disposal options—even if the proposed YM repository was available.

Other countries have adopted a different strategy. Radioactive wastes are categorized by what is in the waste—not where it came from, who generated it, or its history. If a new technology generates a new waste, the composition of the waste is used to determine its category and the disposal requirements. Disposal facilities are built and licensed for all the wastes in a particular category. Sweden has built such a waste management system for all wastes from a once-through fuel cycle. France has partly built such a waste management system for all wastes from a partly closed fuel cycle. The defining characteristics in both systems is that there a waste classification system that categorizes all wastes and well defined pathways for disposal of all materials in each category.

Table 5.1 United States Waste Classification System*

<table>
<thead>
<tr>
<th>WASTE CLASS</th>
<th>DESCRIPTION</th>
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<tbody>
<tr>
<td>DEFENSE WASTE</td>
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<tr>
<td>HLW</td>
<td>Highly radioactive waste material resulting from the reprocessing of SNF, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste containing fission products in sufficient concentrations; and other highly radioactive materials determined, consistent with existing law, to require permanent isolation.</td>
</tr>
<tr>
<td>Transuranic (TRU)</td>
<td>Waste containing more than 3,700 becquerels (100 nanocuries) of alpha-emitting transuranic isotopes per gram of waste, half-lives greater than 20 years, except for: (1) HLW, (2) waste the Secretary of Energy has determined, with the concurrence of the Administrator of the EPA, does not need the degree of isolation required by the 40 CFR Part 191 disposal regulations; or (3) waste NRC has approved for disposal on a case-by-case basis in accordance with 10 CFR Part 61.</td>
</tr>
<tr>
<td>Mixed Waste</td>
<td>Radioactive waste that is also chemically hazardous, as defined by RCRA, is considered mixed-waste and must meet EPA requirements prior to disposal.</td>
</tr>
<tr>
<td>Low-level Waste (LLW)</td>
<td>All other radioactive waste that is not HLW, SNF, TRU waste by-product material (as defined in section 11(e).2 of the Atomic Energy Act of 1954, as amended), or naturally occurring radioactive material.</td>
</tr>
<tr>
<td>11(e).2 By product Material</td>
<td>The tailings or wastes produced by the extraction or concentration of uranium or thorium from any ore processed primarily for its source material content.</td>
</tr>
<tr>
<td>CIVILIAN WASTE</td>
<td></td>
</tr>
<tr>
<td>HLW</td>
<td>Highly radioactive waste material resulting from the reprocessing of SNF, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste containing fission products in sufficient concentrations; and other highly radioactive materials the NRC, consistent with existing law, determines by rule requires permanent isolation.</td>
</tr>
<tr>
<td>Class A LLW</td>
<td>The physical form and characteristics must meet the minimum requirements of 10 CFR 61.56</td>
</tr>
<tr>
<td>Class B LLW</td>
<td>Waste that must meet more rigorous requirements on waste form than class A waste to ensure stability</td>
</tr>
<tr>
<td>Class C LLW</td>
<td>Waste that not only must meet more rigorous requirements on waste form than class B waste to ensure stability but also requires additional measures at the disposal facility to protect against inadvertent intrusion</td>
</tr>
<tr>
<td>Greater than Class C LLW</td>
<td>LLW not generally acceptable for near-surface disposal</td>
</tr>
<tr>
<td>11(e).2 By product Material</td>
<td>The tailings or wastes produced by the extraction or concentration of uranium or thorium from any ore processed primarily for its source material content, including discrete surface wastes resulting from uranium solution extraction process. Underground ore bodies depleted by such solution extraction operations do not constitute &quot;by-product material&quot; within this definition.</td>
</tr>
</tbody>
</table>

Waste Classification Recommendations

We recommend that an integrated risk-informed waste management system be adopted in the U.S. that classifies all wastes according to composition and defines disposal pathways according to risk. The Nuclear Regulatory Commission should take the lead in developing the appropriate framework because waste classification is central to the safe management of radioactive wastes. However, Congress will ultimately need to provide the authority for implementation of such a framework. Such a framework can build upon U.S. waste classification studies\(^5,6\), and the experiences of other nations\(^7\).

