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End of FY10 Report – Used Fuel Disposition Technical Bases and Lessons Learned

Legal and Regulatory Framework for High-Level Waste Disposition in the United States

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Legal and Regulatory Framework for Implementation of High-Level Waste Disposition in the United States

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Abstract

This report examines the current policy, legal, and regulatory framework pertaining to used nuclear fuel and high level waste management in the United States. The goal is to identify potential changes that if made could add flexibility and possibly improve the chances of successfully implementing technical aspects of a nuclear waste policy. Experience suggests that the regulatory framework should be established prior to initiating future repository development. Concerning specifics of the regulatory framework, reasonable expectation as the standard of proof was successfully implemented and could be retained in the future; yet, the current classification system for radioactive waste, including hazardous constituents, warrants reexamination. Whether or not consideration of multiple sites are considered simultaneously in the future, inclusion of mechanisms such as deliberate use of performance assessment to manage site characterization would be wise. Because of experience gained here and abroad, diversity of geologic media is not particularly necessary as a criterion in site selection guidelines for multiple sites. Stepwise development of the repository program that includes flexibility also warrants serious consideration. Furthermore, integration of the waste management system from storage, transportation, and disposition, should be examined and would be facilitated by integration of the legal and regulatory framework. Finally, in order to enhance acceptability of future repository development, the national policy should be cognizant of those policy and technical attributes that enhance initial acceptance, and those policy and technical attributes that maintain and broaden credibility.

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Acronyms

AEC	Atomic Energy Commission
AFR	Away from Reactor
AMFM	Alternative Means of Financing and Management
ANL	Argonne National Laboratory
BLM	Bureau of Land Management
BRWM	Board of Radioactive Waste Management of NAS
CAM	Corrosion Allowance Material
CCA	Compliance Certification Application
CFR	Code of Federal Regulations
CHRBA	Calico Hills Risk/Benefit Analysis
CH-TRU	Contact-Handled Transuranic waste
CRCF	Canister Receipt and Closure Facility
CRM	Corrosion Restraint Material
CSNF	Commercial Spent Nuclear Fuel
DCSC	Dry Cask Storage Characterization
DHLW	Defense High Level Waste
DKM	Dual-permeability Model
DOE	Department of Energy
DSNF	DOE Spent Nuclear Fuel
DST	Drift-Scale Heater Test
EAs	Environmental Assessments
ECM	Equivalent Continuum Model
ECRB	Enhanced Characterization of the Repository Block
EIS	Environmental Impact Statement
EnPA	Energy Policy Act
EPA	Environmental Protection Agency
ERDA	Energy Research and Development Administration
FEP	Feature, event, or process
GTCC	Greater Than Class C (low-level waste)
HLW	High-Level Waste
INL	Idaho National Laboratory
LADS	License Application Design Selection
LANL	Los Alamos National Laboratory
LBT	Large-Block Test
LLNL	Lawrence Livermore National Laboratory
LLW	Low-Level Waste
M&O	Management and Operations
MPC	Multi-Purpose Canister
MRS	Monitored Retrievable Storage
MTHM	Metric Tons of Heavy Metal
NAS	National Academy of Science and Engineering
NC-EWDP	Nye County Early Warning Drilling Program
NEI	Nuclear Energy Institute
NEPA	National Environmental Policy Act
NRC	Nuclear Regulatory Commission
NTS	Nevada Test Site

NWPA	Nuclear Waste Policy Act
NWPAA	Nuclear Waste Policy Amendments Act
NWTRB	Nuclear Waste Technical Review Board
OECD	Organisation of Economic Co-operation and Development
PA	Performance Assessment
PFS	Private Fuel Storage
PNNL	Pacific Northwest National Lab
PSSE	Preliminary Site Suitability Evaluation
PWR	Pressurized Water Reactor
RCRA	Resource Conservation and Recovery Act
RH-TRU	Remote-Handled Transuranic Waste
RSSF	Retrievable Surface Storage Facility
R&D	Research and Development
S&ER	Science & Engineering Report
SAR	Safety Analysis Report
SCP	Site Characterization Plan
SHT	Single Heater Tests
SNF	Spent Nuclear Fuel
SPDV	Site and Preliminary Design Validation
SR	Site Recommendation
SZ	Saturated Zone
TAD	Transportation Aging Disposal
TBM	Tunnel Boring Machine
TEF	Test and Evaluation Facility
TESS	TRW Environmental Safety Systems
TPT	Test Prioritization Task
TRU	Transuranic
UNF	Used Nuclear Fuel
URL	Underground Research Laboratory
UZ	Unsaturated Zone
WHF	Wet Handling Facility
WIPP	Waste Isolation Pilot Plant
WIPP LWA	Waste Isolation Pilot Plant Land Withdrawal Act
WIR	Wastes Incidental to Reprocessing
YMP	Yucca Mountain Project

Executive Summary

Background

The Fuel Cycle Technology Program in the U.S. Department of Energy (DOE) Office of Nuclear Energy is investigating alternative nuclear fuel cycles to provide a basis for future decisions on the nuclear fuel cycle in the United States. The safe management and disposition of radioactive waste is an important aspect of the nuclear fuel cycle. Thus, the Fuel Cycle Technology Program established the Used Fuel Disposition Campaign to identify alternatives and conduct research and development to facilitate storage and disposal of used nuclear fuel and wastes generated by the current and alternative nuclear fuel cycles.

In this report, the Used Fuel Disposition Campaign examines the current policy, legal, and regulatory framework pertaining to used nuclear fuel and high level waste management in the United States. The goal of this effort is to identify potential changes that if made could add flexibility and possibly improve the chances of successfully implementing technical aspects of a nuclear waste policy under all fuel cycle scenarios while maintaining public health and safety. This effort will be conducted over several years. In 2010, the Used Fuel Disposition Campaign hosted a workshop involving a broad set of experts to help identify issues, lessons learned, and potential changes to the legal and regulatory structure. The results of this workshop and other activities to identify lessons learned are described in this report. In future years, specific issues identified in this report will be explored in more detail.

The following sections identify issues, lessons learned, and outline broad concepts for continued discussion of potential regulatory changes.

Waste Disposal Regulations

Disposal of radioactive wastes from the nuclear fuel cycle is subject to a range of regulations governing high-level waste (HLW), spent nuclear fuel (SNF) (i.e., used nuclear fuel—UNF—that has limited economic value), low-level waste (LLW), and mixed waste that contains non-radioactive hazardous materials in addition to radioactive materials. The regulatory framework is established by the *Nuclear Waste Policy Act of 1982* (NWPA), the *Nuclear Waste Policy Amendments Act* (NWPAA), the *Low Level Waste Policy Act* (LLWPA), the *Resource Conservation and Recovery Act* (RCRA), and other statutes. Pursuit of advanced fuel cycles and alternative disposal systems for HLW and UNF other than Yucca Mountain may require, or provide a strong incentive for, revisions to that structure. Several aspects of these regulations are discussed below. Also, important lessons can be learned from the construction and successful operation of the Waste Isolation Pilot Plant (WIPP), DOE's repository for defense transuranic (TRU) waste, and are included when they might also apply to disposal of disposal of defense and commercial HLW and UNF.

Performance Requirements for Spent Fuel and High-Level Waste

Pursuant to the Energy Policy Act of 1992, Yucca Mountain is regulated under site-specific requirements established by Environmental Protection Agency (EPA) in 40 CFR 197 and by Nuclear Regulatory Commission (NRC) in 10 CFR 63. Also, DOE siting guidelines at 10 CFR 963 were established to evaluate the suitability of the site. EPA's older 40 CFR 191 and NRC's older 10 CFR 60 establish the performance requirements for the disposal of wastes in a geologic repository other than at Yucca Mountain. Likewise, DOE's siting guidelines at 10 CFR 960 are still in force for site evaluations made pursuant to §112(b) of the NWPA. One might argue that because generic versions of the EPA and NRC regulations, as well as the DOE siting guidelines, are still in force, they could be used should the nation undertake another site screening program in the near future. However, the technical advances and policy changes that are reflected in the site-specific regulations for Yucca Mountain Project (YMP) and to some degree in the implementing regulation used at the WIPP have set precedents that would likely need to be considered for other repository regulations. Thus, it is likely that both the NRC and the EPA will need to review their disposal standards if other repository sites are considered, and DOE will need to revisit its siting guidelines in light of any changes to the EPA and NRC regulations. EPA may choose to promulgate a new regulation rather than revise 40 CFR 191 since 40 CFR 191 is currently in use at the WIPP.

Experience with WIPP and the YMP suggest that the regulatory framework should be established prior to initiating a future repository development program, with top-level repository regulations established before siting guidelines and site evaluation criteria are developed. While the National Academy of Sciences (NAS) noted in their 1990 report *Rethinking High-Level Waste Disposal* that the regulatory structure in the United States was rigid and inflexible and needed to be developed as the program moved forward, some did not find this to be an acceptable approach. Specifically, the development of the regulatory structure for YMP shows that every change to the EPA standard, the NRC implementing regulations, or the DOE siting guidelines was accompanied by objections by the State of Nevada and stakeholder organizations that the rules were being changed to fit the site; these objections were usually followed by lawsuits. Also, development of and changes to the regulations introduced delays during site characterization (e.g., size of saturated pathway to characterize) in an already lengthy process at Yucca Mountain. Ideally, the past 34-yr experience will make selection of a hazard indicator and its measure less trying in the future, so that the EPA standard can be established, then the NRC implementing regulation promulgated, and finally the site guidelines set prior to selection of a repository site.

Although unique at the time, the regulatory requirement to quantitatively treat uncertainty and use numerical models to evaluate system acceptability was successfully implemented. Consideration should be given to performance-based standards, without specification of rigid criteria for subsystems of the repository, similar to 40 CFR 197 and 10 CFR 63. They should be general and applicable to all sites and designs that could be considered. In addition, the regulatory revisions need to address the entire fuel cycle and take account of fuel cycle scenarios with projections of UNF, HLW, TRU, LLW, and wastes incidental to reprocessing (WIR). The regulations should recognize that multiple nuclear fuel cycle facilities might be combined at a single site (storage and disposal of HLW, disposal of some LLW with HLW, or storage, research, and reprocessing of UNF), and the regulations should be structured to facilitate such co-location without burdensome dual regulators or a need for multiple requests for exceptions through rule making and changes to the law.

Reasonable Expectation as the Standard of Proof

The EPA standards for WIPP and YMP were developed under the concept of reasonable expectation as the standard of proof for compliance. The concept of “reasonable expectation” is an integral part of the EPA standards, and application of a different standard of proof would in effect change those standards. The focus on the use of reasonable models and the full range of parameters is consistent with and supportive of a growing international recognition of the importance of showing an understanding of the performance of a repository system in addition to simply demonstrating compliance with quantitative disposal standards.

The concept of reasonable expectation has been successfully applied by the EPA in certifying and recertifying the 10,000-year performance of WIPP. Because substantial progress in clarifying the intent of reasonable expectation was made during the 34 years of deliberations leading to the promulgation of the final EPA and NRC regulations for WIPP and YMP, future regulations developed for other repositories should retain this clarification.

Retrievability

There are two distinct aspects of retrievability of waste that has been emplaced in a repository: recovery for economic value and retrievability, if necessary, to address public safety (e.g., to correct a problem identified after disposal, or to allow use of an improved disposition system). Regulations in the United States focus on retrievability for reasons of safety. These current retrievability requirements in EPA and NRC regulations did not cause difficulties at WIPP or Yucca Mountain, but they would impact other disposal technologies such as deep boreholes. Future regulations should maintain this clarification and consider clarifications made by the International Atomic Energy Agency (IAEA) and Nuclear Energy Agency (NEA) as well, which note the distinction of designing a repository to facilitate retrieval versus merely avoiding features that obstruct retrieval in a repository design.

The NWPA allows DOE to specify a period of retrievability for used fuel for economic purposes. Requirements to facilitate easy recovery of emplaced spent fuel for economic reuse, which have not been applied to US repository designs to date, could impose more significant constraints on geologic repositories. It may be preferable to initially dispose of HLW and legacy UNF that cannot be economically reprocessed. Any current and future UNF that might be economically attractive for reuse can be left in surface storage until uncertainties about its economic value are resolved. In that case, retrievability for safety reasons would be the only issue affecting repository design.

High-Level and Low-Level Waste Classification

As suggested by several professional societies and National Academies studies, revision to the classification system should be considered to support future fuel cycles. The current regulatory framework generally uses a source based waste classification system. HLW is defined in the NWPA to mean

A. 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; and

B. other highly radioactive material that the Commission, consistent with existing law, determines by rule requires permanent isolation.

Traditionally, the NRC and DOE have used the first aqueous extraction as the point of generation of HLW. However, a Natural Resources Defense Council lawsuit has prompted a re-evaluation. The federal court ruling focused on the word “including” which means an example and cannot be read to be limiting. In other words, HLW waste is any "highly radioactive material resulting from reprocessing;" it is not limited to material derived from the liquid waste of extraction. The lawsuit resulted in a provision in the Defense Authorization Act (in §3116) to provide some flexibility. The Waste Incidental to Reprocessing (WIR) process in §3116 allows flexibility in excising what can be considered "highly radioactive." However, this determination must be done with consultation of the NRC and the state, the process currently applies only to the States of Idaho and South Carolina, and process was designed specifically for the disposition of HLW in tanks.

LLW is defined by what it is not (i.e., LLW is radioactive waste that is not HLW, UNF, nor TRU waste. LLW is functionally characterized in 10 CFR 61.55, based on a scheme developed 30 yr ago. The characterization scheme focused on those radionuclides that caused the greatest concerns for human health and the environment in deterministic calculations that considered the radionuclides in LLW being generated at that time. The characterization system may not be appropriate for LLW resulting from advanced fuel cycles since this LLW may contain a different mix of radionuclides, in particular, higher concentrations of TRU radionuclides and fission products than used to develop the waste characterization and the disposal methods currently required in 10 CFR 61.

Advanced reprocessing methods could potentially separate radionuclides into a variety of waste streams, some being of lower risk to public health and safety. The current definition of HLW presents a disincentive to reprocessing by preventing potential cost savings from use of a more cost-effective disposal method for disposal of low-hazard waste streams that might result from alternative fuel cycles.

The NRC staff may consider revising both HLW and the LLW classifications, and DOE is undertaking a major review and revision of DOE Order 435.1 dealing with its own radioactive waste management activities, in parallel with NRC's update of 10 CFR 61. The lessons learned from application of the WIR process over the last 5 - 6 yr at the Savannah River Site and at Idaho National Laboratory should be considered in developing a revised classification system. The extensive classification system contained in a new Safety Guide issued by the International Atomic Energy Agency should also be considered in making revisions to the US system.

Hazardous Wastes (RCRA Regulation)

Radioactive wastes that also contain hazardous non-radioactive components are "mixed wastes." Mixed waste poses added institutional challenges because of the potential for dual regulation under the *Nuclear Waste Policy Act of 1982* or the *Low-Level Waste Policy Act of 1985* and the *Resource Conservation and Recovery Act (*RCRA). Furthermore, the different statutes are implemented by two or three different regulatory agencies (potentially EPA, NRC, and a state agency). As much as 60% of TRU waste destined for WIPP is mixed waste; thus, WIPP has dual regulation with both a federal and state regulator. While this dual regulation has been workable, it has proven difficult, time consuming, and costly.

To avoid dual regulation, the YMP prohibited acceptance of mixed waste except for any incidental mixed waste that might have been generated during waste handling operations. This acceptance criterion precluded use of some hazardous materials (e.g., lead) as part of the disposal system and may have eventually precluded disposal of some potential forms of defense waste. Some waste streams, both low- and high-level, generated by alternative fuel cycles may involve hazardous wastes that would be regulated by the EPA under RCRA, which would introduce this institutional complication.

Consideration should be given to establishing regulations to ensure that the both the radioactive and hazardous components are addressed while avoiding dual regulation. This might be done with an integrated health-based regulation, rather than a radiation dose-based regulation. Alternatively, regulations could focus on the most hazardous component of the waste (generally the radioactive materials) and exempt HLW geologic repositories from application of RCRA requirements, which were developed for near surface disposal. A performance assessment could be used to show that the contribution of the hazardous materials to overall risk would be minor. Such a framework is described by the National Council of Radiologic Protection and Measurements.

Site Screening and Evaluation

The NWPA set up a detailed process for screening potential repository sites, selecting a small number for detailed evaluation, and then characterizing those sites in great detail. This process was truncated by the 1987 amendments that limited characterization to the Yucca Mountain site. Experience with implementing this process should be considered in developing any new siting process for future repositories.

Siting Guidelines

Under the NWPA, DOE issued guidelines for the repository siting process (10 CFR 960) that were used for selecting the three sites recommended for characterization in 1986. The criteria established in these regulations are generally framed in terms of favorable and potentially adverse conditions, with several disqualifying features specified in the NWPA. Following the promulgation of 40 CFR 197 and 10 CFR 63 for Yucca Mountain, DOE issued a new set of siting guidelines (10 CFR 963) for determining the suitability of Yucca Mountain that focused on total system performance, consistent with the EPA and NRC regulations.

New siting guidelines may need to be developed for a future repository program. As with the establishment of overall performance requirements, developing these in advance of the siting process and using them consistently can avoid delays and increase public confidence by potentially avoiding the perception that the regulations have been specifically crafted to facilitate selection or a determination of suitability for the site in question. However, while developing a regulation early has advantages, it also has a risk of setting a path that the site screening process might not be able to follow effectively.

New or revised guidelines should recognize that there is no such thing as a perfect site and that the objective is to select, characterize, and develop a site that is protective of public health and safety. While simplicity is desirable, absolutes such as rigid pass/fail disqualifying conditions should be avoided if possible, since they can lead to gaming the process to exclude specific sites for other reasons and to rejection of sites that might not meet a rigid criterion but that could still safely host a repository that fully meets disposal requirements. Again, establishment of an overall performance standard prior to setting siting guidelines would help address this issue.

The question of how siting guidelines would be applied at different stages of the process should also be addressed. For example, guidelines favoring simplicity of sites, must consider the reality that the more a site is studied, the more complexity that is revealed. Features may be discovered during detailed site characterization that would be inconsistent with initial screening criteria but would not adversely affect the ability to develop a safe repository. Hence, while simplicity may be an initial selection criterion, complexity discovered during site characterization should not be a disqualifying criterion.

One important lesson to be learned from the siting process in NWPA, as implemented in 10 CFR 960, is that the medium under consideration was not a principal discriminator in the siting process. Under 10 CFR 960, decisions about the medium are quite far down in the decision sequence, and enter only because there is a requirement for diversity in the geologic media in NWPA. Work in the US program in the early and mid 1980s suggesting the potential viability of salt, granite, and clay/shale as disposal media has been confirmed by extensive work internationally. Hence, while several sites may be simultaneously under study in the future (e.g., to reduce program risk or because of social-political issues), diversity of geologic media is not necessary and should not be required in any new legislation. In fact, the consideration two sites in similar media, as done by Sweden and Finland, might allow (a) more cost effective site characterization through joint efforts, (b) more similar engineered barrier designs, and (c) allow other parts of the waste management system to prepare for one type of media rather than several.

Site Screening

The NWPA limits the DOE to using available geophysical, geologic, geochemical, hydrologic and other information to evaluate sites for the recommendation of sites for characterization. With limited exceptions, no new preliminary borings or excavations could be conducted at any site. Limiting characterization to already-available data could bias decisions either toward or against sites for which the most data already exists. Allowing limited additional work at a subset of the sites initially identified for investigation in order to provide an equal level of knowledge to support decisions about which sites are worthy of extensive characterization should be seriously considered.

Site Characterization Requirements

When NRC's original repository regulations (10 CFR 60) were developed, the NRC expected that the *in-situ* site characterization required by the regulation would involve ~1000 feet of underground excavation and cost less than $60 million. By the time the first three sites were recommended for characterization in 1986, the estimated cost of characterization had increased to over $1 billion per site and provided a major rationale for the decision to limit characterization to one site. Continued high costs for site characterization may continue to be an obstacle to characterization of multiple sites.

Experience with characterizing the WIPP and YMP sites showed that once a site is selected for detailed evaluation, the focus moves to uncertainties and the question becomes one of whether enough work has been done to resolve them. The data needs related to uncertainty become driving factors, leading to significantly increasing costs and schedules, if unconstrained, which could occur at every site that is identified for potential selection. Program scientists tend to propose a broad set of activities that could be conducted to address uncertainty. Program managers sometimes have difficulty assessing whether they need to be done without established performance requirements to guide the program.