GEOLOGIC DISPOSAL OF LONG-LIVED RADIOACTIVE WASTES

In 1957, the U.S. Atomic Energy Commission asked the U.S. National Academy of Sciences (NAS) to recommend methods for the safe disposal of high-level radioactive wastes. The NAS\(^8\) concluded that deep underground geological disposal of wastes was the preferred method for the disposal of long-lived radioactive wastes—a conclusion supported by later NAS studies and accepted by all major scientific advisory boards worldwide. Independent of the choice of a fuel cycle, long-lived radioactive wastes will be generated and a repository for their disposal will be required.

Today, geologic disposal is considered the preferred option for the disposal of long-lived wastes that must be isolated from the biosphere for protection of human health and the environment. Both radioactive\(^9\) and chemical wastes are disposed of in geological repositories (Table 5.3). The chemical wastes are primarily those containing elements that are toxic, last forever, and can not be destroyed—such as lead, arsenic, and cadmium. The first operating geologic repository was the Herfa Neurode repository for chemical wastes in Germany. Since then, additional geological repositories have opened elsewhere in Europe for chemical wastes. The only operating repository for long-lived radioactive wastes is WIPP in New Mexico. There is no operating repository for the disposal of HLW and SNF.

<table>
<thead>
<tr>
<th><strong>Table 5.2. International Waste Classification system recommended by IAEA</strong></th>
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</thead>
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<tr>
<td><strong>Very Low-Level Waste</strong></td>
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<tr>
<td><strong>Low-Level Waste</strong></td>
</tr>
<tr>
<td><strong>Intermediate Level Waste</strong></td>
</tr>
<tr>
<td><strong>High-Level Waste</strong></td>
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THE DEVELOPMENT OF GEOLOGICAL REPOSITORIES WORLDWIDE IN MULTIPLE TYPES OF GEOLOGY PROVIDES A STRONG SCIENTIFIC AND TECHNICAL UNDERSTANDING OF WHAT IS REQUIRED FOR THE DESIGN, CONSTRUCTION, AND OPERATION OF SUCH FACILITIES. WITHIN THE UNITED STATES, THE SITING, DESIGN, LICENSING, CONSTRUCTION, AND OPERATION OF WIPP PROVIDES EXPERIENCE IN REPOSITORIES FOR INTERMEDIATE-LEVEL WASTES. IN PARALLEL, THE YUCCA MOUNTAIN PROJECT WAS THE FIRST MAJOR SUSTAINED TECHNICAL EFFORT BY THE UNITED STATES TO DESIGN AND LICENSE A GEOLOGICAL REPOSITORY FOR SNF AND HLW. MUCH OF THE SCIENTIFIC UNDERSTANDING OF REPOSITORIES AND THE TECHNOLOGY THAT WAS DEVELOPED IS APPLICABLE TO ANY FUTURE REPOSITORY.

There are technical characteristics of geological repositories (See Chapter 5 Appendix) that are important to understand in terms of fuel cycles and policy.

- Geologic repositories are located several hundred meters underground to protect the disposal site from natural and man-made events (land erosion, glaciation, war).
- Repository capacities are not limited by volume or mass.
- The primary transport mechanism for radionuclides from the repository to the biosphere is by groundwater and use of that groundwater for drinking or growing food. Local geochemistry determines what radionuclides can be transported by groundwater and thus potentially escape from a repository. In most repository environments, actinides (plutonium, etc.) are not expected to escape from the repository because of their low solubility in groundwater and sorption on rock.
- In disruptive events (volcanism, human intrusion, etc.) actinides become significant contributors to risk.
- Peak temperatures in a repository must be limited to avoid degradation of repository performance. Radioactive decay produces heat. To reduce the size and cost of a repository, repository programs store SNF and HLW for 40 to 60 years before disposal to reduce the decay heat. Alternatively, a repository can have active ventilation for several decades while the decay heat decreases.
- The incentives to burn radionuclides in reactors to improve repository performance are limited.