To counteract the tendency to expand site evaluation activities beyond what is necessary for siting and licensing decisions, several approaches can be applied. First, the regulatory framework should be established in advance of the siting process. Second, selection of multiple sites in similar media may provide both the regulator and the investigating organization a better perspective because relative uncertainties can be compared rather than abstract absolute uncertainties. Third, use of performance assessment (PA) to prioritize data collection needs has proved useful both in the US and internationally, provided the regulations give clear guidance concerning performance measures and scenarios to consider.

Non-Site-Specific Research and Development

The schedule for siting and developing geologic repositories is undetermined, pending the recommendations of the *Blue-Ribbon Commission on America's Nuclear Future* and any subsequent Congressional action to provide the necessary legislative authority for a new repository program. While the US reevaluates nuclear waste management policies, it is important to enable continued development and maintain progress over the next several years in (1) research and development in repository science and (2) technology development in repository operations. Hence, the DOE should consider the use of test facilities and activities that are independent of a particular site. In the near term, progress in repository science can be maintained at international underground laboratories. Technology development in repository operations could be achieved as part of technology development for storage and could occur at existing DOE facilities with nuclear industry participation.

Underground Research Laboratories

A number of countries have developed underground research laboratories (URLs) as an important part of their repository development process. In some, but not all, cases the URLs are at sites that are not expected to be developed into repositories. The DOE cooperated in some of these activities before work was terminated following the 1987 amendments to NWPA. In the US, several small offsite test facilities were used during the repository development program, with work later moved to site-specific facilities sites after selection of sites. For example, the WIPP included an experimental area that was used to evaluate salt creep, brine inflow, and effects of emplacement high-level waste in salt and the YMP bored a tunnel to the proposed repository horizon and excavated several alcoves where a variety of tests were conducted.

For the next several years, there is no clear need for the US to develop generic URLs for purposes of obtaining information about long-term repository performance unless they are in geologic media or technologies where a URL does not currently exist somewhere abroad such as deep borehole disposal research. Although URL data can provide supporting analog information, the current US regulatory framework requires site-specific information and it is difficult to translate general information gained in URL studies to specific sites. This situation is not expected to change in the future.

In the near term, domestic fundamental research and development needs concerning long term repository performance can be met by gaining access to and collaboratively conducting experiments in URLs in other countries. Several international programs maintain and fund limited research collaborations with individual US principal investigators. DOE should broaden and formalize these collaborations to initiate a formal research program to understand key repository processes in alternative geologic media in a time- and cost-effective method.

If the US foregoes repository siting for an extended period of time, studies in a domestic URL and studies of analog sites would help maintain repository development expertise, and would not have to be associated with a specific site. Although the DOE did not exercise the option to develop, the NWPA provides authority for a Test and Evaluation Facility (TEF) at or away from a repository site that could be used as a model for future legislation. Once a geologic medium (or media) and sites have been selected for detailed characterization within the US, URLs at the sites should be established as soon as possible. The insights gained from working in a real geologic system are invaluable and can reveal unexpected conditions much earlier.

A potential ancillary benefit of URLs is that they might help improve regulatory confidence about radioactive waste management by demonstrating fundamental understanding of disposal and operational concepts. URLs are also a vehicle to involve local universities and state oversight agencies in characterization efforts at the very beginning of site characterization. Such research facilities could also be part of a storage site.

Test Facilities for Repository Operations

Implementation of a national system for management of spent fuel and high-level waste will require routine and reliable handling of waste materials at unprecedented amounts and rates, substantially higher than those facing other countries. If decisions about siting and operating large-scale waste management facilities are deferred, ways to continue developing the capability should be considered; specifically, deploying a technology development facility should considered.

The benefits of a technology development facility have been identified before, since provisions of the NWPA concerning a test and evaluation facility (TEF), mentioned above, were also intended to provide data on the operational aspects of a repository (waste packaging, handling, and emplacement). A technology development facility would allow for the development of first-of-a-kind operational techniques that under the current policy framework will not be tested until a repository is constructed and operating. A technology development facility could be generic and independent of any site being considered. Collaborations with nuclear industry to develop and operate facilities to test the capability to handle, transport, and package UNF would be beneficial and could be combined with studies on long-term storage and studies integrating nuclear waste handling, storage, and transportation. Conceivably, collaboration with nuclear industry could occur at NRC licensed storage sites, but regulatory and statutory authority may be needed to include technology development at these sites. However, the TEF provisions of the NWPA authorized DOE to use its existing facilities for conducting “generically applicable tests regarding packaging, handling, and emplacement technology for solidified high level radioactive waste and spent nuclear fuel from civilian nuclear activities” and may serve as a model for future policy. These provisions, perhaps with some modifications, would allow interim steps towards full-scale operations that would support stepwise waste management system deployment.

Stepwise System Development

Both YMP and WIPP moved through several phases of site evaluation and repository development. In each project, the process took considerably longer than expected and adjustments had to be made as new information became available. Flexibility to adapt to changing circumstances was shown to be an important attribute of success. Those experiences provide insights that could help shape any new US repository development program.

Staged Development for Future Repositories

The development scenario that has long been used as the basis for analysis of geologic repositories in the US and that is the reference plan described in the Yucca Mountain License application involves rapid siting and construction of full-scale repository facilities, followed by ramping up to shipping and disposing of spent fuel at a rate of 3000 tons per year as rapidly as feasible after NRC approval. This scenario was initially developed at a time when spent fuel would not be reprocessed, and when it was assumed that disposal of spent fuel in the repository would be the way to meet the contractual obligation to accept spent fuel from utilities. Those assumptions are no longer widely accepted. Slower, more stepwise repository development scenarios focusing on earlier demonstration of disposal capability rather than full-scale disposal have been explored, and the final modular repository design developed for the license application could accommodate such scenarios. Developing and demonstrating the capability to dispose SNF/HLW may be a more important near-term objective rather than rapidly implementing that capability on a large scale. Hence, an adaptive staging approach for stepwise repository development appears more suited to current needs.

The charter for the *Blue-Ribbon Commission on America's Nuclear Future* says that it will consider "Options for decision-making processes for management and disposal that are flexible, adaptive, and responsive." The management approach called "adaptive staging" recommended in the 2003 report from the National Academies (*One Step at a Time: The Staged Development of Geologic Repositories for High-Level Radioactive Waste*) as "a promising means to develop geologic repositories for high-level waste such as the proposed repository at Yucca Mountain, Nevada," appears relevant to this aspect of the Commission's task. This NAS report described adaptive staging as "a learn-as-you-go process that enables project managers to continuously reevaluate and adjust the program in response to new knowledge and stakeholder input." The Organisation of Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA) reported in 2004 (*Stepwise Approach to Decision Making for Long-Term Radioactive Waste Management—Experience, Issues, and Guiding Principles*) that staged development (adaptive staging) is attracting increasing attention internationally as a means to increase the societal acceptability of waste management activities.

The current regulatory and statutory structure appears to be consistent with at least some forms of staging (e.g. constructing the repository facilities in a stepwise manner beginning with pilot scale facilities after a construction authorization for the full repository is granted). However, it would be helpful for new legislation and regulations to explicitly recognize and facilitate staged development. Furthermore, it would be helpful for new generic repository regulations to be crafted to ensure that appropriate interactions with the regulator, such as the Key Technical Issue interactions related to Yucca Mountain, can take place as an important part of a staged development process. A useful model may be in the EPA process for certifying WIPP's compliance with the performance standard via an open rulemaking process rather than a litigated adjudicatory licensing process, which was particularly conducive to open and continued external interactions by project scientists all the way through the certification process.

Flexible Decision-Making

The experiences with WIPP and YMP underlined the importance of flexible decision-making, including (a) the ability to stop and make design changes, and (b) the development of designs that facilitate flexible responses to changing conditions. Flexibility in decision-making is a fundamental aspect of staged development. Contingencies identified that require flexible planning and decision-making include:

1. Uncertainty in the availability and timing of new waste management facility sites and any operational constraints (e.g., capacity limits) that may be imposed on them.
2. Potential need for design or operating mode changes after a repository has received an initial license.
3. Constrained and/or uncertain funding.
4. Uncertainties about future fuel cycles and the associated amounts, types, and timing of waste forms requiring storage and disposal.
5. Uncertainties about the ability to retrieve, transport, and handle UNF after extended storage periods.

An important aspect of flexibility is the ability of the regulatory process to address and make decisions about proposed changes. Sufficient resources and administrative capacity must be maintained for the licensee to develop the scientific and technical basis for proposed changes and for the regulators to review and decide upon such proposals in a timely manner. Hence, continuous support is needed to maintain these capabilities in the waste management program and the regulators during the operating period following initial facility licensing.

Impact of Funding

The clear intent of Congress was that the funding mechanism created by the NWPA in 1982 (the nuclear waste fee and the Nuclear Waste Fund) would free the program from the normal competition for funds within the federal budget process. With the passage of budget deficit control legislation in 1985 that affected expenditures from the Nuclear Waste Fund, this mechanism has not worked as originally intended. Annual appropriations were unpredictable and generally fell short of the levels the waste management program needed to maintain steady progress. This had adverse impacts on the program schedule and caused deferral of some site characterization and design activities that led to problems later.

This experience underlines the necessity of providing funding that is stable, predictable, and available as needed to meet peak demands (e.g., for repository design and construction). To provide confidence in the development of repositories over the periods of decades involved, the funding mechanism needs to assure availability of the level of funds required by the program implementation plan, instead of having funding constraints determine the achievable program. However, in the absence of a high degree of confidence in the availability of funds as needed, staged repository development is a means for the waste management system to better accommodate constrained funding and changes in funding.

Storage and Transportation of Used/Spent Nuclear Fuel

Without a repository at Yucca Mountain for disposal and no plans for reprocessing facilities, the lack of an identified disposition path for commercial UNF makes the time period for storage uncertain and possibly longer than the current regulatory threshold of 60 years. Much longer periods – as much as 500 years – have been discussed. Such long time periods raise technical, regulatory, and policy questions that have not been addressed to date.

Technical Considerations

Protection of public health and safety during storage, transportation, and eventually final disposition through reprocessing or disposal will always be the primary goal of the waste management system. An important question, however, is the cost to provide the required level of safety. In concept, retrieval of

UNF from long term storage after 100 year or so could involve constructing a new large handling facility at each reactor and long-term storage site to process the storage canisters and the UNF fuel inside such that the processed material is safe for transport and disposition at some other location. Although this could be a planned option, it would be somewhat similar to the situation occurring at the Hanford storage site. Because there could be unforeseen problems with removing the UNF from storage containers for reprocessing or disposal, other schemes for retrieval of UNF from long-term storage might involve use of design features such that construction of a new handling and processing facility at each site would not be necessary. Planning and development of storage systems for eventual retrieval from storage without resorting to construction of extensive new retrieval process facilities might provide future generations more flexibility by making retrieval easier and more economical.

Before regulations are contemplated, basic knowledge of the likely and potential extreme degradation of storage casks and inner canisters and UNF after long-term storage must be obtained. Operating reactors are discharging fuel with increasingly higher burnups. This new situation raises additional questions about physical and chemical reactions in storage over the long term (i.e., integrity of the cladding) that could lead to assembly deterioration of commercial UNF. Therefore, a need exists for analysis of possible changes to fuel design that might reduce degradation in long-term storage.

Several dry cask storage designs use reinforced concrete overpacks for dry surface storage of UNF. With less than a century of experience with modern cements, the binder compounds for modern concrete, and the interaction of cement and reinforcing metal structures, the possibility of storage for periods on the order of a century or longer suggests a need for additional investigation regarding the long-term performance of reinforced concrete and any advisable design changes. A need also exists for design changes to canister designs to mitigate the consequences of degradation that will occur. Knowledge acquired in developing corrosion resistant disposal containers in an oxidizing environment at YMP might be applied to developing corrosion resistant handling canisters suitable for storage over 500 yr.

During the last four decades, DOE and its predecessor agencies have generated approximately 250 varieties of SNF from weapons production, nuclear propulsion, and research missions. In addition, a variety of forms of SNF have been accepted from other sources. With the exception of small quantities of commercial UNF included in the latter category, the existing technical basis for storage of commercial UNF for up to 60 years is not directly applicable to storage and subsequent retrieval and transportation of the DOE spent fuel inventory. DOE will need to develop this technical basis for its SNF.

Regulatory Considerations

NRC is already addressing the question of updating storage regulations in light of the increase in projected storage time length to 300 to 500 years. Transportation regulations have not been redrafted since the terrorists attacks on 9/11/2001; however, NRC is prepared to revise these regulations, drawing upon on technical information provided by DOE and its own studies. EPA regulations may also need updating, because 40 CFR Part 190 was developed in 1977 based on short-term storage. It may be appropriate to reexamine the need for dual regulation of facility operations by NRC and EPA.

Current storage regulations allow reliance on administrative controls to guarantee safety and security for no more than 100 years. The role of administrative controls will need to be reconsidered while revising storage regulations to accommodate long storage times. Furthermore, it is not clear what type of assurance will be required and the practical time limit for such assurance for retrieval from long-term storage (i.e., will the standard of proof be reasonable assurance or reasonable expectation at 100 to 500 years?). A very small percentage of UNF might be in the form of damaged assemblies, rubble, or even granular solids after long-term storage in extreme cases. Hence, questions also exist as to how the regulations will want a licensee to deal with extreme cases, and whether the waste management system should anticipate that the development of storage regulations for such long time frames will be similar to those developed for disposal and thus require probabilistic simulation and evaluation of unlikely disturbances to the system.

Long term storage raises issues concerning self protection and security. Radiation from UNF falls below the “self protecting” level after ~100 years of storage, and this period is only slightly longer (120 yr) for high-burnup fuel. Under current regulations, storage after 100 to 120 years could require more stringent and expensive provisions for safeguards and security. This might affect decisions about when it is cost-effective to remove UNF from reactor sites. Obviously, however, a massive storage cask, mitigates against easy diversion and, to some extent, sabotage. Hence, adoption of some form of terrorist attractiveness rankings as a basis for security requirements is needed. The attractiveness rankings developed by DOE can be used as a starting point.

Policy Questions

A key policy question is where long-term storage should occur—at current sites, regional sites, or a centralized site. The long history of resistance to repeated efforts to site central storage facilities beginning with the Atomic Energy Commission (AEC) proposal for a Retrievable Surface Storage Facility (RSSF) in 1970, strongly indicates that gaining acceptance of a facility solely for storage will still be difficult. Survey results concerning public preferences for storage at current sites, regional sites, or two centralized sites are discussed later.

Articulation of a clear rationale for the eventual movement of UNF from existing sites to other facilities for long-term or permanent disposition is an important need. An objection that was raised to the YMP was that no compelling reason had been given for moving UNF from existing sites any time soon, in view of the safety of continued onsite storage. On the other hand, it is clear that permanent surface storage at reactor sites is not a preferred solution.

So called “orphan” sites (i.e., sites that no longer have an operating reactor and may have no facilities at all other than dry storage systems for UNF) raise special issues with respect to the rationale for movement of the UNF stored there. Fuel/canister degradation and decreasing self-protection could provide sufficient motivation for moving fuel from such sites sooner rather than later. With no operating reactor at a site, the full costs of security are attributable to the continued presence of UNF onsite. If any technical difficulties arise after extended storage that necessitated reopening and recovering fuel from storage containers, new handling facilities will have to be built and licensed at each site. These considerations could significantly affect the cost/benefit analysis of removing fuel from these orphan sites to centralized facilities. Further analysis of the issues affecting storage at orphan sites is needed as a basis for both regulatory and policy development. Unless steps are taken to prevent it, the waste management system in the US will continue to evolve on its own in the direction of having substantial quantities of orphaned waste with no ability to repackage or transport if problems occur after 100 yr or more of storage. Better integration of the waste management system may avoid this issue.

Integrated Waste Management System Design

The pre-closure aspects of the waste management system—storage, transportation, and waste packaging, and emplacement at the repository—involve significant challenges because of the large scale operations required to manage and dispose of existing and projected US inventories of SNF and HLW. Without a clear long term plan, individual participants will tend to optimize their own piece of the system based on their own immediate needs, without regard to overall costs and complexity. Without action to develop such a plan, the US will have (1) multiple canister sizes optimized for each reactor site based on their own immediate needs, with substantial amounts stored at orphan sites as discussed above; (2) a contract that allows UNF of various ages to be sent from each reactor site without coordination with transportation and repository operations, based on the immediate needs at the site; and (3) little integration of storage, transportation, and disposal regulations.

Integration between Storage and Disposal Canister Designs

One key area of interdependence between UNF storage and its potential direct disposal is the canisters that are used for storage. Without clear direction and policy decisions, the situation with storage and transportation containers will remain as it is today: storage in many large but different canisters at each individual nuclear utility site. The storage containers are not routinely designed to be reopened for easy repackaging, and the extra handling steps to do that would result in significant exposure and cost.

The challenges of designing licensable waste packaging buildings that would handle bare fuel at very high rates at YMP led to a decision to minimize the problem by integrating the UNF management system using transportation-aging-disposal (TAD) canisters loaded at reactors and never reopened later. Because the large emplacement drifts and gently-sloped access ramps proposed for the Yucca Mountain repository allowed use of very large waste packages, the TAD canisters were able to have a high capacity that was consistent with the desire of utilities to load spent fuel into large containers for storage and transportation. However, other repository sites and designs potentially require use of smaller canisters. There is currently no assurance that canisters of the size of the TAD can be lowered safely down vertical shafts. The equipment does not exist and standard mining practices do not necessitate its development. Similarly, borehole disposal would have a diameter constraint.

DOE should initiate and coordinate analysis to determine whether UNF canisterization and the size of the current canisters in storage casks makes sense in the face of uncertainty about the size of waste package that would be feasible and about how much UNF might be reprocessed. The analysis will need to evaluate the implication for canisterization based on a range of repository media, waste packages, and facility designs. For example, it may be desirable to canisterize in smaller containers that can be bundled into larger overpacks for storage and transportation.

If such evaluation shows that use of standardized canisters would be cost-effective for the waste management system, the question of how to provide incentives for utilities to use such canisters will need to be addressed. The utilities now appear to have little incentive to implement changes in canisterization that might increase initial storage costs while reducing long-term system costs because the federal Judgment Fund will increasingly be paying for storage at reactor sites, and assurances may be required that increased costs incurred because of changes in storage practices would be eligible for compensation.

Integration of Waste Streams

Radioactive waste disposal planning currently assumes separate disposal facilities for HLW and LLW, and a single disposal facility for HLW and UNF from both defense and civilian activities. Both assumptions warrant reconsideration.

Integrated Disposal of Other Radioactive Waste in a Repository

Current statute and regulation define separate disposal pathways for (1) high-level waste/used nuclear fuel (using geologic disposal); (2) LLW types A, B, and C (using shallow land burial); and (3) Greater than Class C (GTCC) LLW (using geologic disposal unless another method approved by NRC). The disposal pathways for these three waste types (i.e., shallow land burial and geologic disposal) are based on the waste hazard and cost for disposal (e.g., LLW requires the lowest degree of isolation and thus incurs the lowest cost). Although the NRC designated geologic disposal for GTCC LLW, integration of the LLW and HLW regulations would facilitate implementation of this requirement. Furthermore, the flexibility to dispose of LLW generated during repository and/or reprocessing operations in a single repository could be advantageous, particularly if there are regulatory changes to allow easy implementation.

A technical evaluation of such concepts by DOE would contribute to the reconsideration of HLW/SNF and LLW disposal regulations. For example, it may be possible to use rooms or drifts for low- or non-heat generating wastes (e.g., GTCC LLW) without requiring significant additional excavation. Such integrated disposal concepts might be able to reduce total fuel cycle waste disposal costs for small amounts of LLW, because the front-end costs of developing a high-level waste repository will have to be borne in any event and the incremental cost of disposing of other wastes in the unused areas may be low, provided the LLW and HLW regulations are integrated as discussed in a later section.

Decoupled Disposal of Defense and Commercial HLW/SNF

Current waste management system planning has been based on completely integrated and synchronous co-disposal of defense and commercial waste in the same repository, following a presidential determination in 1985 that a separate repository would not be necessary. However, less tightly coupled disposal plans warrant consideration in view of the current uncertainty about the timing of production of the defense high-level waste forms for disposal and about the timing and relative amounts of commercial used fuel and high-level waste to be disposed. Other options include (1) disposal in the same repository but (a) sequential emplacement of defense waste followed by portions of the commercial waste or (b) decoupled emplacement of defense and commercial waste in designated areas of the same repository, or (2) use of separate repositories developed at different times for defense and commercial waste.

No statutory or regulatory obstacles to such options have been identified, although disposal in separate defense and commercial repositories would require revisiting the 1985 determination that separate repositories are not required. Repositories solely for defense wastes (subject to NRC regulation) are allowed by the NWPA, but that approach might preclude future use for non-defense wastes. Sequential or decoupled emplacement of defense and commercial waste in the same repository could be part of a stepwise development plan, in which disposal begins with materials having little or no prospect of future reuse, or for defense waste, which may find greater public or state acceptance than commercial waste. This approach can be accommodated within the current legal structure because NWPA allows NRC to consider an application for "all or part of a repository."

Integration between UNF Contract and Repository Operations

The current contract between the utilities and DOE does not allow DOE, the operator of the repository, much control as to the type and age of UNF sent to the repository. Instead the repository operations must plan for a variety of receipt scenarios. Although designing and constructing facilities with flexibility is desirable, the inability to plan an operating receipt schedule poses challenges to both operational efficiency and feasibility. Planning at the storage/disposal facility would benefit greatly if the facility could manage the types and age of UNF received. The facility could combine UNF types and ages to maintain high radiation during transportation for security, and maintain more uniform heat loads within the repository without excessive aging at the repository. Control of the age and type of UNF received would also be beneficial if the storage/disposal facility were combined with reprocessing facilities as might occur in the future.

Integration of Regulations

At present there are separate legal and regulatory frameworks for reactors, storage, transportation, and disposal. These regulatory frameworks were developed over time around the current once-through fuel cycle. Having to design and operate the waste management system under multiple regulations (e.g., 10 CFR 71 for transportation, 10 CFR 72 for storage, and 10 CFR 63 for disposal at Yucca Mountain) poses challenges. For example, the requirement of 10 CFR 63 to evaluate the consequences of events with a frequency as low as 10^{-6}/year during the operational period had an impact on the design of the TAD canister that was not otherwise required under 10 CFR 71 or 10 CFR 72. It can also make handling facilities at reactor sites less costly than at a repository. The NRC is currently undertaking an integrated review of its UNF/HLW storage, transportation, and disposal regulations. If the regulations are integrated, future storage, transportation, and disposal could be better integrated. Specifically, the DOE should encourage the regulator to develop a single set of uniform regulatory requirements for spent fuel casks that spans the storage, transportation, and waste disposal phases. As noted above, the DOE should also encourage the regulator to integrate HLW and LLW disposal regulations to facilitate disposal of GTCC LLW and LLW produced during repository operations in the HLW repository. Without such integration, it is likely that two entities would be regulating the facility (e.g., NRC for HLW and possibly GTCC LLW, and usually the host state for LLW, both using EPA or equivalent standards).

Compatibility with Alternative Fuel Cycles and Disposal Systems

When the current statutory and regulatory structure was developed, it was widely anticipated that commercial waste management would primarily involve direct disposal of light water reactor (LWR) spent fuel in a mined, geologic repository. With renewed interest in reprocessing, possible advanced separations and transmutation, advanced reactor types, and the potential for alternative disposal systems, reconsideration of the current structure is appropriate to determine whether modifications would be needed to ensure compatibility with such changes and/or to ensure that alternative fuel cycle decisions are not unwittingly biased by unforeseen effects of legislative or regulatory requirements.

Compatibility with Alternative Fuel Cycles

Impact of Nuclear Waste Fee Structure

One of the potential advantages of reprocessing and recycling is the possible reduction in the cost of disposal of the resulting high level waste form compared to spent fuel because of the reduction in volume and heat output of the waste. However, the current statutory fee structure in NWPA does not distinguish between UNF and reprocessed waste, between different high-level waste forms involving different degrees of partitioning and transmutation, or between significantly different UNF forms (e.g., light water reactor used fuel, mixed oxide used fuel, or advanced reactor fuel). Yet, these different waste forms may have different costs for management and disposal. The current fee mechanism, which does not reflect these differences to the owners and generators of waste, eliminates incentives to take actions that could reduce total waste management system cost or otherwise benefit the waste management system.

Providing fee adjustments or rebates for any actions taken by waste owners/generators to reduce the disposal burden merit consideration. However, additional technical analysis is needed to determine (1) the potential reduction in disposal burden both (a) on repository performance (if any) and (b) on operational waste handling costs; and (2) how such rebates/reductions would be calculated. In addition, the possibility that some waste forms (e.g. advanced reactor UNF) might increase disposal costs should be evaluated. If analysis show that costs differences are measureable, explicit statutory language may be needed to enable or direct an approach that would link disposal charges to the actual cost of disposal.

Compatibility with Alternative Disposal Systems

The NWPA selected mined, geologic repositories for disposal of commercially-generated high-level but directed continued research on subseabed and deep borehole disposal as potential backup technologies; however, little funding has been provided since.

Although the Seabed Working Group of the Nuclear Energy Agency concluded after 11 years of research that subseabed burial was technically feasible for disposing HLW and SNF, interest in subseabed disposal is dormant because it is now prohibited under the London Dumping Convention. International agreement would be needed to enable its use.

The advances in drilling technology have decreased the costs and increased the probability of successfully implementing a deep borehole disposal program for low-volume, HLW with the potential for excellent long-term isolation at costs competitive with mined repositories. However, at present there is no statutory or regulatory framework governing siting, construction, and operation of any long-term disposal systems other than mined, geologic repositories.

Another long term disposition option that has been suggested is the use of heavily engineered above ground storage facilities (such as an elaborate, engineered mountain). This concept would likely raise new regulatory issues related to how to address human intrusion and whether institutional controls can be relied upon over long time periods to prevent human intrusion or repair damage or deterioration, as previous mentioned for long-term storage.

Enhancing Acceptability and Credibility of Repository Development

Perceptions of nuclear energy provide the context in which siting issues are perceived. The Used Fuel Disposition Campaign took advantage of a national survey Sandia National Laboratories conducts annually on security issues such as energy and added several questions related to nuclear waste disposal with the goal of identifying what might enhance acceptability and credibility of repository development. The questions delved into the public perception of the risks and benefits of nuclear energy, the perception of current waste management practices, and design attributes of a repository (e.g., number, depth, and type)

As reported herein, the US public is supportive of nuclear energy, and in recent years has consistently expressed support for expanded reliance on nuclear energy. The risks of nuclear energy, overall, are seen to be slightly less than those from fossil fuels. At the same time, average US residents do not seek information about and, thus, remain generally uninformed about the current policies for managing UNF, though trends suggest that awareness is growing.

The following discussion has been divided into two aspects of a UNF management facility: (1) policy and technical attributes that enhance initial acceptance of a facility, and (2) policy and technical processes that maintain credibility and broaden acceptance.

Enhancing Initial Acceptability

Survey research shows public attitudes toward UNF management options are sensitive to specified policy design elements. Retrievability is generally preferred, both because the public views UNF as a possible future resource and because the public prefers to retain the option to revise UNF storage strategies in light of new learning. Survey research shows that the public favors retaining the option for reprocessing UNF by a two-to-one majority.

Survey research shows that specific facility design elements can substantially alter the level of public support for storage/disposal facility siting. Public support for a UNF repository is increased substantially if it is combined with a national laboratory focused on increasing safety of UNF storage. Rather than separating storage/disposal function, combining the storage/disposal facility with reprocessing UNF also increases public support for siting the storage/disposal facility. Overall, it appears that combining a storage/disposal repository with other UNF management functions to construct a facility that seeks to examine and eventually solve many of the risk issues involved with nuclear material reduces the negative, stigmatizing imagery attached to strictly disposal facilities that, by their very function, treat these materials solely as a waste.

In 2010, 40% of the respondents surveyed opposed indefinite on-site storage and 34% were undecided. The remaining 26% favored continuing the current practice. These responses indicate that, although the public is decidedly uneasy about indefinite on-site storage, there remains sufficient latitude (with a third of the public undecided) for determining an acceptable option.

Mean preferences for continued on-site storage and between six and eight regional storage/disposal facilities are statistically indistinguishable; both are preferred over two centralized storage/disposal facilities. Although strong preferences for the number of storage/disposal facilities have yet to develop, support for a larger number of sites—whether regional or continued at reactors—was greater than support for two centralized sites. This suggests that the public would not rule out multiple storage/disposal facilities, in concept.

Maintaining Credibility

The experience at Yucca Mountain shows that scientists and engineers and their work products alone cannot resolve initial state and public concerns about accepting nuclear waste storage or disposal facilities. At the same time, the experience at WIPP shows that the credibility of the science and engineering underlying waste management program is a necessary condition for achieving acceptability once a community has entertained the idea of hosting a UNF management facility.

Direct interactions of the technical staff with peer review groups, the host state, and the public is an important aspect of the openness and transparency that is a key need in the repository siting and development process. Collaboration with the host state university system, interactions with public safety officers, site visits, and engagement with the National Academy of Sciences and other external reviewer groups have proved to be beneficial. The organizational structure at WIPP with a science advisor and lead science organization, which had an identity separate from the DOE and the Management and Operator Contractor, was important to maintaining the visibility and independence of science. It was useful for establishing and maintaining credibility for the science advisor to also inform the public and state about problems or unexpected results that have been encountered since they could explain the significance of the results.

Publication of scientific results in the peer-reviewed literature is an important way to enhance credibility and transparency. Peer reviewed publications were used to some extent in both the WIPP and Yucca Mountain projects, but obstacles to such publication were encountered: including lack of funding, tight time schedules to produce work needed by the program, and perceived legal constraints associated with the Yucca Mountain licensing process (particularly towards the end of the preparation of the license application). The desirability of facilitating peer-reviewed publication of key results related to repository performance should be given careful consideration in designing future institutional arrangements for maintaining credibility of a repository program.

Experience with WIPP shows that a siting and facility development process with contractual arrangements that are not easily altered and state monitoring/oversight of facility operations, can enhance trust and maintain credibility with a state. The WIPP development process benefited from a formal and binding consultation and cooperation agreement between the State of New Mexico and DOE that included discrete points where issues of concern to the State of New Mexico were addressed prior to moving forward. When unexpected situations arose, the program was able to back-up, change the design, and move forward in a manner that maintained credibility with the state. The consultation and cooperation agreement provisions in the NWPA, modeled on the WIPP agreement, would allow negotiation of such a stepwise and consultative decision process for a repository developed under that NWPA, although none of the states with sites selected for characterization chose to take advantage of the right to such an agreement. The WIPP experience suggests that it would be helpful for future legislation to retain the provisions that allow such agreements as part of a stepwise staged development process.

1. Introduction

The Fuel Cycle Technology Program in the U.S. Department of Energy (DOE) Office of Nuclear Energy is investigating alternative nuclear fuel cycles to provide a sound basis for future decisions on the U.S. nuclear fuel cycle. The safe management and disposition of radioactive waste is an important aspect of the nuclear fuel cycle. Thus, the Fuel Cycle Technology Office established the Used Fuel Disposition Campaign to identify alternatives and conduct research to facilitate storage and disposal of used nuclear fuel and wastes generated by the current and alternative nuclear fuel cycles.

As part of identifying alternatives, the Used Fuel Disposition Campaign is examining lessons learned from experience gained in implementing the current nuclear waste policy in the United States. The goal of this effort is to identify potential changes that if made could add flexibility and possibly improve the chances of successfully implementing a revised nuclear waste policy applicable to all fuel cycle scenarios that the public values and the states accept while maintaining public health and safety. The first topical area chosen was the current legal and regulatory framework pertaining to used nuclear fuel and high-level waste management.

Disposal of radioactive wastes from the nuclear fuel cycle is subject to a range of regulations governing high-level waste (HLW), spent nuclear fuel (SNF) (i.e., used nuclear fuel or UNF[1] that has limited economic value), low-level waste (LLW), and mixed waste that contains hazardous materials in addition to radioactive materials. The regulatory framework is established by the *Nuclear Waste Policy Act of 1982* (NWPA), the *Nuclear Waste Policy Amendments Act* (NWPAA), the *Low Level Waste Policy Act* (LLWPA), the *Resource Conservation and Recovery Act* (RCRA), and other statutes. The framework includes Nuclear Regulatory Commission (NRC) regulation to established safety standards and to Environmental Protection Agency (EPA) established environmental standards. Several aspects of these regulations are discussed below. Also, important lessons can be learned from the construction and successful operation of the Waste Isolation Pilot Plant (WIPP), DOE's repository for defense transuranic (TRU) waste, and are included when they might also apply to disposal of disposal of defense and commercial HLW and UNF.

1.1. Approaches Used for Identifying Potential Lessons

The strategy adopted for identifying potential lessons to learn was to start at a high level and move into details in later years. The first topical area chosen was the current legal and regulatory framework pertaining to used nuclear fuel and high-level waste management and its implementation at the Waste Isolation Pilot Plant (WIPP) and the Yucca Mountain Project (YMP). Hence, the goal for this report in this first year is to suggest areas where lessons can be learned that should be examined in more detail in future years.

Two additional approaches were used to obtain information to develop this report: First, the Used Fuel Disposition Campaign hosted a workshop at Sandia National Laboratories in Albuquerque on 18 and 19 May 2010 in order to (1) understand events related to the legal and regulatory framework through several technical perspectives, (2) identify potential lessons to be learned, and (3) discuss the impact of changes on the technical implementation. A broad set of subject matter experts in the waste management field participated in this workshop. The ideas and issues expressed at the workshop were used as input in

[1]For this paper, the term "used fuel" or "used nuclear fuel" (UNF) is applied to fuel that has been irradiated in a reactor but for which no decision has been made about whether it will be reprocessed to recover usable materials or disposed. The public perception of UNF as a resource is discussed in §9.0. The *Nuclear Waste Policy Act of 1982* (NWPA)[Pub. L. 97-425] defines spent nuclear fuel (SNF) as "fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated by reprocessing." This paper uses the term "spent fuel" or "spent nuclear fuel" (SNF) for fuel that has been designated as having no further economic value and is destined for disposal.

developing this report. However, not all the ideas and issues could be addressed here. Future reports will be able to delve into other ideas and issues in more depth.

Second, the Used Fuel Disposition Campaign took advantage of a national survey Sandia National Laboratories conducts annually on security issues such as energy and added several questions related to nuclear waste disposal with the goal of identifying what might enhance acceptability and credibility of waste management facility development. The questions delved into the public perception of the risks and benefits of nuclear energy, the perception of current waste management practices, and design attributes of a storage/disposal facility (e.g., number, depth, and type).

1.2. Selected Topics and Organization

Eight general topical concepts and their expression in regulation are discussed in the following sections: (1) waste disposal regulations related to performance measures, reasonable expectation, retrievability, waste classification, and hazardous waste; (2) site screening and evaluation; (3) research and development facilities; (4) staged development of a storage/disposal system; (5) concepts of interim storage and the transition to disposal; (6) concepts of a waste management system that better integrates storage, transportation, and disposal; (7) flexibility of regulations to accommodated a mix of alternative fuel cycles; and (8) enhancing acceptability and credibility of repository development. Background is presented and several issues raised and discussed for each topic. The report typically does not present conclusions, but rather suggests areas to explore in the coming years. Expanded background material with detailed histories and timelines of events for the YMP and WIPP is included in Appendix A to provide the reader a fuller understanding of the complexity of the programs.

2. Waste Disposal Laws and Regulations

Disposal of radioactive wastes from the nuclear fuel cycle is subject to a range of regulations. Pursuit of advanced fuel cycles and repositories (or alternative disposal systems) for high level waste and used fuel other than Yucca Mountain could require or provide a strong incentive for revisions to the existing structure. The NRC is currently reviewing its regulations for disposal of HLW and LLW, and EPA may need to review its disposal standards if other repository sites are considered.[Davis 2010] The experiences with WIPP and YMP provide useful input by identifying possible revisions to HLW waste disposal regulations that would be beneficial to smooth development of advanced fuel cycle facilities and waste management facilities.

2.1. Participants and Roles for WIPP and YMP

The United States legal framework is similar to other international programs in many aspects, but differences are evident.[IAEA 2006, §3] In the United States, DOE sites, builds, and operates the repositories. In several countries (e.g., France, Sweden, Finland, Switzerland, and Japan), public utilities have set up a private entity to site, build, and operate the repository rather than required to use a government agency as in the United States. This private entity in other countries may also be more closely integrated with the storage and transportation operations than in the United States.

Another difference is that regulatory responsibility is divided among several entities in the United States. In 1974, Congress to split the Atomic Energy Commission (AEC), formed in 1946, into two parts (1) the Energy Research and Development Administration (ERDA) (and in 1977, the cabinet level DOE) to operate disposal facilities (among many other activities such as nuclear weapon production and nuclear power research); and (2) the NRC to regulate civilian use of nuclear materials. Under the NWPA, EPA sets the pre- and post-closure standards for repositories for HLW and SNF and NRC implements those standards. Also, NRC sets and implements standards for storage of waste and transportation of all radioactive waste. For the disposal of defense TRU at the WIPP, the EPA set and implemented the standards. For hazardous waste constituents in the TRU, the EPA granted the State of New Mexico the authority to regulate, and so WIPP has both a federal and state regulator. Besides the NRC and EPA, Congress sets policy and sets funding levels, and private utility ratepayers or taxpayers, are the funding sources for radioactive waste disposal (Table 2-1).

2.2. HLW/SNF Post- Closure Performance Requirements

In 1977, EPA conducted several public meetings to begin a lengthy process of developing a consensus of society's concept of acceptable risk (i.e., safety) from geologic disposal of radioactive waste.[41 FR 53363] The NWPA of 1982 (§121a) directed the EPA to "promulgate generally applicable standards for protection of the general environment from offsite releases from radioactive material in repositories." The NWPA (§121b) also directed the NRC to promulgate technical requirements and criteria that will apply "in approving or disapproving 1) applications for authorization to construct repositories; 2) applications for licenses to receive and possess spent nuclear fuel and high-level radioactive waste in such repositories; and 3) applications for authorization for closure and decommissioning of such repositories." The technical requirements and criteria promulgated by the NRC "shall not be inconsistent with any comparable standards promulgated" by the EPA. What follows is a discussion of the performance measures and technical requirements. Later sections discuss the standard of proof for compliance and retrievablity.

Table 2-1: Policy, regulatory, and operational framework for geologic disposal of SNF, HLW, and TRU radioactive waste and mixed radioactive waste in the United States

Entity	Function	Disposal System	Action
Congress	Set policy and set funding levels of agencies	YMP	NEPA—National Environmental Policy (1970)[Pub. L. 91-190] NWPA—Nuclear Waste Policy (1984; 1987)[Pub. L. 97-425; Pub. L. 100-203] EnPA—Energy Policy (1992)[Pub. L. 102-486] YMP Authorization (2002)[Pub. L. 107-200]
		WIPP	NEPA (1970) [Pub. L. 91-190] RCRA—Hazardous Waste Policy (1976,1984)[Pub. L. 94-580; Pub. L. 98-616] WIPP Authorization (1979)[Pub. L. 96-164] WIPP Land Withdrawal Act (1992)[Pub. L. 102-579]
EPA (1970)[35 FR 15623]	Set standards	YMP	40 CFR 191—generic waste standard (1985) (prior to 1992 EnPA) 40 CFR 197—YMP standard (2001, 2008)[66 FR 32074; 73 FR 61256]
		WIPP	40 CFR 261, 268 RCRA waste standards (1976) RCRA applies to mixed waste (1986)[586 Fed Sup 1163; 51 FR 24504] 40 CFR 191 (1985, 1993)[50 FR 38066; 58 FR 66398]
	Certify TRU disposal	WIPP	40 CFR 194—EPA implementation criteria (1996)[61 FR 5224] Letter notice for formal review (1997)[Rechard 2000] Compliance certification (1998)[63 FR 27354]
State of New Mexico[a]	Regulate RCRA constituent of TRU	WIPP	Judicial hearings (1999) RCRA Permit (1999)
NRC (1974) [Pub. L. 93-438]	Regulate CSNF disposal via license	YMP	10 CFR 60—generic technical criteria (1983)[48 FR 28194] 10 CFR 63—YMP technical criteria (2001, 2008)[66 FR 55732] Docket notice for formal review (2008)[73 FR 53284]
	Certify transport casks	YMP/ WIPP	10 CFR 71—Transport packaging of radioactive material (containment, shielding, subcriticality, heat)
Department of Transportation (DOT)	Regulate transport routes, handling, documentation, and hazardous material	YMP/ WIPP	49 CFR 173— requirements for packaging and transport 49 CFR 174—handling requirements for rail shipments 49 CFR 176—handling requirements for vessel shipments 49 CFR 178—packaging requirements
DOE (1974; 1977) [Pub. L. 93-438: Pub. L. 95-91]	Site repository	YMP	Generic EIS for mined, geologic disposal (1980)[DOE 1980c] 10 CFR 960—generic site guidelines (1984)[49 FR 47714] Environmental Assessment required by NWPA (1986)[DOE 1986a] Site Characterization Plan required by NWPA (1988)[DOE 1988] 10 CFR 963—YMP site guidelines (2001)[66 FR 57297] EIS for site selection (2002)[DOE 2002]
		WIPP	EIS for site selection (1980, 1990)[DOE 1980a; DOE 1990]
	Build repository	YMP	EIS for construction (2008)[DOE 2008a] SAR/PA-LA—safety assessment for construction (2008) [DOE 2008b]
		WIPP	Notice to construct (1983)[48 FR 30427]
	Operate	WIPP	SAR—safety assessment for operation (1990)[DOE 1990b] RCRA Part B application (1995)[DOE 1995c] Compliance certification application (1996)[DOE 1996] EIS for operation (1997)[DOE 1997b] Record of decision (1998)[Rechard 2000]
Utility payers	Provide funding	YMP	Nuclear Waste Fund for civilian waste appropriated by Congress
Taxpayers		YMP WIPP	Yearly budget for defense waste disposal authorized by Congress Yearly DOE budget authorized by Congress

[a]EPA has granted states the right to regulate aspects of RCRA hazardous waste on the behalf of EPA, and so the State of New Mexico has a regulatory role for TRU waste with hazardous waste constituents disposed at WIPP.