### Institutional Aspects of Geological Waste Disposal

There have been a few successes and many failures in the siting of repositories. Europe has successfully sited and operates multiple geological repositories for chemical wastes. Finland has sited but not completed a SNF repository with public acceptance of the site. Sweden has two communities that have been competing for a SNF repository in their communities and in June 2009 chose one of those communities to host the repository. France may have a repository site. The United States has successfully sited and now operates WIPP. However, there have been multiple failures.

### Table 5.3 Examples of Operational Geological Repositories

<table>
<thead>
<tr>
<th>REPOSITORY</th>
<th>CHEMICAL</th>
<th>RADIOACTIVE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facility</td>
<td>Herfa Neurode (Germany)</td>
<td>Waste Isolation Pilot Plant (U.S.)</td>
</tr>
<tr>
<td>Operational</td>
<td>1975</td>
<td>1999</td>
</tr>
<tr>
<td>Capacity</td>
<td>200,000 tons/y</td>
<td>175,570 m³ (Lifetime)</td>
</tr>
<tr>
<td>Hazard Lifetime</td>
<td>Forever</td>
<td>&gt; 10,000 years</td>
</tr>
</tbody>
</table>
The United States initiated its repository program in the mid 1950s for the disposal of defense wastes. After a series of failed attempts\textsuperscript{10, 11} a major effort was undertaken in 1982 to develop a long-term strategic program to build a repository for SNF and HLW. This effort was supported by the Office of Technology Assessment\textsuperscript{12} report that made recommendations on how to site a repository. Its executive summary (including what was put in bold in the original report) defined the challenge.

“The greatest single obstacle that a successful waste management program must overcome is the severe erosion of public confidence in the Federal Government that past problems have created. Federal credibility is questioned on three main grounds: 1) whether the Federal Government will stick to any waste policy through changes in administration; 2) whether it has the institutional capability to carry out a technically complex and politically sensitive program over a period of decades; and 3) whether it can be trusted to respond adequately to the concerns of States and others who will be affected by the waste management program.

OTA’s analysis suggests that, if history is not to repeat itself, and the current stalemate on nuclear waste is not to continue, a comprehensive policy is needed that addresses the near-term problems of interim storage as part of an explicit and credible program for dealing with the longer-term problem of developing a final waste isolation system. Such a policy must: 1) adequately address the concerns and win the support of all the major interested parties, and 2) adopt a conservative technical and institutional approach—one that places high priority on avoiding the problems that have repeatedly beset the program in the past.”

The history of efforts to build a geological repository for SNF and HLW since 1982 validate many of the concerns of OTA. A number of lessons have been learned.

**Waste program continuity is important.** Successful waste programs have long-term continuity in management. In the United States, WIPP had changes in management at the Department of Energy but there was a stable management team at Sandia National Laboratory\textsuperscript{13}. The continuity helped provide the trust at the local and state level. The same characteristics are seen in successful foreign programs.

**An appropriate funding mechanism is required that raises the funds and makes those funds available to the repository program when required.** The Nuclear Waste Policy Act authorized that disposal services be specified through contracts between DOE and the nuclear utilities. Customers who use nuclear power pay for the disposal of spent fuel. As of December, 2009, the Nuclear Waste Fund has about $29 billion. The funding mechanisms to collect funds for the repository program have worked as intended. However, changes in the law resulted in the Nuclear Waste Fund being part of the general federal budget. Congress limited annual appropriations for the repository below the amounts requested to a very small percentage of the waste fund balances.\textsuperscript{14} The program has been funding limited. DOE has failed to meet its contractual obligations. As a result, the nuclear utilities have won significant financial judgments. The U.S. waste program does not have a viable mechanism to use collected fees on an appropriate schedule to develop and build a repository.

**Public transparency and major outreach programs are critical.** There are striking differences between the large Swedish\textsuperscript{15}, Finnish, and French repository outreach programs and the limited outreach programs of the U.S. repository program. Partly this reflects siting philosophy. Nations with voluntary siting strategies by definition must have major outreach
programs whereas in the U.S. the Congress chose the Yucca Mountain site when it passed the Waste Policy Act 1987 and assumed that such programs were not required.