2.2.1. EPA Standard, 40 CFR 191

Immediately following congressional passage of the NWPA in December 1992, the EPA promulgated the draft 40 CFR 191 standard for SNF, HLW, and TRU disposal. The limits were set to allow no more than 1000 deaths over 10^4 yr for a repository with 100,000 metric tons of heavy metal (MTHM).[47 FR 58196] The EPA promulgated the final version of 40 CFR 191 in 1985, 3 years later.[50 FR 38066]

The Standard specified a performance assessment (PA) to show compliance of a disposal system where PA was defined as an "analysis that (1) identifies the processes and events that might affect the disposal system; (2) examines the effects of these processes and events on the performance of the disposal system; and (3) estimates the cumulative release of radionuclides, considering the associated uncertainties by all the significant processes and events."

As originally promulgated, the EPA Standard, 40 CFR 191, consisted of two subparts: Subpart A described criteria for management and storage during operations. Subpart B described repository Containment Requirements (§191.13) related to the post-closure PA; design Assurance Requirements (§191.14), which are discussed further in relation to retreivablity; Individual Protection Requirements (§191.15); and Groundwater Protection Requirements (§191.16). The Containment Requirements selected the cumulative release of radionuclides as the primary compliance indicator. The measure of this indicator was the cumulative release 10,000 years after disposal of long-lived radionuclides that reached the surface or crossed a vertical boundary a maximum of 5 km in any direction from the site. The cumulative release was normalized by (a) EPA derived limits for specific radionuclides and (b) the mass placed in the repository expressed as a waste unit factor.[2]

As a new regulatory concept, 40 CFR 191 required the measure to be expressed as a complementary cumulative distribution function (CCDF) to display uncertainty. Hence, the risk performance measure in 40 CFR 191 was not simply a limit on the expected value of a cumulative release, nor the variance, but rather a limit on the distribution of cumulative releases (primarily the extreme tail).

By specifying cumulative release, normalized by the size of the repository, as the primary indicator, the EPA accomplished several goals. First, by normalizing the release limit by the size of the repository, the Containment Requirements did not penalize use of one or two large repositories, which inherently creates a large source-term.[47 FR 58196]

Second, the use of cumulative release (i.e., the time integral) did not penalize the location of the repository away from large volumes of water along the coast (which promotes dilution and thus lowers dose).[47 FR 58196] Third, the use of cumulative release was less sensitive to the release rate of radionuclides from the engineered barrier and dispersion coefficients in the geologic barrier, thus, the fidelity of the source-term model could be less and, hence, the regulation did not promote use of expensive engineered barriers.[47 FR 58196] Finally, cumulative release was less easily manipulated by the use of parameters with overly broad uncertainty ranges than the time of peak dose.[3]

However, based on comments received on the proposed regulation, the EPA decided to also require an evaluation of individual annual dose (i.e., potential *rate* of exposure by an individual) in addition to the

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[2] In a 1999 special issue of *Risk Analysis*, Rechard provides a historical context of this regulation,[Rechard 1999] and Okrent compiles reviews and philosophical discussions held during the development of 40 CFR 191 that gives the reader more background on the regulatory spirit of 40 CFR 191 (as related, for example, to the concept of intergeneration equity).[Okrent 1999]

[3] Committees of the Nuclear Energy Agency (NEA) of the Organisation of Economic Co-operation and Development (OECD) and IAEA have coined the term "risk dilution" where risk is a place holder for whatever performance measure is being used and "dilution" refers to the use of overly broad ranges for parameters distributions. The usual example given is where the performance measure is mean peak dose. The concern cited is where the parameters that influence the time of peak dose are assigned overly broad ranges such that the time of the peak dose varies greatly, and, thus, the mean peak dose averaged over numerous simulations is greatly reduced from that calculated with narrow distributions.[OECD-NEA 2002; Rechard and Tierney 2005]

cumulative release standard as a secondary indicator of risk in the Individual Protection Requirements (§191.15) of the Standard. The measure was individual mean whole-body dose and mean critical organ dose in the first 1,000 years assuming an undisturbed disposal system.[58 FR 66398] The pathways comprising the dose measure were to include only undisturbed features, events, and processes (FEPs).

The form of the Individual and Groundwater Protection Requirements in 40 CFR 191 led to a lawsuit. The court remanded 40 CFR 191 in 1987.[824 F2d 1258] In response to the court remand, the EPA issued a revised standard (as directed by the *WIPP Land Withdrawal Act)* in 1993 to (1) increase the regulatory period for the dose calculation to 10,000 years, identical to the Containment Requirements, (2) lower the limit for the mean dose from 0.25 mSv/yr to 0.15 mSv/yr, and (3) update the method of calculating dose. Also in response to the court remand, the Groundwater Protection Requirements (§191.16) were made similar to those promulgated for the *Clean Water Act* in 40 CFR 141 (as of 1994) in a new Subpart C. The Groundwater Protection Requirements are somewhat redundant in that the Containment Requirements would be exceeded in most cases before the Groundwater Protection Requirements were exceeded.

2.2.2. NRC Implementing Regulation, 10 CFR 60

In 1981, the NRC had already issued repository regulations (10 CFR 60) pursuant to the authority established in the *Energy Reorganization Act of 1974*.[Pub. L. 93-438] This version of 10 CFR 60 set forth the requirements applicable to the DOE for submitting an application for a license and specified the procedures which the NRC would follow in considering the application. The NRC licensing proceeding were to be formal and involve a judicial process involving administrative judges, judicial hearings, attorneys, rules of evidence, and cross-examination of witnesses.

In 1983, prior to final promulgation of 40 CFR 191 but cognizant of its likely contents, the NRC promulgated technical requirements in 10 CFR 60,[46 FR 13971; 48 FR 28194] which set deterministic criteria on subsystems of the waste disposal system in addition to the expected EPA criteria for overall performance of the repository (subsequently issued in 1985 as 40 CFR 191). The criteria were (a) 1000 yr groundwater travel requirement for the geologic barrier, (b) 300- to 1000-yr container life without substantial failure, and (c) a maximum fractional release rate of 10^{-5} from the engineered barrier system for radionuclides after 1000 years of decay provided this rate limit is not less than 0.1% of a similarly calculated total release limit.[4] The rule included a requirement to maintain the ability to retrieve waste packages for safety reasons up to 50 yr after disposal operations begin, as discussed further in a later section.

The 10 CFR 60 also invoked "reasonable assurance" as the standard of proof for compliance with the limits, similar to reactor licensing, rather than "reasonable expectation" as subsequently specified by EPA (discussed further in §2.6).[66 FR 55732]

2.2.3. EPA Standard, 40 CFR 197

The *Energy Policy Act of 1992* required EPA to issue a site-specific standard for Yucca Mountain, based upon and consistent with recommendations and findings of a study to be performed by the National Academy of Sciences. The National Academy of Sciences completed their study entitled *Technical Bases for Yucca Mountain Standards* in 1995.[NAS 1995a] The NAS made three primary recommendations in 1995: (1) use of a standard that sets a limit on the risk to individuals of adverse health effects from repository releases; (2) conduct the compliance assessment for the time when the greatest risk occurs, within the

[4] NRC promulgated amendments to 10 CFR 60 in 1985 to include criteria for siting in the UZ; in 1986 to revise the licensing procedures to agree with the NWPA; in 1989 to clarify the need to update the YMP EIS when filing for construction authorization, operation, and closure; and in 1996 to clarify terms, but these amendments are not germane to the performance measures.

limits imposed by the long term stability of the geologic environment (which was stated to be on the order of one million years at the Yucca Mountain site); and (3) evaluate only the potential consequences (not probability) of a few selected situations of inadvertent human intrusion. Another recommendation was to avoid specifying criteria for subsystems of the disposal system, since these criteria could potentially result in suboptimal behavior of the overall disposal system.

In 2001, EPA promulgated[64 FR 46976; 66 FR 32074] the site-specific standard (40 CFR 197), leaving the generic 40 CFR 191 applicable to other geologic repositories such as WIPP. In 40 CFR 197, the EPA selected individual dose as the primary risk indicator and the expected value of the maximum committed expected dose equivalent to a reasonably maximally exposed individual at a point of compliance 18 km from the repository over a regulatory period of 10,000 years as its primary measure for undisturbed and disturbed performance of the disposal system. Similar to 40 CFR 191, the EPA set a limit of 0.15 mSv/yr for the peak dose over time. EPA judged that a performance measure based on dose captured the NAS recommendation that it be based on risk and would be consistent with the requirement in the *Energy Policy Act* for a dose standard. In the initial promulgation of 40 CFR 197, the EPA also required projections of peak annual dose beyond 10,000 years using expected parameter values for undisturbed performance as secondary measures for inclusion in an accompanying EIS. No limit for the peak of the mean dose beyond 10,000 years was set.

The EPA required a calculation of groundwater dose and peak dose (over periods much greater than 10^4 yr) using mean parameter values for undisturbed performance as secondary measures for inclusion in an accompanying EIS, but did not set a limit for peak dose. Although mostly redundant, the EPA also established concentration limits for radium and alpha emitting radionuclides, and dose limits for beta and photon emitting radionuclides to protect groundwater, similar to those included in 40 CFR 191.

The use of *individual* dose has two advantages over a population risk indicator. First, the measure is comparable to individual dose measures in other international radioactive waste programs (provided the FEPs and regulatory period considered are similar).[5] Second, dose is directly evaluated from concentrations calculated from the exposure consequence model using a dose conversion factor. Thus, development of the regulatory limit for dose is more transparent than development of a generic regulatory limit for cumulative release and large populations, which requires EPA to develop the derived limits for large population exposure that can more easily be misapplied.[6] However, since the dose measure is an *expected* dose, not an actual dose exposure to a human, judgment must still be applied by the regulator in selecting a numerical limit.

2.2.4. NRC Implementing Regulation 10 CFR 63

In 1999, NRC proposed the 10 CFR 63 implementing regulations specifically for Yucca Mountain (leaving 10 CFR 60 unchanged) that adopted the 10^4yr regulatory period but called for "reasonable

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[5] For example, NEA, ICRP, and IAEA have recommended a maximum health risk of 10^{-5}/yr or maximum public dose limit of 1 mSv/yr (about average from natural sources at sea level) and average of 0.3 mSv/yr.[ICRP 1991, ¶191; IAEA 2006] Many radioactive waste programs have specified design targets about a factor of 10 lower for some variable period after disposal. For example, Canada and United Kingdom sets the cancer fatality frequency at 10^{-6}/yr (0.08 mSv/yr using 1.25×10^{-2}/Sv conversion applicable at time of promulgation[ICRP 1991 ¶C66] versus the current 5×10^{-2}/Sv[ICRP 1991, ¶C68]) for 10^4 yr; Sweden sets the exposure limit at 0.1 mSv/yr for 10^4 yr; Switzerland sets the exposure limit at 0.1 mSv/yr without time limit; Finland sets the exposure limit at 0.1 mSv/yr for several thousand yr, and at 5 mSv/yr for accident conditions; France sets the exposure limit at 0.25 mSv/yr for 10^4 yr; Germany sets the exposure limit at 0.3 mSv/yr for 10^4 yr.[GAO 1994; Rechard 1999, Figure 13]

[6] The individual dose approach is more transparent even though the two approaches have similarities. For example, both require dose conversion factors, which are similar if a linear no threshold model of radiation exposure is assumed. Also, both approaches require a dilution volume. However, without a specific site, the EPA first developed a generic standard and so the primary exposure pathway, the population size, and the corresponding large-population water volume were more difficult to specify. Furthermore, selecting the cumulative release to correspond to a dose rate requires another difficulty that reduced the transparency.

assurance" concept that historically has been applied to nuclear reactors. However, by 2001, the final regulations promulgated by NRC regulations adopted[66 FR 55732] the EPA characterization of "reasonable expectation" as the standard of proof for compliance that represented a subtle but important conceptual change as discussed further in a later section. Furthermore, NRC removed subsystem performance objectives as recommended by the NAS[NAS 1995a] as well as the design and siting criteria that existed in 10 CFR 60. However, NRC still required maintaining the ability to retrieve waste packages for safety reasons up to 50 yr after disposal operations begin as previously required in 10 CFR 60 and as discussed further in a later section.

2.2.5. Repromulgation of 40 CFR 197 and 10 CFR 63

Although the 10,000 year period of compliance in 40 CFR 197 as promulgated in 2001[66 FR 32074] was consistent with other regulations (e.g., EPA's generic regulation for radioactive waste disposal, 40 CFR 191,[50 FR 38066] and EPA's guidance on no-migration petitions for hazardous, non-radioactive materials, specifically, 40 CFR 268, as discussed in a later section), the U.S. Court of Appeals for the District of Columbia Circuit vacated the portion of EPA's 40 CFR 197 dealing with the 10^4 yr regulatory period in 2004. The Appeals Court stated EPA rejected, without sufficient basis, the recommendation by the NAS for a regulatory period over the period of geologic stability.[NAS 1995a; 70 FR 49014]

In response to the remand, the EPA repromulgated a revised version of 40 CFR 197 in September 2008, that set limits on dose for two periods: a limit on the peak of the mean annual dose of 0.15 mSv/yr up to 10,000 years and a limit on the peak of the mean annual dose of 1 mSv/yr after 10,000 years out to one million years. The 1 mSv/yr limit is consistent with the IAEA model standard in 2006 and ICRP recommendation in 1997.[IAEA 2006; ICRP 1997; 70 FR 49014; 73 FR 61256, preamble] In March 2009, NRC promulgated changes to 10 CFR 63 that adopted the EPA changes.[74 FR 10811]

2.2.6. Lessons Learned on Regulatory Development

All of the debates about regulations for disposal of high-level waste and spent fuel that have taken place since passage of the *Energy Policy Act of 1992* have focused on site-specific regulations for Yucca Mountain. These site-specific regulations differ in several noticeable ways from the generic regulations—40 CFR 191 and 10 CFR 60—that establish the post closure performance requirements for the disposal of wastes in a geologic repository other than at Yucca Mountain, Nevada.

It is likely that EPA would have to revisit its generic repository standards (40 CFR 191) in order for development of a repository at a site other than Yucca Mountain to proceed. The NAS recommendations for Yucca Mountain-specific standards developed pursuant to the *Energy Policy Act of 1992* may be judged to be applicable to other repositories for SNF and HLW even though the Act only requires that the Yucca Mountain standards be consistent with those recommendations. While the EPA generic geological disposal standard at 40 CFR 191 might be applicable to other repository sites, it does not address either the peak of the dose within the geologic stability period (one million years for Yucca Mountain) performance standard recommended by the NAS and incorporated in 40 CFR 197, or the guidance developed by EPA to address uncertainties in projecting performance over this very great time horizon. The EPA may choose to promulgate a new regulation since 40 CFR 191 is in currently in use in the regulation of WIPP. Although unique at the time, the requirement to quantitatively treat uncertainty and use numerical models to access compliance was successfully implemented and could be retained in future regulations.

Any changes to EPA's standards for repositories other than Yucca Mountain would have to be reflected in changes to NRC's repository regulations, 10 CFR 60. These regulations, while still applicable any repository other than Yucca Mountain, were not revisited when fundamental changes were made to performance assessment methodologies in the promulgation of 10 CFR Part 63. For example, 10 CFR 60 still contains subsystem performance requirements that were dropped in 10 CFR 63.

Furthermore, 10 CFR 60 also contains the "reasonable assurance" standard of proof applied to the demonstration of postclosure performance instead of the "reasonable expectation" standard in 10 CFR 63.

Experience with WIPP and the Yucca Mountain Project suggests that the regulatory framework should be established prior to initiating a future repository development program, with top-level repository regulations established first followed by siting guidelines and site evaluation criteria, to provide clear guidance to repository developers. From 1992 through the promulgation of 40 CFR 197 in 2002 site characterization activities at the Yucca Mountain site proceeded essentially with no regulatory framework in place. In addition, the 2004 court ruling requiring that EPA revise portions of 40 CFR 197 to be consistent with recommendations of the National Academy of Sciences added some uncertainty to license application preparation process.

Consideration should be given to performance-based standards, without specification of rigid criteria for subsystems of the repository, as in 40 CFR 197 and 10 CFR 63. They should be general, applicable to all sites and designs that could be considered. Site specific regulations are subject to public perception that the regulations have been specifically crafted to facilitate selection or determinations of suitability of the site in question.

The NRC is currently in the process of identifying and resolving regulatory gaps associated with moving to different disposal media and waste forms.[Davis 2010] Ideally the past 34-yr experience will facilitate selection of a hazard indicator, its measure, and the standard of proof, so that the standard can be set prior to selection of a repository site. Nonetheless and as evident from the timeline of events above, a new regulatory effort may take many years.

Interactions with the regulator were relatively straightforward for WIPP because the certification process used a standard rulemaking process under the *Administrative Procedures Act*. A key development in certifying the WIPP was engaging the EPA regulator.[Larson et al. 1999]

Beginning in 1994, a series of EPA-Stakeholder Technical Exchange meetings oriented EPA technical staff on the status and history of data collection and model development on the WIPP project. PA model training sessions began about the same time, during which EPA staff became familiar with WIPP PA methods and models. This provided opportunities for exposing technical questions and concerns early, resulting in improvements in the technical quality of the compliance application. Of particular importance during the PA training was familiarization with the WIPP use of feature, event, and process (FEP) screening as a method in issue resolution. EPA QA staff were invited to audit relevant procedures, and corrective action requests from the audit resulted in significant improvement in the implementation of the WIPP QA program.

Interaction with the NRC during the Yucca Mountain Project were much more formal, lengthy, and costly, but very useful nonetheless. Pre-licensing interactions between DOE and NRC on the Yucca Mountain project, such as the interactions on key technical issues, criticality topical report, and an NRC review of a dry spent fuel transfer system, showed the value of such interactions as an indicator of progress during repository development even though they did not constrain the NRC in its formal licensing review. It would be helpful for new generic repository regulations to be crafted to ensure that such interactions can take place. This interaction would be especially an important part of a staged development process (as discussed in §5.0).

2.3. Reasonable Expectation as the Standard of Proof

The standard of proof for the demonstration of compliance with the quantitative post-closure performance standard is an integral part of the standard. In its standards for geologic repositories, EPA has employed "reasonable expectation" as the standard of proof, used it successfully in certifying compliance of WIPP with its 10,000 year performance requirement, and included it in the Yucca Mountain standard (40 CFR 197) to apply to both the 10,000 year and one million year standards. In promulgating its final rule for Yucca Mountain, 10 CFR 63, NRC explicitly adopted EPA's concept of reasonable expectation as the standard of proof for post-closure performance, while retaining the familiar NRC concept of reasonable assurance for pre-closure regulation. What follows is a summary of findings and then the timeline of events whereby EPA and other reviewers clarified the concept of reasonable expectation as the standard of proof.

2.3.1. EPA Concept of Reasonable Expectation in 40 CFR 191

Demonstrating compliance with regulations for geologic disposal requires predicting the performance of natural systems over very long time frames. It is not possible to provide the same kind of assurance of performance for a geologic disposal system as it is for present day engineered facilities, like nuclear plants. As noted by the NAS in its report supporting development of a Yucca Mountain standard,[NAS 1995a, p. 71] "No analysis of compliance will ever constitute an absolute proof; the objective instead is a reasonable level of confidence in analyses that indicates whether limits established by the standard will be exceeded."

EPA explicitly recognized this in promulgating its general standard for disposal of high-level waste, 40 CFR Part 191: [50 FR 38066, preamble]

> Performance assessments need not provide complete assurance that the requirements ... will be met. Because of the long time period involved and the nature of the events and processes of interest, there will inevitably be substantial uncertainties in projecting disposal system performance. Proof of the future performance of a disposal system is not to be had in the ordinary sense of the word in situations that deal with much shorter time frames. Instead, what is required is a reasonable expectation ... that compliance ... will be achieved.

The EPA specifically chose not to use the NRC term "reasonable assurance" because that phrase[50 FR 38066, preamble]

> ... has come to be associated with a level of confidence that may not be appropriate for the very long-term analytical projections that are called for by 191.13. The use of a different test of judgment is meant to acknowledge the unique considerations likely to be encountered upon implementation of these disposal standards

EPA's position on reasonable expectation was challenged as being arbitrary and capricious in the lawsuit that led to the remand of parts of 40 CFR 191 in 1987, but was upheld by the Court: [824 F.2d 1258]

> Given that absolute proof of compliance is impossible to predict because of the inherent uncertainties, we find that the Agency's decision to require "reasonable expectation" of compliance is a rational one. It would be irrational for the Agency to require proof which is scientifically impossible to obtain. Any such purported absolute proof would be of questionable veracity, and thus of little value to the implementing agencies. Nor can we say that this provision is arbitrary and capricious because it will afford the implementing agencies a degree of discretion, since such imprecision is unavoidable given the current state of scientific knowledge. Thus we are again faced with a decision that is within the Agency's area of expertise and on the frontiers of science, and, as such, we refuse to substitute our judgment for that of the Agency.

EPA subsequently reaffirmed its position on reasonable expectation in its repromulgation of 40 CFR 191 to apply to WIPP in 1993.[58 FR 66398]

2.3.2. Application of Reasonable Expectation at WIPP

Early on, the WIPP Project interpreted EPA's "reasonable expectation" standard as requiring that the performance assessment (PA) for the repository use an approach that quantified uncertainties realistically and over their full range, rather than one that involved conservative point estimates or a bounding assessment. By 1996, the EPA explicitly stated this intent in the implementing regulations 40 CFR 194.34. For the WIPP certification, EPA was also the implementing agency, and issued separate regulations (40 CFR194) clarifying the implementation requirements. EPA's final certification of compliance in 1998, and its 5-year recertification in 2003 and 2008, demonstrates that a 10,000 year performance standard, subject to a reasonable expectation standard of proof as understood by EPA, can be successfully applied to a geologic repository.

The reasonable expectation approach placed a requirement to be neither too optimistic about the information that was available nor too pessimistic about the uncertainty in the data when assigning parameter values. Maintaining a focus on realistic models and parameters proved challenging. Participants often had the mistaken notion that "conservative" models and parameters values were "more defensible" and thus results using these models and parameters were "more convincing." However, conservatism was often not "more defensible" or "more convincing" at WIPP, for a number of reasons:[Rechard and Tierney 2005]

1. Parameters values that are conservative for all scenarios cannot be assigned in a complex system. A value that is "conservative" for one scenario might be non-conservative for another.
2. Maintaining a consistent level of "conservatism" for such a complex system is difficult. For example, in the 1989 PA, individuals had different notions of 'conservatism'.
3. Casual readers might not fully understand the concepts in a conceptual model, in which case an appeal to conservatism is futile.
4. An appeal to conservatism can engender a suspicion that the model and parameters have not been developed using current scientific knowledge. Technically astute reviewers understand the concepts of a conceptual model but often want convincing evidence that the analyst can quantify how much uncertainty this component contributes to the overall uncertainty in the results.

An example of the latter risk of reliance on conservatism is found in the conceptual model (and corresponding parameters) for spalling of pressurized waste from the sides of a borehole during exploratory drilling (in addition to the normal caving of wastes). The model used in the PA was thought to be highly conservative since the heterogeneous waste was assumed to have the characteristics of a fine sand with practically zero cementation strength and, thus, was thought to be more defensible by those analysts who constructed the model. However, the peer panel mandated by the EPA to review the 24 major conceptual models of the 1996 PA found this conceptual model to be the least defensible of the 24 because it could not be defended with scientifically based information and experimentally based parameter values. Instead, the peer panel suggested that the WIPP Project develop a more realistic, mechanistic model of the spalling phenomenon and directly use measured data on waste characteristics to quantify the suspected but unsupported conservatism of the model and parameters. Furthermore, because of the inadequate defense of the spalling component of the drill cuttings model, the EPA in their verification of the 1996 PA simply replaced the spalling component with a uniform distribution over a specified range of waste volumes per spall event.

2.3.3. Reasonable Expectation in EPA and NRC Regulations for YMP

Since the initial promulgation of 40 CFR 191, EPA has maintained the position that reasonable expectation is different from NRC's concept of reasonable assurance as it has been traditionally applied in the reactor licensing process, and made that point clear in its initial promulgation of 40 CFR 197 in 2001.[66 FR 32074, preamble] In that promulgation, EPA noted that the concept of reasonable expectation had been sustained in court against a legal challenge in 1987, and had been applied successfully to a geologic repository in the case of the Waste Isolation Pilot Plant. In contrast, the traditional reasonable assurance standard had never been applied in the context of a geologic repository.

In commenting on NRC's draft of 10 CFR 63 (NRC's regulation for implementing 10 CFR 197), which used "reasonable assurance" as a standard of proof for both pre-closure and post-closure repository performance, EPA observed that it would in effect change the standard. This observation recognized that the standard of proof is an integral part of the overall standard. NRC summarized the EPA comments as follows:[66 FR 55732]

> EPA believes that "reasonable assurance" is appropriate for operating facilities or in the context of the nuclear power plant-licensing program where facilities operate under active institutional controls during their lifetime. It is not appropriate, in EPA's view, for the licensing of a repository where projections of performance have inherently large ranges of uncertainty. EPA prefers ``reasonable expectation'' because it believes "reasonable assurance" has come to be associated with a level of confidence that is not appropriate for the very long term analytical projections that will be necessary for evaluating Yucca Mountain.
>
> EPA commented that a connotation has developed around "reasonable assurance" that could lead to an extreme approach to selecting worst case values for important parameters used to calculate individual dose (for example, precipitation rates, seepage rates, and flow in the unsaturated zone). According to the EPA, that approach, coupled with an equally extreme approach in selecting engineered barrier performance factors, would lead to assessments that represent situations with little or no probability of occurring but which become the basis for licensing decisions. The EPA concludes that the application of the "reasonable assurance" standard: (1) Is inconsistent with the NAS recommendation to use "cautious, but reasonable" assumptions when projecting the performance of the geologic repository; and (2) would result in applying margins of safety beyond the standard for individual protection set by EPA, which, in effect, alters that standard.

Reiterating its long-standing position that reasonable assurance and reasonable expectation were equivalent, the NRC stated it "does not believe that NRC's use of ''reasonable assurance'' as a basis for judging compliance compels focus on extreme values (i.e., tails of distributions) for representing the performance of a Yucca Mountain repository."[66 FR 55732] However, to avoid misinterpretations, NRC adopted EPA's "reasonable expectation" for the standard of proof to apply to post-closure performance. In deciding to use reasonable expectation as the standard of proof for the long term performance of the repository, the NRC explained:[66 FR 55732]

> To avoid any misunderstanding and to achieve consistency with final EPA standards, the Commission has decided to adopt EPA's preferred criterion of ''reasonable expectation'' for purposes of judging compliance with the postclosure performance objectives. The Commission is satisfied that a standard of ''reasonable expectation'' allows it the necessary flexibility to account for the inherently greater uncertainties in making long-term projections of a repository's performance. The Commission agrees with EPA and others that it is important to not exclude important parameters from assessments and analyses simply because they are difficult to precisely quantify to a high degree of confidence. By adopting what EPA has characterized as a more flexible standard of ''reasonable expectation'' for determining compliance with postclosure performance objectives, the Commission hopes to make clear its expectations. The Commission expects that the required analyses of postclosure performance will focus on the full range of defensible and reasonable parameter distributions, and that they should not be constrained only to extreme physical situations and parameter values. For other determinations regarding compliance of the repository with preclosure objectives, the Commission will retain a standard of ''reasonable assurance,'' consistent with its practice for other licensed operating facilities subject to active licensee oversight and control.

In dropping the criterion of "reasonable assurance" in favor of "reasonable expectation" with respect to the postclosure period while retaining it for the pre-closure period of the repository, NRC explicitly recognized EPA's distinction between the standard of proof appropriate for approving operation of an engineered facility with a limited operating life and the standard of proof appropriate for the very long term performance of a geologic repository. Furthermore, in approving the draft of the final version of 10 CFR 63 Commissioner McGaffigan commented:[NRC 2001]

> This is an area [Reasonable Expectation versus Reasonable Assurance] where EPA made a contribution to the overall standard setting effort. Our proposed rule used the term ‘reasonable assurance,’ partly because we had always used it, but the proposed § 63.101 really was describing ‘reasonable expectation.’ The final rule is an improvement.

EPA also provided flexibility in the interpretation of reasonable expectation for application in time periods longer than the 10,000 years in 40 CFR 191 and the initial version of 40 CFR 197. In the 1999 preamble to proposed 40 CFR Part 197, EPA said that if they were to regulate longer than 10,000 years, they would expect the licensing judgment to be less strict in relying on dose projections compared to 10,000 years. [64 FR 46998] Specifically, they noted

> … that if the compliance period for the individual-protection standard extended to the time of peak dose within the period of geologic stability (which NAS estimated to be 1 million years for the Yucca Mountain site), this [reasonable expectation] test would allow for decreasing confidence in the numerical results of the performance assessments as the compliance period increases beyond 10,000 years. For example, this means that the weight of evidence necessary, based upon reasonable expectation, for a compliance period of 10,000 years would be greater than that required for a compliance period of hundreds of thousands of years.

When issuing the final version of 40 CFR 197 that did indeed regulate past 10,000 years, EPA expanded on that point, explicitly allowing NRC flexibility to apply the concept of reasonable expectation differently in the very long term (Docket No. EPA–HQ–OAR–2005–0083–0417, Paragraph 8):[73 FR 61256]

> However, NRC’s compliance determination will consist of more than a simple comparison of the mean of projected doses with the dose standard. Rather, as stated in 40 CFR 197.14, NRC will reach its determination ‘‘based upon the full record before it.’’ Regardless of whether the mean of projected doses is well below the dose standard or not, NRC will examine the assumptions, data, models, and other aspects of DOE’s projections to ensure that it has an understanding of those projections sufficient to reach a ‘‘reasonable expectation’’ as to their compliance with the standard (40 CFR 197.13). While applying the principles of reasonable expectation at all times, NRC may also use its judgment as to whether it would apply the concept in exactly the same way for times as long as 1 million years as it would for much shorter times. A key element of reasonable expectation is that it ‘‘accounts for the inherently greater uncertainties in making long-term projections of the performance of the Yucca Mountain disposal system’’ (§ 197.14(b)), we would consider it logical as well as practical for NRC, in reaching its compliance decision, to evaluate the sources and effects of uncertainties in DOE’s analyses, as well as DOE’s treatment of them.

2.3.4. Application of Reasonable Expectation at YMP

In addition to the uncertainties about the nature of the final performance measure, the YMP faced some uncertainty about the standard of proof. The standard of proof for post-closure performance specified in the original NRC repository regulation, 10 CFR 60, was “reasonable assurance,” the more common standard in NRC licensing proceedings. Through the 1990s, persons working on the YMP were faced with uncertainty about how EPA's reasonable expectation standard of proof would be reflected in NRC’s application of reasonable assurance in the NRC licensing proceeding. Hence, YMP was cautious in applying reasonable expectation as noted by several review groups.

Independent reviews of the TSPA-SR concluded that the use of conservative assumptions focused primarily on compliance demonstration masked a clear understanding of the actual level of risk involved, and recommended use of more realistic assumptions. (Recommendations that DOE make its analysis more “realistic” generally meant it should rely less on conservatism and bounding assumptions to overcome uncertainty.)

NRC Advisory Committee on Nuclear Waste

In September 2001, the NRC’s Advisory Committee on Nuclear Waste (ACNW) stated in a review of DOE's Total System Performance Assessment-Site Recommendation (TSPA-SR):[Hornberger 2001]

[B]ased on the Committee's vertical slice review, the principal findings are that the TSPA-SR does not lead to a realistic risk-informed result, and it does not inspire confidence in the TSPA-SR process. In particular, the TSPA-SR reflects the input and results of models and assumptions that are not founded on a realistic assessment of the evidence. The consequence is that the TSPA-SR does not provide a basis for estimating margins of safety.

The Committee believes that the TSPA-SR is driven more by an attempt to demonstrate compliance with the standards than by the need to provide an assessment designed to answer the question: What is the risk? The result is that the assessment does not really risk-inform the safety of the repository…

Working from 5th and 95th percentiles of bounding parameter uncertainties in the TSPA-SR does not have much to do with "pessimistic" and "optimistic" results. It would have been much more informative if the TSPA-SR provided sensitivity analyses with respect to parameter values that are probabilistic, but also realistic, reasonable, and supported by evidence. The idea is to move in the direction of "evidence-supported" analyses and away from "assumption-base" analyses.

The ACNW recommended that the NRC staff ensure that "DOE has adopted an evidence-supported approach and realistic modeling assumptions for use in the TSPA-SR while reducing the dependence on parameter bounding and conservatism to overcome uncertainty and increase the reliance on such available evidence as site-specific field and laboratory data, natural analogs, and expert knowledge."

Nuclear Energy Agency – International Atomic Energy Agency Review

An independent Nuclear Energy Agency/International Atomic Energy Agency (NEA/IAEA) review of the TSPA-SR concluded that it provided an adequate basis for statements concerning likely compliance with the regulations, but noted the need for more realistic assessments that demonstrated an understanding of system behavior that is masked by more conservative compliance-oriented analysis:[OECD-NEA 2002]

The way the regulations are formulated has contributed to the tendency of the TSPA-SR to focus more on demonstrating numerical compliance with quantitative criteria than on demonstrating an understanding of repository performance. Also, the US approach to regulation has focussed attention on the presentation of aggregated results that can be compared directly with regulatory requirements. The IRT considers that more intermediate results and dis-aggregated end results should be given. This would provide more information to decision-makers, a point emphasised in recent international recommendations on the safety of radioactive waste disposal.

…Within the TSPA-SR report most attention is given to demonstrating quantitative compliance with regulatory criteria. Relatively little emphasis is placed on the important issue of presenting an understanding of system behaviour, which is required to enable decisions to be made based on the full body of evidence. The IRT considers that demonstrating understanding should be complementary to demonstrating compliance and of at least equal importance. Two approaches are needed.

The first is to present what is considered to be a realistic (i.e. non-conservative) analysis of the likely performance of the repository using realistic model assumptions and data. This could usefully draw on evidence from natural and archaeological/historical analogues and should aim to communicate the likely evolution of the repository and its surroundings to a range of stakeholders and give an indication of the safety margins inherent in the analysis.

The second approach is an analysis for compliance purposes where conservative assumptions and parameter values are used to make the case more defensible. Specific assumptions and models are needed for this and should be identified separately from the less conservative analysis. Finally, in order to communicate understanding, the USDOE should take steps to improve its corporate memory and make more use of the extensive archive of technical and non-technical reports produced during earlier phases of the programme.

Nuclear Waste Technical Review Board

In a January 24, 2002 letter report, the Nuclear Waste Technical Review Board (NWTRB), formed by the NWPAA, endorsed the importance of demonstrating an understanding of the behavior of the repository system and its associated uncertainties unmasked by conservative assumptions. Noting that conservative (or bounding) models and assumptions can be used to mitigate some of the effects of uncertainty, the NWTRB added: "Conservative models and assumptions, however, provide unrealistic estimates of risk, and if used inconsistently and along with realistic and optimistic models and assumptions, they leave unclear the true level of conservatism and risk in calculated performance estimates." Quoting further

> An international consensus is emerging that a fundamental understanding of the potential behavior of a proposed repository system is of importance comparable to the importance of showing compliance with regulations. The Board agrees that such basic understanding is very important. Therefore, if policy-makers decide to approve the Yucca Mountain site, the Board strongly recommends that, in addition to demonstrating regulatory compliance, the DOE continue a vigorous, well-integrated scientific investigation to increase its fundamental understanding of the potential behavior of the repository system. Increased understanding could show that components of the repository system perform better than or not as well as the DOE's performance assessment model now projects. In either case, making performance projections more realistic and characterizing the full range of uncertainty could increase confidence in the DOE's performance estimates.

In response to the NWTRB comments the DOE conducted further analysis. The NWTRB commended DOE efforts to quantify the uncertainty and the conservatisms in the performance estimates:

> Although the DOE's efforts in this area are incomplete, the Board believes that real and important progress has been made. A primary product of this effort is Supplemental Science and Performance Analyses (SSPA), issued in July 2001. The Board found that SSPA is a considerable improvement over Total System Performance Assessment for the Site Recommendation, issued in December 2000. Improvement is defined here as reflecting a more accurate representation of reality, the state of knowledge, and uncertainties.

EPA analyses of Performance Assessment for the Site Recommendation

EPA's own analysis of the Total System Performance Assessment for the Site Recommendation (TSPA-SR) also concluded that it incorporated substantial conservatisms. In an economic analysis of the impacts of the standard that accompanied the issuance of the standard, EPA examined the evolution of the Yucca Mountain repository design and concluded:[EPA 2001] "The new repository design was not developed to respond to any provisions of the EPA standard, but rather to reduce or eliminate uncertainties in the very conservative performance assessments of the previous design.."

This conclusion was based on a review of the TSPA-SR, the analysis that had also been found to be conservative by the reviews cited above. The following gives a flavor of the EPA's views on conservatism in the TSPA-SR:

> …several examples of models in the TSPA-SR appear to be so conservative that they fall outside of the realm of expected system behavior, and the tails of the parameter distributions appear to compound these conservatisms. The igneous scenarios in the TSPA-SR appear to be an example of compounding conservatisms. The annual probability of occurrence is highly uncertain, and one must look to the high end of the possible values for the probability to consider the scenario at all, based on NRC guidance on probability of scenarios (NRC99). The scenario description itself is for an extreme type of volcanic event in a location in which such events are highly unlikely. The model for magmatic interaction with the waste packages also takes extremely conservative assumptions, so that 5-9 waste packages are entirely destroyed, and the radionuclides are mobilized as an extreme finely ground- up, easily dispersed powder. Despite these extreme assumptions, the central tendency of the output distribution associated with parameter uncertainty

> provides a probability-weighted mean dose of around 10^{-2} mrem/yr…However, the concept of Reasonable Expectation would recognize that it is inappropriate to use the results of extreme values of parameters applied in an extremely conservative model in an extremely conservative scenario for prudent decision making. Similar, though less extreme, examples are possible to elaborate for the nominal scenario of TSPA-SR as well.

Discussing the impact of implementation of the concept of reasonable expectation for Yucca Mountain, EPA observed:

> The concept of Reasonable Expectation was developed by EPA to recognize that "absolute proof" of repository performance projections can not be obtained in the commonly understood meaning of the term, because of the long time frames and inherent uncertainties of the extrapolations involved in projecting repository performance. The approach, however, is intended to encourage realistic assumptions and assessments of repository performance, which recognize these inherent limitations. "Bounding" approaches that exclude important processes which will affect performance because these processes are not readily quantified with high precision and accuracy, or that frame performance scenarios unrealistically, have the danger of disguising important aspects of the site performance. The effect of overly conservative analyses can be to drive repository design efforts to unnecessary extremes or to set performance expectations beyond what can be reasonably demonstrated with conservative but reasonable analyses. As discussed above, the EPA standards for Yucca Mountain were developed under the concept of reasonable expectation. In examining the conservative basis for the TSPA-SR results, a reasonable expectation approach to framing the performance scenarios and assumptions indicates that expected performance would be orders of magnitude better than the TSPA-SR results. This difference would be more than enough to compensate for the uncertainties in the assessments.
>
> We believe the reasonable expectation approach is more appropriate for repository compliance evaluations and provides a more realistic link between design and anticipated performance in the iterative process of developing a repository design for licensing.