**Compensation and local involvement are important.** A geological repository is a large industrial facility with major impacts. In the United States, the successful siting of WIPP involved a significant compensation package for New Mexico and partial regulatory oversight by the State of New Mexico. Similar compensation packages are components of successful foreign programs. For example, the Swedish program has signed a $240 million dollar agreement with the two communities that were considered for a final repository to help improve infrastructure and make other investments—although only one community was chosen to host the repository.

In contrast, the U.S. repository program compensation to communities is limited and depends upon yearly Congressional appropriations. The Waste Policy Act allows for $20 million per year or less than 0.5% of the total estimated inflation-adjusted lifetime cost of the repository. We believe a strong case can be made that the benefits to a local community should at least be comparable to the benefits a community would receive by the construction and operation of an equivalent industrial facility.

**Social science input into the program and technical design is important.** A feature of successful foreign programs is the significant scale of effort to understand public concerns.

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**Waste Isolation Pilot Plant**

The United States is operating a geological repository for defense transuranic wastes near Carlsbad, New Mexico. The existence of WIPP indicates that geological repositories can be sited and built in the United States. The ultimate WIPP waste inventory in terms of long-lived radioactive materials will be 1 to 2% of a SNF repository. The siting, construction, and operation of WIPP was difficult with no assurance of success when it started.* Several factors explain much of the success in siting and operating this geological repository.

WIPP was a high priority of the U.S. government because the failure to dispose of weapons wastes was becoming a barrier for operations of the nuclear weapons complex—a high priority of the federal government. That priority led the U.S. government to provide compensation for hosting such a facility and power-sharing in the form of an oversight role by the State of New Mexico. State cooperation was also partly influenced by the presence of Los Alamos National Laboratory in New Mexico that had a large inventory of transuranic waste that would be disposed of in WIPP. The City of Carlsbad and the surrounding region wanted WIPP to provide a long-term stable economic basis for the economy. The development of WIPP resulted in other fuel cycle facilities moving to Carlsbad—including a several billion dollar enrichment plant. It has been an engine of local economic development.

The technical team supporting the development of WIPP was competent, given the freedom to develop the repository, and had long-term continuity. This included a standing committee of the National Research Council that provided both a review function and an open forum for the expression of NGO and public concerns.

WIPP was defined as a facility in bedded salt near Carlsbad—not a specific piece of salt. As the investigations proceeded, discoveries about the local geology resulted in the specific site being moved twice (geology is extremely site dependent). This ability to move locally depending upon what the geologists found resulted in both a better facility and ultimately higher credibility.

**Note**

about repositories. Because of cross cultural differences, the conclusions of these foreign studies are not necessarily translatable to the United States. Nevertheless, the French\textsuperscript{20} and Swedish\textsuperscript{21} programs have come to some conclusions.

- Repositories should be designed to enable long-term waste retrievability. The public has major concerns about irrevocable decisions, a dread of radioactivity, and a concern for safety for the first few centuries. These social concerns can be partly addressed by repository designs that explicitly include long-term retrievability of wastes as a societal design requirement to provide confidence.\textsuperscript{22}

- Repositories and the safety case should be understandable.

The U.S. National Academy of Science\textsuperscript{23} has recommended a focused social science research program as an integral component of a repository program. However, historically U.S. repository programs have been compliance driven; that is, the repository is acceptable if it meets regulatory requirements. Experience suggests that meeting legal requirements is a necessary but not sufficient condition for a successful repository program.

**Successful repository programs have had strong voluntary components as part of their siting programs.**\textsuperscript{24} All of the geological repositories for chemical wastes in Europe, the WIPP repository in New Mexico, and the siting of the SNF/HLW repositories in Finland, Sweden and France involved programs that obtained local approval for the repositories. These successes have led other countries\textsuperscript{25,26} to adopt volunteer siting strategies.