Views within the Yucca Mountain Project on Reasonable Expectation

DOE defended the project's approach to use of conservatisms in a presentation to the NWTRB in November 2005.[Van Luik and Andrews 2005] DOE pointed out that "Conservatism has been and continues to be a part of the licensing approach adopted by DOE to: simplify models, reduce the need for additional data, address alternative conceptual models"

DOE noted that NRC guidance allowed use of conservatism, provided there is supporting technical basis:[NRC 2003, §2.2.1]

> The total system performance assessment is a complex analysis with many parameters, and the U.S. Department of Energy may use conservative assumptions to simplify its approaches and data collection needs. However, a technical basis that supports the selection of models and parameter ranges or distributions must be provided.

DOE also noted that use of conservatism is consistent with internationally thinking about repository performance assessments:[OECD-NEA 2004]

> Conservatism of the analyses constitutes an additional qualitative argument for safety, although conservatism in and of itself may also be interpreted as a lack of knowledge, and thus may detract from confidence. Conservatism is inevitable, and greatly to be preferred to optimism, but should be used and managed judiciously.

Recognizing the importance of avoiding optimism, DOE emphasized the goal of providing "a demonstration of post-closure performance that does not underestimate dose." To achieve this, "DOE's assessments of post-closure performance are consistent with the 'cautious, but reasonable' approach articulated by the NAS, EPA and NRC" - an approach that "balances the need to be defensible with the desire to incorporate the full range of possible parameter distributions." At the same time, DOE indicated that it would continue to evaluate the range of conservatisms "to ensure no unintended optimisms (including potential risk dilution) result."

DOE noted that it had considered approaches for developing less-conservative assessments in certain areas in recognition of external comments that "have indicated a desire to parallel conservative compliance assessments with a 'realistic' nonconservative assessment to allow evaluating the 'safety margin'." Recognizing that "identifying less conservative representations may require additional data or modeling complexity," DOE indicated that "Importance analyses are to be used to guide the need for such efforts."

As a specific example of efforts to reduce conservatisms, DOE pointed out that "Seismic ground motions at annual exceedance probabilities of less than 10^{-6} per year are highly conservative and may be 'physically unrealizable'" and noted that "Several different studies are ongoing to bound the very low probability ground motions in order to provide a more realistic set of ground motions." DOE also indicated that it's Science and Technology Program "continues to develop data to evaluate and potentially reduce conservatisms in post-closure models."

2.3.5. Lessons Learned on Reasonable Expectation

1. The EPA standards for Yucca Mountain were developed under the concept of reasonable expectation as the standard of proof for compliance. The concept of "reasonable expectation" is therefore an integral part of the EPA standards, and application of a different standard of proof would in effect change those standards.
2. The focus on the use of reasonable models and the full range of parameters is consistent with and supportive of a growing international recognition of the importance of showing an understanding of the performance of a repository system in addition to simply demonstrating compliance with quantitative disposal standards.
3. The concept of reasonable expectation has been successfully applied by the EPA in certifying and recertifying the 10,000-year performance of WIPP.
4. While the NRC has explicitly adopted reasonable expectation as the standard of proof for post closure performance, there has as yet been no demonstration of the successful application of the concept in an NRC licensing proceeding for the demonstration of performance of repository over the 1 million year time horizon of the Yucca mountain peak dose standard. Such a demonstration would require completion of the licensing process.
5. Any regulations developed for repositories other than Yucca Mountain for high-level waste and spent fuel should retain all of the clarifications of the intent of reasonable expectation that have been made during its application to the certification of WIPP and during the deliberations leading to the promulgation of the final EPA and NRC regulations for Yucca Mountain, to avoid the sort of disagreements and misunderstandings of intent that were experienced in preparation of the Yucca Mountain license application.
6. Consideration should be given to further clarification of how reasonable expectation would be applied in regulatory time periods greatly exceeding the 10,000 years for which the concept has been demonstrated at WIPP. The difference in time between the 1 million year peak dose standard and the 10,000 year individual dose standard in 40 CFR 197 is nearly 100 times greater than the difference in time between the original 10,000 year standard in 40 CFR 191 for which the concept of reasonable expectation was developed and the 100-or-so year period for which the traditional NRC reasonable assurance concept was developed. The same arguments used to conclude that reasonable assurance was not the appropriate standard for 10,000 year performance might be used to argue that reasonable expectation as it has been

operationally defined for 10,000 year performance might not be appropriate for performance over a period of one million years.

2.4. Retrievability of Waste Emplaced in a Repository

The question of whether and for what purpose nuclear waste should be retrievable after it has been emplaced in a repository has been debated for decades. As discussed below, retrievability during repository operations is required under the NWPA, and EPA and NRC have provided additional relevant regulatory requirements. These regulatory requirements have not been a significant complicating factor in the certification and operation of WIPP, nor did they raise difficulties during the preparation of the proposed Yucca Mountain License Application. However, retrievability requirements could impact future disposal concepts, and, as discussed further in §9.0, members of the public consider the possibility of waste retrieval in their preferences for disposal concepts.

2.4.1. Regulatory Requirements for WIPP

The Assurance Requirements in EPA's generic high-level waste disposal regulations for WIPP (40 CFR 191.14(f)) state that "disposal systems shall be selected so that removal of most of the waste is not precluded for a reasonable period of time after disposal." In promulgating the rule,[50 FR 38066, preamble] EPA noted that positive and negative comments about this provision were divided fairly evenly, and that many of the critics were concerned that it "would encourage designing a geologic repository to make retrieving waste relatively easy -- which might compromise the isolation capabilities of the repository or which might encourage recovery of the waste to make use of some intrinsic value it might retain (the potential energy content of spent nuclear fuel, for example)." In other words, some objected to retrievability precisely on the grounds that it might encourage recovery of spent fuel for economic reasons. In response, EPA noted that the intent of the provision "was not to make recovery of waste easy or cheap, but merely possible in case some future discovery or insight made it clear that the wastes needed to be relocated," and re-iterated that "any current concept for a mined geologic repository meets this requirement without any additional procedures or design features." There would be no need to keep repository shafts open, but only for it to be technologically feasible "to mine the sealed repository and recover the waste -- albeit at substantial cost and occupational risk." In summary, "this provision should not have any effect upon plans for mined geologic repositories. Rather, it is intended to call into question any other disposal concept that might not be so reversible -- because the agency believes that future generations should have options to correct any mistakes that this generation might unintentionally make."

The EPA specified that the Assurance Requirements at 191.14 did not apply to repositories licensed by the NRC, leaving it up to the NRC to specify its own requirements. However, EPA stated: "the Commission's requirements for multiple engineered barriers within a repository … adequately address any concerns about the feasibility of recovering wastes from a repository."

2.4.2. Legal Requirements for HLW and SNF

The NWPA sidesteps the question of retrievablity in its definition of disposal of SNF and HLW: disposal is "the emplacement in a repository of high-level radioactive waste, spent nuclear fuel, or other highly radioactive material with no foreseeable intent of recovery, *whether or not such emplacement permits the recovery of such waste*" (emphasis added). However, §122 of the NWPA requires repositories to be "designed and constructed to permit the retrieval of any spent nuclear fuel placed in such repository, during an appropriate period of operation of the facility, for any reason pertaining to the public health and safety, or the environment, or for the purpose of permitting the recovery of the economically valuable contents of such spent fuel." Inclusion of the provision specifically requiring retrievability of spent fuel for economic purposes reflected a compromise between those who thought spent fuel should be treated as an energy resource and those who saw it as a waste. The NWPA stated that the appropriate period of retrievability for spent fuel would be defined by the DOE, subject to the approval or disapproval by the Nuclear Regulatory Commission during licensing. The DOE has never formally defined such a period specifically for economic retrievability of spent fuel pursuant to this section of the NWPA. Instead, the license application for Yucca Mountain simply describes how the repository will meet the NRC retrievability requirements (discussed below), with no distinction between SNF and HLW or reference to recoverability of spent fuel for economic purposes.

2.4.3. NRC Regulatory Requirements

Both NRC's generic and Yucca Mountain-specific repository regulations include essentially identical requirements for retrievability of waste (in 10 CFR 60.111(b) and 10 CFR 63.111(e)):

> (e) Retrievability of waste.
>
> (1) The geologic repository operations area must 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 must 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.
>
> (2) This requirement may not preclude decisions by the Commission to allow backfilling part or all of, or permanent closure of, the geologic repository operations area prior to the end of the period of design for retrievability.
>
> (3) For the purposes of paragraph (e) of this section, a reasonable schedule is one that would permit retrieval in about the same time as that required to construct the geologic repository operations area and emplace waste.

In explaining the 50 year retrievability period, the Commission stated that "After 50 years of waste emplacement operations and performance confirmation …it is likely that significant technical uncertainties will be resolved, thereby providing greater assurance that the performance objectives will be met," and noted that DOE could design a repository for a longer retrieval period if desired. However, in responding to a suggestion "that stewardship of the waste be maintained (indefinitely) so that waste could be made available for future energy needs," the Commission noted that its retrieval provision is not intended to facilitate recovery of the material in the repository as a potential resource. Instead, "Waste retrieval is intended to be an unusual event only to be undertaken to protect public health and safety."

The question of whether a repository in salt or basalt, would preclude the retrievability required by the regulations was raised during Senate hearings following the nomination of three sites for characterization in 1986 and prior to the 1987 decision to focus characterization efforts on a repository in tuff at Yucca Mountain.[Senate 1987] Representatives of Texas, location of a nominated site in bedded salt in Deaf Smith County, observed that the high rate of salt creep observed at WIPP suggested that a repository in salt would have difficulty meeting the retrievability requirements. DOE responded that predicted and experienced closure rates do not preclude retrievability, but do increase the cost of maintaining retrievability. Ben Rusche, the Director of the Office of Civilian Radioactive Waste Management (OCRWM) formed by the NWPA, stated "If we were required to maintain access to that salt site, as fully as might be the case, the cost of that salt site might go up by a substantial amount."

2.4.4. Ready Retrievability

A distinction exists between the "retrievability" required for safety reasons by the regulations, which does not preclude backfilling of disposal rooms and allows a long time for the process at possibly high cost and difficulty, and "ready retrievability" to allow relatively rapid and inexpensive recovery of materials for economic reuse, which requires maintaining open access to the disposal rooms.[OTA 1985] As noted above, NRC and EPA regulations focus on safety while the NWPA allows DOE to specify a period of retrievability for used fuel for economic purposes as well. The designation of Yucca Mountain as the only site to be characterized rendered the distinction between ready retrievability and retrievability for safety reasons moot, since Yucca Mountain faced no difficulty in meeting a 50-yr retrieval period because of the relative ease of maintaining open drifts in unsaturated tuff for an extended period compared to plastic salt and highly stressed saturated basalt.

Nonetheless, future legal and regulatory discussions should retain a clear distinction between these two concepts of retrievability. As noted earlier, EPA concluded that any mined geologic repository concept under consideration (which included salt and basalt media at the time) would meet their Assurance Requirements for retrievability for safety reasons. However, keeping salt rooms open for an extended period to maintain ready retrievability for economical recovery would be a different question.

A requirement for ready retrievability could impose significant constraints on repositories and the preferred geologic media. However, the likelihood of needing to be able to recovery SNF economically may be low. Obviously, HLW would have little economic value. It appears that at least some defense and commercial SNF that is relatively unattractive for reprocessing could be disposed of under any reasonable reprocessing scenario, with little likelihood of being recovered later. It may be preferable to simply leave UNF that might be economically attractive for reuse in surface storage until uncertainty about its reuse is resolved. In that case, retrievablity for reasons of safety would be the only issue affecting repository design.

2.4.5. International Discussion on Retrievability

The Nuclear Energy Agency (NEA) of OECD pointed out in 2004 that the concept of retrievability of waste from a repository after emplacement is gaining increasing attention internationally in the context of stepwise decision making, where the transition from readily retrievable economically to merely retrievable is a decision point.[OECD-NEA 2004] In 2001, a group established by the NEA Radioactive Waste Management Committee specifically to explore the topic of retrievability summarized arguments for and against retrievability:[OECD-NEA 2001a]

> Broad factors that might lead or contribute to a decision to retrieve waste and weigh in favour of building provisions for retrievability are as follows:
>
> - technical safety concerns that are only recognised after waste emplacement and/or changes in acceptable safety standards,
> - a desire to recover resources from the repository, e.g. components of the waste itself, or the recognition or development of some new resource or amenity value at the site,
> - a desire to use alternative waste treatment or disposal techniques that may be developed in the future,
> - to respond to changes in social acceptance and perception of risk, or changed policy requirements.
>
> Reasons for not including retrievability provisions in repository design may be connected to factors such as the additional complexity entailed, the cost-worthiness of a retrieval option, and long term security concerns. They include:
>
> - uncertainty about negative effects, including conventional safety and radiological exposure of workers engaged in extended operations and/or associated monitoring, or marginal gains;
> - the possibility of failure to seal a repository properly due to the adoption of extended or more complex operational plans to favour retrievability;
> - the favouring of irresponsible attempts to retrieve or interfere with the waste during times of political and/or social turmoil; and

- a possible need for enhanced nuclear safeguards.

Stepwise decision making, which is getting increased attention internationally (refer to §5.0), might use the transition from readily retrievable for economic reasons to merely retrievable for safety reasons as a decision point. In Finland, the public was clear that they wanted their repository to be designed for retrievability (refer to §9.0). Hence, expanded use of retrievable repository design concepts may be necessary. Also, the public uses retrievability to discriminate between disposal concepts (refer to §9.0).

2.4.6. Lessons Learned on Retrievability

1. The current regulatory requirements for retrievability for safety-related reasons did not cause difficulties at WIPP or Yucca Mountain, but they potentially impact other disposal technologies such as deep boreholes.
2. Requirements to facilitate easy recovery of emplaced spent fuel for economic reuse, which have not been applied to US repository designs to date, could impose more significant constraints on geologic repositories.
3. A future regulatory framework should clearly define the roles of recovery for economic reuse and retrievability for safety reasons.
4. The definition of retrievability should clarify whether it means that a repository is to be constructed to facilitate retrieval of the disposed waste, or only that nothing should be done in construction to obstruct retrieval.

2.5. Waste Classification Issues

The United States uses an eclectic mix of methods to define classes of radioactive waste: HLW is defined by its source, TRU contaminated waste destined for deep geologic disposal is defined by its activity level and defense source, LLW is defined by what it is not. Furthermore, LLW is divided into four categories based on length of the isolation period necessary to protect human health derived from deterministic estimates of a mix of radionuclides in LLW being generated 30 years ago. The definitions have been workable, but present a disincentive to using advanced fuel cycles to separate radionuclides in UNF into various waste streams. Also, the LLW produced from advanced fuel cycles would have a different mix of radionuclides than considered 30 yr ago. Regardless of the overall economics of reprocessing and advanced fuel cycles, the waste classification system should neither provide a disincentive to pursue such advances nor provide a disincentive to lower the volume of waste that is sent to a repository per unit of electricity produced. Hence, revisions to the classification system need to be considered. Also, because performance requirements for future repositories and decisions about waste processing, separations, and waste forms would depend upon the classification system, any resulting revision of the regulations should be completed in advance of the need to make such decisions.

Complicating any revision to the classification system for HLW with respect to future fuel cycles, however, are current legal agreements for cleanup activities at Hanford and Idaho that use current the current radioactive waste classifications, but current definitions could be grandfathered for the purpose of past legal agreements. In addition, because some of the classification is defined in legislation, modification to the classification system may require legislative amendments. Although a revision to the classification for LLW would also cause complications, the situation for the LLW classification system is slightly different in that difficulties already exist and have prompted NRC to begin a comprehensive study of alternative LLW classification systems. What follows is a more detailed description of the current classification system and potential current and future problems.

2.5.1. High Level Waste Classification

In the present classification system, HLW is defined in the NWPA based on its source. It is defined as the highly radioactive wastes generated from reprocessing. The HLW class was developed when PUREX was the state-of-the-art reprocessing technology. Advanced reprocessing methods could potentially separate radionuclides into a variety of waste streams, some being of lower risk to public health and safety or being of risk for shorter periods. The current classification would generally require that all such reprocessing waste be disposed of in a deep geologic repository regardless of their risk. Traditionally, the NRC and DOE has used the first aqueous extraction as the point of generation of HLW. However, the Natural Resources Defense Council lawsuit which resulted in § 3116 of the 2005 *National Defense Authorization Act* has prompted a re-evaluation. The court's ruling focused on the word “including” which means an example and cannot be read to be limiting. In other words, HLW waste is *any* "highly radioactive material resulting from reprocessing" and is not limited to material derived from the liquid waste of extraction. The lessons learned from application of the classification process in §3116 of the *National Defense Authorization Act* over the last 5 - 6 years at the Savannah River Site and at the Idaho National Laboratory may be relevant. The §3116 Waste Incidental to Reprocessing (WIR) process allows some flexibility in excising what can be considered "highly radioactive" but this determination must be done with consultation of the NRC and the state. The process currently applies only to the states of Idaho and South Carolina.

Advanced reprocessing methods could potentially separate radioisotopes into a variety of waste streams, some being of lower risk to public health and safety. The current classification of HLW presents a disincentive to reprocessing by preventing potential cost savings from use of a more cost-effective disposal method for disposal of low-hazard waste streams that might result from alternative fuel cycles. A mix of disposal systems for various levels of radioactive waste activity that are still protective of public health and safety may be possible using a revised classification system. Both the Health Physics Society and the National Council on Radiation Protection and Measurements have recommended that the entire radioactive waste classification system be based only on risk and include mixed waste in the classification.[HPS 2005] A revised classification system may also make separate waste streams from advanced reprocessing desirable. Continued classification of HLW by source would reduce the potential economic benefits associated with disposing of less-demanding wastes generated by an advanced fuel cycle.

2.5.2. Low-Level Waste Classification

Disposal requirements for LLW are based on a classification scheme developed 30 years ago by the NRC in 10 CFR 61. This classification scheme focuses on those radionuclides that were expected to cause the greatest short-term and long-term concerns for human health and the environment in 1981. The NRC defined four classes of LLW in 10 CFR 61.55 based on the concentrations of specific short-lived and long-lived radionuclides. These four classes are A (not hazardous to a human intruder after 100 yr), B (not hazardous to a human intruder after 100 yr), C (not dangerous to a human intruder after 500 yr), and greater-than-class C (GTCC) (dangerous to a human intruder beyond 500 yr). Although other radionuclides can cause a waste to be categorized as LLW GTCC, generally the activity is >100 nCi/g of long-lived radionuclides and is thus similar to defense TRU except that defense TRU derives from DOE defense activities.[Duran et al. 2008] This LLW classification scheme may not be appropriate for LLW resulting from advanced fuel cycles and the reprocessing of uranium and plutonium from UNF, since new LLW may contain a different mix of radionuclides (in particular higher concentrations of various TRU radionuclides and some fission products) than used to develop the waste classifications in 10 CFR 61 based on the radionuclides in LLW being generated 30 yr ago. Similar to the situation with HLW, a mix of disposal systems for various levels of radioactive waste activity that are still protective of public health and safety may be possible using revised classification system. A revised classification system may also make separation of waste streams from advanced reprocessing more economically attractive. A risk-based approach may be appropriate, since the NRC is moving in the direction of the risk-informed regulatory approach, and it is likely that future compliance may rely heavily on the results of performance assessment. The NAS recommended that LLW be regulated according to intrinsic hazardous properties and the associated health risk.[NAS 2006]

The Nuclear Regulatory Commissioners have directed the staff to request the resources needed to revise the LLW classification system.[Kennedy 2010] The context was the licensing decision for an enrichment plant, which had identified the fact that the existing classification system was developed without taking into account the possibility that there would be very large quantities of depleted uranium (DU) to dispose after processing (a problem analogous to the potential for significantly different waste streams generated by advanced fuel cycles). The NRC staff is now working on the LLW classification issue and is considering a number of options: specific changes to the existing structure, a new classification system, and even other changes to Part 61 beyond waste classification (e.g. the siting criteria). In addition, DOE itself is undertaking a major review and revision of DOE Order 435.1 dealing with its own radioactive waste management activities. The Office of Environmental Management of DOE conducted a complex wide review in 2009 and is drafting a report on the results of that review. Once that is complete, DOE will start a formal process for updating the order with a 2012 time frame for the new order. This updating process will proceed in parallel with NRC's update of 10 CFR 61.

2.5.3. Lessons Learned about HLW and LLW Classification

1. Revision to the classification system should be considered to support future fuel cycles.
2. Advanced reprocessing methods could potentially separate radioisotopes into a variety of waste streams, some being of lower risk to public health and safety. The current classification presents a disincentive to reprocessing by preventing potential cost savings from use of a more cost-effective disposal method for disposal of low-hazard waste streams that might result from alternative fuel cycles.
3. Regardless of the overall economics of reprocessing and advanced fuel cycles, the waste classification system should neither provide a disincentive to pursue such advances nor provide a disincentive to lower the volume of waste that is sent to a repository per unit of electricity produced.
4. The existing LLW characterization system may not be appropriate for LLW resulting from advanced fuel cycles since this LLW may contain a different mix of radionuclides (in particular, higher concentrations of TRU radionuclides and fission products) than used to develop the current waste characterization and the resulting disposal methods required in 10 CFR 61.
5. The lessons learned from application of the waste incidental to reprocessing (WIR) determination process (application of §3116 of the *National Defense Authorization Act*) over the last 5 - 6 yr should be considered in developing a revised classification system.
6. Current legal agreements concerning cleanup at Hanford and Idaho that use the current radioactive waste classifications may complicate any revision to the classification system for HLW with respect to future fuel cycles, but might be addressed by retaining past definitions for existing agreements . In addition, because some of the classification is defined in legislation, modification to the classification system may require legislative amendments.
7. Ideally a classification system should be based upon the hazard which integrates both the nuclear and chemical hazards (see below). Such systems include those developed by the

International Atomic Energy Agency [IAEA 2009] and the integrated hazard methodology described by National Council of Radiological Protection and Measurements.[NCRP 2005]

2.6. RCRA Requirements

2.6.1. Overview

HLW, LLW, or TRU waste that contain hazardous non-radioactive waste in addition to the radioactive components ("mixed wastes") poses added institutional challenges because of the potential for dual regulation under regulations established for two different statutes (*Nuclear Waste Policy Act of 1982* and the *Resource Conservation and Recovery Act* (RCRA) in 1976.[Pub. L. 94-580; Pub. L. 98-616]) and implementation by two or three different regulatory agencies (potentially EPA, NRC, and a state agency), as previously mentioned in §2.2.

Difficulties with mixed waste are exemplified by the history of mercury (Hg) releases at the DOE's Oak Ridge, Tennessee, facility between 1950 and 1977. In 1983, DOE reported a total discharge of 2×10^6 lb of Hg. The revelation prompted a lawsuit by Legal Environmental Assistance Foundation and Natural Resources Defense Council. In 1984, a federal court found that hazardous wastes at sites within the DOE complex, some of which were mixed wastes, were subject to RCRA.[586 F.Supp 1163] DOE sought to avoid dual regulation of the mixed wastes in 1985 by defining mixed waste as "byproduct material" under the *Atomic Energy Act*.[Pub. L. 585] However, EPA determined that "wastes containing both hazardous waste and radioactive waste are subject to RCRA regulation" in 1986.[51 FR 24504] Hence in 1987, DOE defined "byproduct material" to exclude everything except radionuclides and thereby acknowledge that its mixed wastes were subject to regulation under RCRA as well as the AEA.[52 FR 15937]

In amendments to RCRA and the *Solid Waste Disposal Act*, Congress imposed land disposal restrictions in the *Hazardous & Solid Waste Amendments of 1984* (HSWA).[Pub. L. 98-616] EPA implemented the land disposal restriction but provided for a variance if the petitioner could demonstrate "to a reasonable degree of certainty, that there will be no migration of hazardous constituents from the disposal unit or injection zone for as long as the wastes remain hazardous." (40 CFR 268.6)

2.6.2. Experience with RCRA at WIPP

As much as 60% of the TRU waste destined for the WIPP has hazardous waste constituents. In the Final Supplemental Environmental Impact Statement (SEIS) for WIPP, DOE stated that it was "...committed to full compliance with RCRA requirements..." for the portion of TRU mixed with hazardous waste constituents,[DOE 1990] and the WIPP LWA passed in 1992 formalized the requirement.

In 1989, the WIPP M&O contractor, Westinghouse, submitted a no-migration variance petition for the WIPP pilot phase to allow the disposal of waste containing chemically hazardous constituents regulated under RCRA, and in 1990, the EPA granted a variance for the WIPP pilot phase. Shortly afterwards, DOE decided to abandon a pilot phase and seek certification for full operations. Westinghouse began preparing another no-migration variance petition for full operations. The EPA had interpreted the RCRA requirement of demonstration of compliance "for as long as the waste remains hazardous" to be sufficient if projected for 10,000 years, stating that "for the purposes of demonstrating compliance with RCRA no-migration standards, it is not particularly useful to extend this model beyond 10,000 years into the future." [55 FR 47700] Because Congress subsequently exempted WIPP from compliance with the RCRA land disposal restrictions in a 1996 amendment to the *WIPP Land Withdrawal Act*, DOE no longer was required to obtain a variance and withdrew its petition to EPA. However, Congress did not exempt WIPP from other RCRA requirements

The remaining RCRA requirements applicable to WIPP are enforced by the State of New Mexico, which is authorized by EPA to carry out the State's base RCRA and mixed waste programs in lieu of the equivalent Federal programs under a process encouraged by Congress. The New Mexico Environment

Department reviews permit applications for treatment, storage, and disposal facilities for hazardous waste, under Subtitle C of RCRA. (FR 2006) [51 FR 24504] The State's authority for such actions as issuing a hazardous waste operating permit for the WIPP is in not affected by EPA actions in certifying and recertifying WIPP's compliance with EPA's regulations concerning disposal of TRU waste. Hence, the WIPP has both a federal and state regulator.

DOE filed a RCRA Part B application in 1995. The New Mexico Environment Department issued its draft RCRA permit on May 15, 1998 for a 90-day public comment period (two days after EPA certified WIPP). After formal hearings conducted by the New Mexico Environment Department, the New Mexico Environment Department issued the RCRA permit on October 27. 1999. WIPP received its first shipment of mixed waste on September 9, 2000. While this dual regulation has been workable, experience in operating WIPP under such dual regulations has proven difficult, time consuming, and costly.

2.6.3. Approach with RCRA at YMP

The situation could be potentially more complex for HLW with hazardous constituents in that NRC would be implementing EPA's radioactive standards, EPA would be implementing its own regulations pertaining to the no migration requirements related to RCRA, and the State would be implementing the standards related to characterization (which must be at least as stringent as EPA's standards).

Yucca Mountain's experience with RCRA issues is associated primarily with consideration of mixed wastes that might be produced at the repository as a byproduct of normal operation, rather than materials that would be destined for disposal there. In the past, questions have arisen about whether some materials considered for disposal in Yucca Mountain (e.g. calcined HLW at INL or sodium-bonded fuels) would be considered to be potentially hazardous wastes subject to RCRA. Under the waste acceptance requirements, the Civilian Radioactive Waste Management System "shall only accept, transport, and dispose of SNF or HLW that is not subject to regulation as hazardous waste under the Resource Conservation and Recovery Act of 1976 (RCRA) Subtitle C in the first geologic repository licensed by NRC under the NWPA."[DOE 2008c] Under this requirement, DOE waste forms that are classified as RCRA waste will not be accepted at the repository. This requirement also extends to materials used in fabricating the Transportation, Aging, and Disposal (TAD) canisters intended for use with most of the used fuel expected to be delivered to the repository. TAD materials are limited to those not subject to regulation as hazardous waste under Subtitle C of RCRA (e.g., lead shield plugs are not acceptable).

In 2006, the DOE sent to the Congress a legislative proposal, titled the *Nuclear Fuel Management and Disposal Act*,[NFMDA 2006] containing an exemption from RCRA requirements for materials under NRC license for disposal at Yucca Mountain.

> Section 6 would exempt from the requirements of the Resource Conservation and Recovery Act (RCRA) any material owned by the Secretary if it is transported in a package, cask, or other container certified by the NRC for transportation or storage of that type of material. Similarly, any material located at the Yucca Mountain site would be exempt from RCRA if managed in accordance with a license issued by the NRC to receive and possess high-level waste and spent nuclear fuel. The NRC licensing process is complex and comprehensive, designed to protect public health and safety. This section would eliminate lengthy, largely duplicative reviews under a different regulatory scheme.

It was intended to avoid dual regulation of high-level radioactive waste and spent nuclear fuel under 10 CFR Part 63 and EPA's RCRA regulations but no action was taken on the bill:[NFDMA 2006]

2.6.4. Advanced fuel cycles

Some fuel cycle waste will be both chemically hazardous as well as radioactive. RCRA will apply to many of the waste forms produced from reprocessing (silver getters for iodine capture, and cesium, strontium barium, and rubidium waste forms) at the time of disposal. This is problematic for wastes containing cesium/strontium (Cs/Sr) for which decay storage is planned. Solid waste must be shown to pass a Toxicity Chemical Leaching Protocol (TCLP) at the time of disposal. A waste may pass the TCLP at the time of production; however, as Cs decays to Ba it may not pass the TCLP at the time of disposal (100 to 500 years later). If the Cs/Sr is classified as a mixed waste because of the barium in-growth content, the long-term storage facility would also be subject to RCRA requirements.[Duran et al. 2008]

2.6.5. Lessons Learned from RCRA Experience

Consideration should be given to changing radioactive wastes regulations to ensure that the hazardous components are addressed while avoiding dual regulation. This might be done with a single health-based regulation, rather than a radiation dose-based regulation. Alternatively, regulations could focus on the most hazardous component of the waste—the radioactive materials—and geologic radioactive waste repositories from application of RCRA requirements that were developed assuming near surface disposal (such a framework is described National Commission on Radiological Protection and Measurements, as mentioned when discusses waste classification schemes [NCRP 2005]). Performance assessments could be used to show that the contribution of the hazardous materials to overall risk would be minor.

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3. Site Screening and Characterization

The NWPA and the regulations established under it set up a detailed process for screening potential repository sites, selecting a small number for detailed evaluation, and then characterizing those sites in great detail. Characterization was limited to a single site, Yucca Mountain, in the *Nuclear Waste Policy Amendments Act of 1987* (NWPAA). The *Blue-Ribbon Commission on America's Nuclear Future* is investigating future alternatives for managing nuclear waste and may recommend another siting process for a geologic disposal facility. In addition, voluntary siting processes that begin with the search for willing host communities before technical evaluation of the sites may also be considered. The experience with the entire NWPA siting process from its initiation in 1983, as well as the very different process for selecting and evaluating the WIPP site, are examined in this section for possible implications for future statutory and regulatory requirements for repository siting.

3.1. Phases of Site Screening and Characterization

Site characterization at WIPP and Yucca Mountain progressed through three study phases (Table 3-1): (1) non-intrusive evaluation and literature search for site selection; (2) exploration from the surface for evaluating repository feasibility; and (3) *in-situ* exploration underground to evaluate viability, recommend the site, and support the compliance assessment.

Table 3-1: Study phases for radioactive wastes disposal in the United States

Study Phase	Disposal System	System Studies and Other Activities
0. Commitment to mined, geologic disposal	YMP	ERDA recommends geologic disposal (1976)[ERDA 1976] Interagency Review Group recommends geologic disposal (1979) [IRG 1979] DOE Generic EIS selects mined, geologic disposal (1980)[DOE 1980c] Nuclear Waste Policy (NWPA) (1984; 1987)[Pub. L. 97-425; Pub. L. 100-203]
	WIPP	NAS recommends exploring disposal in salt (1957) [NAS 1957] NAS concludes bedded salt satisfactory host media (1970)[Rechard 2000]
1. Siting analysis based on regional geologic characterization via literature search and analogous data	YMP	Literature search starts after President Ford request (1976) USGS suggests NTS (1976) [McKelvey 1976, p 4] UE-25a#1 drilled in SW NTS to confirm thick tuff (1978) [Spengler et al. 1979] Repository moved to unsaturated zone (1982) [Roseboom 1983] 1982 volcanism consequences[Link et al. 1982] PA-84[Sinnock et al. 1984] NWPA Environmental Assessment (1986)[DOE 1986a] NWPA Site Characterization Plan (SCP) (1988)[DOE 1988]
	WIPP	Literature search by ORNL & USGS (1972 to 1973)[Rechard 2000] AEC-6 & AEC-8 drilled in Delaware Basin (1974)[Rechard 2000] ERDA-6 (1975) & ERDA-9 drilled at WIPP (1976)[Rechard 2000] Site characterization plans (1975-1976)[Rechard 2000]
2. Feasibility analysis demonstrating calculation procedures, and importance of system components based on rough measures of performance using surface exploration, waste process knowledge, and general laboratory experiments	YMP	G, H, WT, UZ boreholes drilled (1981-1984) Heater tests in G-Tunnel at NTS (1980-1989)[Zimmerman and Finley 1987] Bomb pulse ^{36}Cl measured in boreholes (1993)[Fabryka-Martin et al. 1993] CSNF release measured in batch tests (1987-1990).[Wilson 1987a;Wilson 1990a;] PACE-90[Barnard and Dockery 1991] PA-91,[Barnard et al. 1992] PA-PNNL-91[Eslinger et al. 1993] Early Site Suitability Evaluation (ESSE) (1992)[Younker et al. 1992] TSPA-93[Wilson et al. 1994], TSPA-M&O-93[Andrews et al. 1994] TSPA-95,[Atkins et al. 1995] TSPA-96, [CRWMS M&O 1996a] PA-97, [CRWMS M&O 1997a] PA-SNL-95,[Rechard 1995] PA-SNL-97 (for DSNF)[Rechard 1998]
	WIPP	Laboratory tests on TRU wastes (1976)[Rechard 2000] Geologic characterization report (1978)[Rechard 2000] EIS for site selection (1980)[DOE 1980a] SAR for construction (1980)[Rechard 2000] 1989 WIPP PA [Marietta et al. 1989]

Table 3-2: Study phases for radioactive wastes disposal in the United States (con't)

Study Phase	Disposal System	System Studies and Other Activities
3. Viability analysis demonstrating suitability of disposal system based on underground disposal system characterization, in-situ experiments, and environment-specific laboratory experiments	YMP	SD boreholes (1994-1998) Excavation of ESF and ECRB and process testing (1994-1998) Infiltration monitoring (1984-1996) Seepage tests at niches (1997-1999) Single Heater Test (SHT) in Alcove 5 (1996-1997)[CRWMS M&) 1999d, Ch 10] Drift Scale Test (DST) in Alcove 5 (1997-2002)[NWTRB 1998] Large-Block heater Test at Fran Ridge (1996-1997)[NWTRB 1998] Migration tests at Busted Butte (1998-2003)[Tseng et al. 2003] TSPA-VA (1998),[DOE 1998] LADS (1999)[CRWMS M&O 1999c] TSPA-SR (2000),[DOE 2001a] SSPA (2001)[DOE 2001b] Site Suitability Evaluation (PSSE) EIS (2002)[DOE 2002]
	WIPP	1st (1981), 2nd (1982), 3rd (1985), and 4th (1988) shafts drilled [Rechard 2000] Excavation of experimental rooms (1983-1984)[Rechard 2000] Supplemental siting EIS (1990)[DOE 1990] 1990, 1991, 1992 WIPP PAs[Bertram-Howery et al. 1990; WIPP PA 1991; WIPP PA 1992]
4. Compliance analysis	YMP	Supplemental EIS for construction (2008)[DOE 2008a] 2004 and 2005 drafts of TSPA-LA for internal review PA-LA/SAR—safety assessment for construction (2008) [DOE 2008b]
	WIPP	Draft Compliance Certification Application (1994)[Rechard 2000] WIPP PA and Compliance Certification Application (1996)[DOE 1996] EIS for operation (1997)[DOE 1997]

Site characterization performs two functions: (1) it provides information to demonstrate understanding of the behavior of the natural barriers of the disposal system; and (2) it provides information for the performance assessment, which uses scientific information to analyze the potential behavior of the waste in the engineered barriers and natural barriers in order to assess the compliance of a disposal system with regulatory requirements.

3.2. Site Selection for WIPP

Quoting from the Historical Background on Performance Assessment for the Waste Isolation Pilot Plant and as summarized in Appendix B:[Rechard 2000]

> With the encouragement of Carlsbad's politicians and citizens, and the tacit approval of New Mexico's governor Bruce King, ORNL [Oak Ridge National Laboratory] examined a portion of the Permian Basin called the Delaware Basin in southeastern New Mexico in the early 1970s for a suitable disposal site for nuclear waste. The area was semi-arid with little potable water and no significant, highly permeable aquifers near the surface. At that time, the area was being considered for disposal of both high-level waste and TRU waste generated during production of nuclear weapons. A potential site near the edge of the basin along the Capitan Reef was identified in 1973. ORNL drilled two wells, AEC-7 and AEC-8, in March 1974 near the northeastern and southwestern corners of the rectangular site for the first large-scale field test in the basin. (Prior to this test, the USGS had conducted some tests for the AEC in 1961 for the Gnome Project and so some data on aquifers were already available.) The cores from the two wells indicated fairly predictable stratigraphy…
>
> One of New Mexico's ERDA laboratories, Sandia National Laboratories, began work at the site selected by ORNL in January 1975... In May 1975, Sandia drilled a combination geologic and exploratory well, ERDA-6, at the northwestern corner of the proposed site. The well encountered up to 75^o dipping beds and, at a depth of 826 m, artesian brine and H_2S gas…
>
> … In late 1975, after examining the stratigraphy shown in the ERDA wells, along with confidential data from numerous private wells owned by oil companies and confidential

geophysical seismic data, Sandia recommended locating the potential repository site nearer the basin center. The USGS independently suggested a similar location. The new site was about 11 km from the first location, away from the ~10-km band around the Capitan Reef where deformation of the salt beds occurred, and with more predictable horizontal stratigraphy. In April 1976, Sandia drilled ERDA-9 through the Salado Formation into the Castile Formation at the center of the proposed site, which was 42 km from the town of Carlsbad, New Mexico. The stratigraphy was horizontal and no brine was encountered [down to the Castile Formation]. This site became the Waste Isolation Pilot Plant (WIPP).

3.3. Site Selection Guidelines for HLW/SNF Repositories

3.3.1. Site Selection Schedule and Guidelines

The NWPA established a program and an aggressive schedule for characterizing and selecting sites for two repositories (Table 3-2).

Table 3-3: Site screening schedule of *Nuclear Waste Policy Act of 1982* as amended.

Repository Action	First repository	Second repository
Issue siting guidelines	Within 180 days of passage of Act	Same
Nominate at least five sites suitable for characterization	Following issuance of guidelines	No later than July 1, 1989 and must include at least 3 sites not nominated in first round (deleted by NWPAA)
Recommend three sites for characterization	January 1, 1985	July 1, 1989 (deleted by NWPAA)
Recommend one site for construction authorization	March 31, 1987 (extendable by 1 year) (deleted by NWPAA)	March 31, 1990 (extendable by 1 year) (deleted by NWPAA)
Recommend another site if first is disapproved	Within one year of disapproval (deleted by NWPAA)	Within one year of disapproval (deleted by NWPAA)

3.3.2. General Guidelines (10 CFR 960)

The NWPA requires DOE to issue general guidelines for the recommendation of sites for repositories to apply to both the first and second repository programs. The very tight timetable for developing the siting guidelines soon demonstrated the conflict between the Act's aggressive schedule for operation of the first repository in 1998 and the intent of the Act to promote public involvement and credibility. The DOE chose to take the time for a formal rulemaking proceeding with public participation (although a rulemaking was not required by NWPA), and did not complete the guidelines (10 CFR 960) until December of 1984. Nonetheless, key stakeholders remained dissatisfied with the process and result, calling the guidelines "overly general, lacking in specificity and capable only of subjective application."[7]

The NRC's generic repository regulations, 10 CFR 60, also contain criteria related to evaluation of specific characteristics of a site separately from evaluation of its long-term performance. The criteria

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[7] Nevada's Statement of Position Re: Shortcomings in the Repository Program,[Senate 1987a] "The Department's site selection guidelines, the fundamental vehicle which Congress intended to insure the objectivity and sound technical basis for site selection in the entire program, are hopelessly flawed, and violate the fundamental standard adopted by Congress in the Act. They are incapable of objective application, but were rather designed to insure that none of the current sites would be disqualified early, thus maintaining the Department's predetermination in the selection of sites for characterization." ….."The program is driven by a schedule that is itself propelled by a fixed and, some would argue, unrealistic target date. The framework by which siting and suitability decisions will be made, the siting guidelines, is overly general, lacking in specificity and capable only of subjective application."

established in these regulations are generally framed in terms of qualifying, favorable, potentially adverse, and disqualifying conditions, with several disqualifying features specified in the NWPA. Examples of favorable criteria include a stable tectonic setting with a low probability of seismic or igneous disruption, groundwater chemistry that is reducing, low groundwater fluxes, and a rock body that meets geomechanical criteria to reasonably host a repository.