Local acceptance impacts national acceptance of a geological repository. As part of our fuel cycle study, a national opinion poll was commissioned (Chapter 9) to better understand public acceptance dynamics associated with nuclear power, spent nuclear fuel storage, and alternative fuel cycles. The question was asked: “Should the United States complete and use the Yucca Mountain facility to store wastes underground?” The results show that national public acceptance of a repository partly depends upon local acceptance of the repository—a result supported by foreign studies.\textsuperscript{27}

There is a caveat with respect to the United States. The structure of the U.S. federal system with a federal government and state governments makes it more difficult to site unwanted facilities in the U.S. than in many other countries. In most countries, if the national government and local community agree, the project goes forward. This is not true in the U.S. There are many localities that would accept a repository. For example, the proposed Yucca Mountain repository is supported by the county government in Nevada but opposed by the state government. The local community sees the benefits but the state government sees an unwanted facility with little benefit to the state as a whole. The successes have occurred when all three levels of government have concurred.

**Successful repository programs manage all long-lived radioactive wastes requiring geological disposal.** The Swedish and French waste programs have responsibility for disposal of all long-lived radioactive wastes in their countries. The U.S. repository program has responsibility for disposal of SNF and HLW—but not the small quantities of other long-lived wastes from the once-through fuel cycle and various industries. The storage of SNF by utilities, the navy, and others is not integrated with respect to the repository requirements for SNF storage.
Successful repository programs are managed with specialized government or utility organizations with strong waste generator commitment. Different countries have adopted different models\textsuperscript{28,29} for the management of radioactive wastes: government agencies (U.S.), government-owned corporations, public-private partnerships, and private corporations.\textsuperscript{30} The private corporations are owned by the nuclear utilities. At one extreme are Sweden and Finland where the utilities have primary responsibility for managing SNF and other wastes—including the siting, building, and operating of a geological repository. Waste liability is transferred to the state after disposal. At the other extreme is the United States where the Federal government assumes liability for SNF when it leaves the reactor site based on payment of a fee as electricity is generated. The Federal government is responsible for siting, building, and operating of the geological repository. The countries with strong waste generator involvement (Sweden, Finland, and to a lesser degree France) have made more progress and have repository sites with public acceptance. The same is true in the United States where DOE is the waste generator and operator of WIPP.

Successful waste management programs are adaptive.\textsuperscript{31} The Swedish program developed two repository sites before selecting a single site, developed a wide variety of repository design options, and examined both conventional geological disposal and borehole disposal. The French program is examining three waste management strategies: very long-term storage, conventional geological disposal, and burning of selected actinides to reduce repository inventories of long-lived radionuclides. Both programs have formal and deliberate decision making processes. This strategy (1) provides confidence to the public that a realistic examination of the alternatives has been undertaken before decisions were made and (2) provides backup options if unforeseen problems are identified with any single route to manage wastes. In contrast the U.S. program by law was defined by a rigid path to a repository that included a narrow focus on a single site with a single technology.

Successful repository programs maintain options until there is high confidence in the selected option. Different options (Appendix) have different institutional characteristics that provide policy makers with choices and increase the likelihood of success. Some options, such as borehole disposal, may provide alternative methods of geological isolation that can be implemented economically on a small scale—creating an economically viable option for regional repositories. For the United States, there is also the incentive to create options to support national nonproliferation policies. Options such as borehole disposal of SNF may have superior nonproliferation characteristics and be suitable for countries with small nuclear power programs; Consequently, the benefits of such R&D support both domestic waste management and foreign policy objectives such as nonproliferation. We recommend an R&D program to improve existing repository options and develop alternative options with different technical, economic, geological isolation, and institutional characteristics.

Recommendations on the Structure of Repository Programs

There have been many proposals on how to manage the U.S. repository program.\textsuperscript{32,33,34} Based on our analysis, we have concluded that the U.S. should create a new organization responsible for the management of long-lived radioactive wastes—indeed, independent of the final outcome of the Yucca Mountain Project. However, we have not defined the specific structure of such an organization but rather the necessary functions and characteristics required for waste management based on experience worldwide.
The organization should be responsible for management of all HLW, SNF, and all other radioactive wastes requiring geological disposal. This would include responsibility for off-utility-site SNF and HLW storage because storage is a required “pretreatment” step before disposal. It would also include greater-than-class-C wastes from utility, scientific, and industrial generators.

The organization must have the mission to create and implement an integrated waste management program that addresses both technical and institutional issues. The charter must state goals but the organization must be able to develop, change, and implement the repository program. This includes adaptive staging strategies.

The organization should be independent of any other organization and have a single focus.

The organization should be structured for long-term continuity in management where there is not a changeover in management and directions after each presidential or congressional election.

The board of directors of the organization should include representatives of major groups with an important stake in waste management. This includes but is not limited to one or more board members:

- Who are cabinet members reporting to the President of the United States. This is to provide access, if required, to the decision-making levels of the executive branch of the U.S. government.
- Representing the utilities—the waste generators.
- Representing the Public Service Commissions—the state regulatory agencies that approve utility electric rates.
- Representing the public

The organization should be funded with user fees (like the existing program) but with all funds used for the intended purposes and authority to use those funds.

In cooperation with the Department of Energy, the organization should investigate alternative waste management options. There will be areas of common and separate interests because of the different missions. The organization’s goal is safe disposal of U.S. wastes. The DOE interests will be based on responsibilities for defense wastes, nonproliferation, and developing future energy options.

The organization should be a participant in planning and discussions on development and implementation of alternative fuel cycles.

INTEGRATION OF FUEL CYCLES AND WASTE MANAGEMENT

The United States has not historically integrated development of fuel cycles with waste management. In the cold war the defense programs built separations plants for the recovery of fissile materials and placed the wastes in temporary storage. Decades later disposal facilities such as WIPP were built. The high costs and associated risks associated with the U.S. defense waste cleanup programs are a consequence of not coupling the defense fuel cycle with waste management.

The commercial nuclear power industry initially assumed that it would adopt a closed fuel cycle. Because SNF would be shipped to reprocessing facilities, nuclear power plants were
designed with limited SNF storage capacity. In a closed fuel cycle SNF storage is done at the reprocessing facility to provide an operating inventory of SNF for the reprocessing plant. HLW storage before disposal is done at the reprocessing facilities. This is the model used in France and other countries with partly closed fuel cycles.

When the U.S. switched to the once-through fuel cycle, the waste management requirement to store SNF to allow reductions in decay heat before disposal was not addressed. By law the U.S. government was to begin to accept SNF from utilities by 1998; but federal law prohibited the building of a centralized SNF storage facility at the repository site to age the SNF to reduce radioactive decay heat until after the repository was licensed. The engineering solution to this legal constraint was to design a repository that could be ventilated for 50 years before closure to provide the time for the decay heat to decrease in the SNF. In effect, the proposed YM repository would become an underground SNF storage facility for 50 years after the last SNF is placed in the repository. Only after this cooling period is the decay heat low enough in the waste packages for the facility to become a repository. The constraints on SNF storage were (1) a major factor in the proposed Yucca Mountain design, cost, and performance characteristics and (2) responsible for many of its unique design features—good and bad. Delays in the repository program resulted in utilities developing at-reactor SNF storage systems (Chapter 4).

Some countries have integrated waste management and the fuel cycle. The Swedish repository program concluded that SNF storage was required in their system to reduce SNF decay heat before disposal and in 1985 opened its centralized SNF storage facility. France has developed a parallel system for a partly closed fuel cycle.

**Repository Options for Integrating Waste Management with the Fuel Cycle**

There are a wider set of options for integrating fuel cycles with waste management than generally recognized with different technical and policy implications. Several examples are described herein to illustrate some of the choices.

**Traditional Repository**

The U.S. has the choice to build repositories for all wastes requiring geological isolation or a repository for intermediate-level (low-heat) wastes and a second repository for high-heat wastes (SNF and HLW). WIPP, the existing U.S. repository designed for intermediate-level low-heat wastes, by law only accepts defense transuranic wastes—the largest category of long-lived low-heat radioactive wastes. The U.S. has small quantities of other intermediate wastes where there is no strategy for disposal and will continue to generate those wastes from defense facilities and the open fuel cycle. There are significant incentives to use WIPP for all such wastes that require geological isolation. This would be a small expansion of WIPP in terms of capacity—but would eliminate many classes of orphan wastes that are difficult to manage. An inquiry of and negotiation with the State of New Mexico is called for.

The performance of geological repositories is partly determined by waste form chemistry. With closed fuel cycles, waste forms can be selected with superior performance in a geological repository. For open fuel cycles the strategy is to develop whatever waste packages and other engineered barriers are necessary for direct disposal of SNF. There may be alternative strategies. For example, fuels might be designed with improved performance of the SNF in a repository environment (Appendix C). Another example could involve partitioning of
SNF to improve repository performance, perhaps by disposing of small amounts of selected actinides or long-lived fission products in deep boreholes.

**Repository with Multi-Century SNF Retrievability**

We do not know today if LWR SNF is a waste or a valuable resource. There is the option of building repositories for disposal of SNF where the SNF can be credibly retrieved if needed for many centuries. The planned French repository\(^{35}\) has retrievability of waste as an explicit design goal whereas the Swedish repository design would allow long-term retrievability although it is not a design goal. It is an option that minimizes waste burdens to future generations while maintaining options for future generations.

**Collocation and Integration of Repositories with Closed Fuel Cycle Facilities**

When the U.S. initially tried to implement a closed fuel cycle in the 1960s and 1970s, there was no repository; thus, the closed fuel-cycle model was created of separate siting of reprocessing, fuel fabrication, and repository facilities. If a repository is sited before adoption of a closed fuel cycle, there is the option (Appendix B) for closed fuel cycles to create a single backend fuel-cycle facility that (1) produces fuel elements for reactors using materials recovered from SNF, and (2) locally disposes of all wastes. Such a facility could potentially reduce closed fuel cycle costs and risks, improve repository performance while eliminating the need for long-term repository safeguards, and mitigate proliferation concerns. Collocating reprocessing and fuel fabrication facilities with the repository would provide thousands of jobs and other benefits to the community and state hosting the repository—a form of compensation.

**Alternative Waste Isolation Systems**

There is the option of building a traditional repository for most wastes and specialized facilities for difficult to manage wastes. For example, borehole disposal may offer superior waste isolation but with the restriction that it is not suitable for large waste volumes. It could enable economic small regional repositories for SNF. Enhanced isolation could be used for plutonium disposal without recovery to address proliferation concerns, disposal of high-hazard wastes (minor actinides and certain fission products), or disposal of high-heat wastes ($^{90}$Sr/$^{137}$Cs). It is an alternative to selective transmutation of radionuclides.

**RECOMMENDATIONS**

Based on the above findings, we make the following recommendations.

- **Waste management must become an integral part of the development of any fuel cycle, including an open fuel cycle. The impact of waste management must be included in cost and risk evaluations of alternative fuel cycles.**

- **The U.S. should map out and determine in a broad context the costs and risks of alternative options for integrating fuel cycles with waste management as a basis for future decisions. Alternative disposal options should be developed to provide long-term policy options for management of U.S. wastes and to support nonproliferation and other national security interests of the United States.**
CITATIONS AND NOTES


2. The Nuclear Regulatory Commission definition of HLW in 10CFR63.2 is “High-level radioactive waste or HLW means: (1) The highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations; (2) Irradiated reactor fuel; and (3) Other highly radioactive material that the Commission, consistent with existing law, determines by rule requires permanent isolation.”


9. WIPP is the only operating geological repository for radioactive wastes. There have been multiple pilot plants for radioactive waste geological repositories. Russia injected liquid HLW underground and the U.S. has injected high-activity wastes underground in the form of a cement grout.


14. The balances of the fund are only available when appropriated – these appropriations count toward total discretionary appropriations.


17. www.skb.se/default____24417.aspx

18. Title I, Subtitle F, Sec. 171(a) (1)


20. www.irsn.fr/FR/Pages/home.aspx


22. The U.S. Nuclear Regulatory Commission requires wastes be retrievable for 50 years.


27. France initiated a series of studies on French beliefs and implications for waste management.