U.S. guidelines as framed in 10 CFR 60 and 10 CFR 960 are generally consistent with international criteria that have been adopted, to the extent allowed by a country's geologic setting, by virtually all countries with repository programs. These generally accepted criteria have been formalized in the reports of numerous national programs and by international bodies such as the IAEA. An overriding condition for an acceptable site is that of stability and the avoidance of highly dynamic geologic settings (e.g., tectonically active regions) that could change the predicted performance of a repository system over time. As describe by the IAEA, typically suitable environments for geologic disposal would satisfy the following conditions:[IAEA 2003]

- Long term (millions of years) geological stability, in terms of major earth movements and deformation, faulting, seismicity and heat flow;
- Low groundwater content and flow at repository depths, which can be shown to have been stable for periods of at least tens of thousands of years;
- Stable geochemical or hydrochemical conditions at depth, mainly described by a reducing environment and a composition controlled by equilibrium between water and rock forming minerals;
- Good engineering properties which readily allow construction of a repositories well as operation for periods which may be measured in decades.

An example from the Japanese repository program describes siting criteria that emphasize simplicity and predictability, and would streamline site characterization relative to more complex sites:[NUMO 2004]

> **Geological and hydrogeological simplicity:** areas with geological structures and groundwater flow systems that are less complex and more readily predictable are preferred. They are also easier to investigate and characterise. Sedimentary rocks with uniform lithology and structure over many kilometres, and crystalline rocks that are relatively homogeneous and undeformed, are considered to provide the simplest geological environments in this respect. The geological environment that can be characterised using currently available remote sensing, geological, geophysical, drilling and borehole investigation techniques are preferred (NUMO, 2004).

While probably not wise to be overly proscriptive, specifying a few simple and basic site conditions that would exclude a site could provide long-term benefits in enhancing credibility with the scientific community and the public, saving time and cost during the site characterization phase, reducing uncertainty in the safety case, and streamlining the process of determining the initial feasibility of a site in the event that a future siting process includes the volunteering.

3.3.3. Yucca Mountain-Specific Guidelines (10 CFR 963)

The 1987 amendments to the NWPA designating Yucca Mountain as the single site to be characterized did not lead to any changes in 10 CFR 960, which was still expected to be used in the determination of whether to recommend Yucca Mountain for licensing. However, when the Energy Policy Act of 1992 directed EPA and NRC to issue Yucca Mountain-specific regulations, the Department decided to issue a Yucca Mountain-specific set of Site Suitability Guidelines at 10 CFR 963 for the evaluation of the suitability of the Yucca Mountain site that focused on total repository system performance. These new guidelines are tied to EPA and NRC's Yucca Mountain regulations, 40 CFR 197 and 10 CFR 63. The old siting guidelines of 10 CFR 960 remain tied to the generic EPA and NRC repository regulations, 40 CFR 191 and 10 CFR 60. While 40 CFR 191, 10 CFR 60 and 10 CFR 960 remain applicable to any repository site other than Yucca Mountain, certain considerations call into question their viability for a new repository site screening task. Hence, a decision to seek other repository sites must consider the necessity of revising the DOE siting guidelines at 10 CFR 960, as well as the NRC and EPA regulations at 10 CFR 60 and 10 CFR 191.

3.3.4. Lessons Learned about Siting Guidelines

1. Assuming new siting guidelines need to be developed, developing these well in advance of the siting process and using them consistently throughout may be needed to avoid the perception of “changing the rules to fit the site” that occurred with the change from generally-applicable guidelines to Yucca Mountain site-specific guidelines.
2. Establishment of an overall performance standard prior to the establishment of siting guidelines would help avoid a potential perception that the regulations can be changed to match the site(s) under consideration. However, while developing a regulation early has advantages, it also has a risk of setting a path that the site screening process might not be able to follow effectively. This consequence is discussed in the 1990 NAS report *Rethinking High-level Radioactive Waste Disposal.*
3. New guidelines should recognize that there is no such thing as a perfect site and that the objective is to select, characterize, and develop a site that is protective of public health and safety.
4. Absolutes such as rigid pass/fail disqualifying conditions should be avoided if possible, since they can lead to “gaming” the process to exclude specific sites for other reasons and to rejection of sites that might not meet a rigid criterion but that could still host a safe repository that fully meets disposal requirements.
5. Guidelines favoring simplicity of sites must consider that the experiences with WIPP and Yucca Mountain show that the more a site is studied, the more complexity is revealed. Features may be discovered during detailed site characterization that would be inconsistent with initial screening criteria, but would not adversely affect the ability to develop a safe repository. Hence, while simplicity may be an initial selection criterion, complexity discovered during site characterization should not be a disqualifying criterion.
6. The question of how siting guidelines would be applied for a stepwise development process needs to be addressed.

3.4. Implementation of Siting Process

3.4.1. Siting Process for a First Repository

After a potential disposal site in bedded salt in Kansas was rejected in 1972, ERDA, the successor to AEC, searched again for permanent disposal sites with the help of the US Geological Survey (USGS). Winograd, a geologist at the USGS, had earlier suggested disposal in unsaturated thick alluvium for HLW and TRU (as summarized in Appendix A). In 1972, Senator Cannon (NV) urged the AEC to consider the Nevada Test Site (NTS). In 1975, the Nevada legislature asked ERDA to consider NTS for management of radioactive waste.

In 1978, the newly formed DOE decided that a repository could be built in the southwestern portion of NTS and not disrupt weapons tests. Site investigations began at the Calico Hills area to look at granite and argillite; Wahmonie to look at granite, and Yucca Mountain to look at volcanic tuff. The investigations found only small, highly fracture granite masses and structurally complex argillite; however, borehole UE-25a#1, cored to ~2,500 ft, confirmed the presence of thick volcanic tuff deposits.

In 1979, the USGS recommended that investigations focus on welded tuff at Yucca Mountain underlying Yucca Mountain.[DOE 1985] By 1982, s Site Evaluation Working Group had formally screened 15 locations in southwestern portion of NTS and reported that Yucca Mountain remained the preferred site for a repository.

Due to the extremely tight schedule constraints on the siting process for the first repository, the nine sites that were previously under consideration using administrative procedures formed the basis for site screening for the first repository under NWPA: two sites in Texas and two sites in Utah, all in bedded salt; two sites in Mississippi and one in Louisiana in dome salt; one site in Washington State in basalt; and the Yucca Mountain site in Nevada in tuff. (The alternative of starting with a national site screening process had been explicitly considered and rejected during the debates on the NWPA.) This led to some questions about whether the guidelines could be applied fairly and effectively if the sites for initial consideration were already selected before the guidelines were developed.[OTA 1985]

By December 1984, DOE had issued draft Environmental Assessments (EAs) of all nine sites as required by NWPA. The draft EAs suggested five candidate sites for nomination (three salt sites: Davis Canyon, Utah; Deaf Smith, Texas; Richton dome, Mississippi; one basalt site: Hanford, Washington; and one tuff site: Yucca Mountain). The DOE also presented a ranking analysis in the draft EAs, that suggested Deaf Smith, Yucca Mountain, and Hanford were the top three of the five candidate sites.[Joy et al. 1985] As part of the EA, DOE also completed a preliminary evaluation of Yucca Mountain against 10 CFR 960 site selection guidelines and found no disqualifying conditions.

DOE completed final EAs for the five sites by May 1986. Because of criticism of the ranking analysis used for identifying the list of five nominated sites, multi-attributive utility decision analysis was applied. The multi-attribute analysis ranked Deaf Smith 1st, Yucca Mountain 3rd, and Hanford 5th. However, when DOE included the concept of lowering overall program risk by using a "portfolio" of sites, as suggested by the Interagency Review Group in 1979,[IRG 1979] required by NWPA to recommend sites in different geologic media, and codified in the site guidelines (10 CFR 960), the Secretary of Energy recommended and President Reagan concurred in characterizing three different media for a repository. The Yucca Mountain tuff site added diversity to the sites in salt and basalt.

Congress decided to continue characterization of only Yucca Mountain in the *Nuclear Waste Policy Amendments Act of 1987* (NWPAA). Site selection by Congress was perceived as unfair and led to unwavering opposition to Yucca Mountain by state officials thereafter. The Early Site Suitability Evaluation (ESSE), a second preliminary evaluation of Yucca Mountain against 10 CFR 960 guidelines, was published in January 1992. Again, DOE reported no disqualifying conditions.

3.4.2. Siting Process for Second Repository

The site for the second repository was to be selected in a similar process, and the DOE chose to pursue a crystalline rock site in the eastern United States in order to comply with the requirement for a regional distribution of repositories. By 1986, more than 200 crystalline rock bodies in 17 states had been screened prior to selecting 12 rock bodies in the 7 states of Michigan, Wisconsin, Maine, New Hampshire, Virginia, North Carolina, and Georgia for further consideration. However, in the announcement that designated the three candidate first round sites, DOE also indefinitely deferred the search for a second repository site because the additional waste disposal capacity was not needed because new reactors were not being built as had previously been expected.

In the 1987 Mission Plan Amendment released before passage of the Amendments Act, the Department described an alternative program for proceeding with a second repository that started the second repository program over again with a national site screening process that would expand the types of geologic media and number of geographical areas considered. Some work already existed at that time to provide a basis for such an alternative approach. For example, in order to increase the diversity of rock types under consideration by the geologic repository program, the DOE had initiated the Sedimentary Rock Program (SERP) in 1984. The objective of this program was to evaluate five types of sedimentary rock (sandstone, shale, chalk, carbonate rocks, and anhydrock) to determine the potential for locating a geologic repository site in one of these rock types. In that evaluation, shales were found to be equal to, or better than, the other four rock types. Hard or rocklike shales having the favorable characteristics leading to this conclusion occur extensively in the conterminous United States.[DOE 2008]

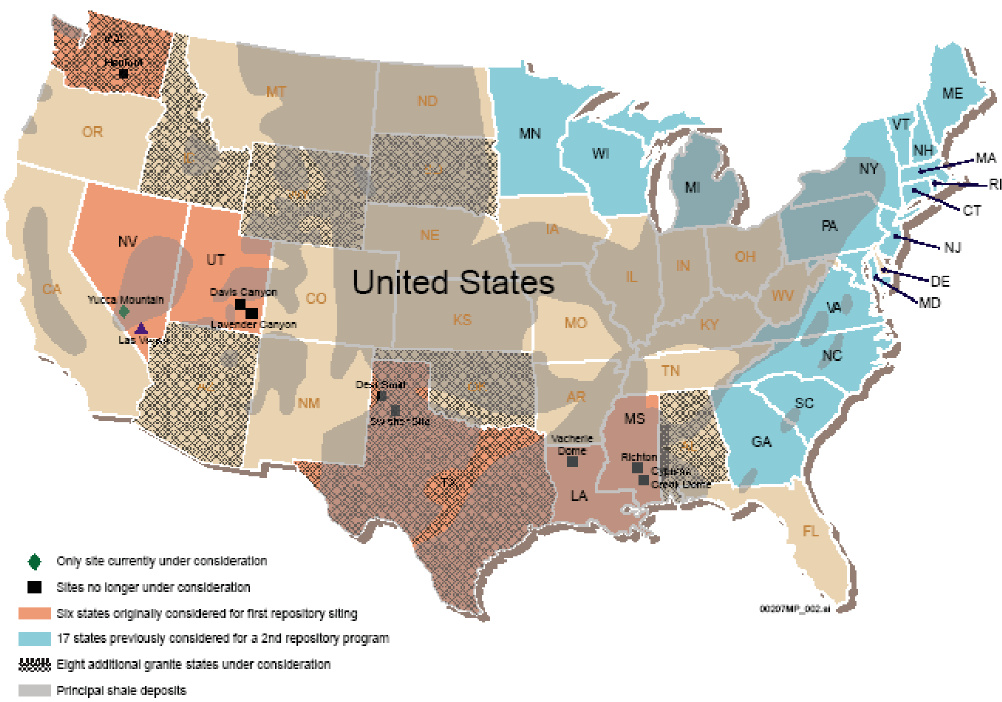

Figure 3-1: First repository sites, second repository areas, and shale deposits potentially suitable for a repository.[DOE 2008]

3.4.3. Lessons Learned from Implementing Siting Process

1. The diversity of sites that have been or are being considered in the U.S. and the international community indicates that many different media can host a repository. Granite repository concepts have been evaluated in detail in Sweden, Finland, Switzerland, and Japan. Clay/shale disposal concepts have been evaluated in detail in France, Belgium, and Switzerland. Salt has been shown to be a viable medium for disposal of non-heat-generating transuranic waste at the Waste Isolation Pilot Plant in the US, and research in Germany continues to show promise for the disposal of heat-generating waste in salt. Tuff has also been shown to be a viable medium in the US. Other geologic media are under consideration for specific purposes (e.g., Canada is investigating the use of a mined repository in carbonate rocks to dispose of intermediate level waste, and the US has disposed of low-level and transuranic waste in near-surface alluvium). In the future, a few sites may need to be simultaneously under examination to reduce program risk because of social-political issues, but diversity of media should not be particularly necessary.

2. One important lesson to be learned from the siting process of the NWPA was that the medium under consideration was not a principal discriminator in the siting process. Under 10 CFR 960 decisions about the medium are quite far down in decision sequence, and enter only because there is a requirement for diversity in the geologic media.
3. Use of a systematic, unconstrained site screening process (as in the case of the second repository) was not sufficient to avoid strong public and political reactions when the process began to narrow down to specific areas. Although the schedule in the NWPA required the DOE to essentially adopt the sites for first repository that where under study using the administrative procedures prior to NWPA, the second repository did follow the legislative procedures of NWPA as codified in 10 CFR 960 and still generated strong opposition when 12 rock bodies were identified for further investigation.[Carter 1987]

3.5. Collection of Data for Site Selection

3.5.1. Legislative Constraints on Data Collection

One of the challenging issues for site screening and for the comparative evaluations needed to choose candidate sites for full site characterization is the need, availability and ability to acquire the necessary data needed to reach siting decisions. Currently, the NWPA, §112(b)(3), places restrictions on what data can be gathered during site screening and evaluation:

> ... prior to any decision to recommend a site as a candidate site, the Secretary shall use available geophysical, geologic, geochemical and hydrologic, and other information and shall not conduct any preliminary borings or excavations at a site unless (i) such preliminary boring or excavation activities were in progress upon the date of enactment of this Act or (ii) the Secretary certifies that such available information from other sources, in the absence of preliminary borings or excavations, will not be adequate to satisfy applicable requirements of this Act or any other law: Provided, That preliminary borings or excavations under this section shall not exceed a diameter of 6 inches.

The fact that there was a wide variation in the quantity and quality of data available for the various sites under consideration for the first repository led to some concern that it would not be possible to make a sound technical choice among the available sites, and to arguments that DOE should postpone selecting sites for characterization until more information on the current sites could be obtained or even until additional sites could be identified and evaluated. However, the Act's provisions concerning pre-characterization data collection emphasized use of already-available data and would have constrained the ability to obtain new information. Although clause (ii) above allows for exceptions to the general prohibition on new borings or excavations at sites under consideration, it requires a Secretarial certification that existing data is inadequate to meet statutory requirements that do not clearly define data needs. The need for a case-by-case Secretarial certification that existing data is inadequate—not merely a Secretarial approval—would discourage exercise of the exemption, particularly in view of the tight NWPA schedules for the siting process.

During Senate hearings on the waste program in 1987, the NRC stated that it might be possible to obtain conclusive data for some disqualifying factors from surface-based testing alone, in which case it would not be necessary to complete the entire site characterization program. With the restrictions included in the original Nuclear Waste Policy Act, however, such testing could only be performed as an initial phase of tests at a site that had already been selected for characterization, instead of being used as a way to screen a larger suite of sites that were being considered for selection for characterization.

Countries that are currently in the early stages of repository development have sought to apply lessons learned from more mature international programs to develop data-gathering strategies. In the

Czech Republic, for example, a process began in 2001 to survey the entire country for potential sites.[Witherspoon and Bodvarsson 2006] Using exclusion criteria that included the presence of volcanism, faults, hydrothermal activity, mineralization, and rock bodies that would not feasibly allow repository construction, eleven sites were chosen as suitable for further evaluation. The eleven sites were chosen on the basis of existing information and data. Based on and "advantages and disadvantages" analysis that considered factors such as transportation infrastructure, population density, land ownership and public acceptance, the implementing organization decided to begin preliminary site investigation and characterization at six sites.

In 2003, as part of the earliest stage of data gathering, the Czech program completed a standardized set of airborne geophysical measurements that included gamma-ray spectrometry, magnetic and electromagnetic data.[Barta 2005] These data provided insight into lithologic boundaries, fault and fracture zones, alteration and mineralization zones, and hydrologic saturation. One of the benefits of the Czech approach is that the comparative evaluation of all six candidate sites is proceeding from a common and equal geophysical database that will mitigate biasing of future decisions that could arise from unequal availability of data among multiple sites. This approach has the additional benefit of building technical and implementer credibility with stakeholders. A future down-selection among alternative site is planned that will lead to two sites being fully characterized.

Gathering of site-wide geophysical data for characterizing subsurface geology is considered to be one of the most valuable and non-intrusive data-gathering methods that can be employed during the early stages of site screening or evaluation.[NWMO 2008] One of the issues identified during the earliest stage of the Yucca Mountain site investigations was the possible presence of buried volcanoes in alluvial basins surrounding Yucca Mountain. Data on the age, number and location of potentially buried volcanoes was important in building volcanic framework models that provided the data to conduct probabilistic volcanic hazard analyses. Plans to obtain ground-based magnetic data for identifying and characterizing buried volcanoes were formulated in the mid-1980s but the work was continually deferred due to funding limitations and changing programmatic priorities. In the end, these studies were never conducted as part of formal site characterization activities prior to the time of the Site Recommendation in 2002. A site-wide aeromagnetic survey was eventually flown in 2004 in response to a Request for Additional Information from the NRC in 2002.[Perry et al. 2005] This survey resolved remaining questions concerning the volcanic history of the region and provided programmatic and regulatory confidence in the results of a 1996 probabilistic volcanic hazard analysis that was used to support the Yucca Mountain safety case.

3.5.2. Lessons Learned Concerning Collection of Data for Site Selection

1. One of the lessons learned from the Yucca Mountain Project is the value in obtaining basic subsurface data as early as possible during site evaluation and characterization.
2. A site screening process should allow an intermediate stage and level of data collection between use of already available data in early phases of screening multiple sites and detailed at-depth evaluation of one or a few sites selected as primary candidates for a repository.
3. Site screening processes being undertaken in other countries warrant additional evaluation.

3.6. Site Screening with Voluntary Siting

3.6.1. Voluntary Siting

An additional consideration for the establishment of any new siting guidelines is the policy adopted in many countries to encourage applications from volunteer communities to host a repository. At issue for siting is whether it would be desirable to have guidelines that are sufficiently proscriptive so that a volunteered site could be quickly excluded if it does not meet simple and basic siting criteria, or instead whether guidelines should be less rigid (e.g., current US regulations), which might require a more extensive process of evaluation to determine whether a volunteered site is potentially suitable.

The 1987 NWPAA created a Nuclear Waste Negotiator empowered to seek a voluntary site for either a monitored retrievable storage facility (MRS) or a repository. However, the Negotiator focused on finding an MRS site, and the issue of precisely whether and how the Act's repository siting guidelines and site characterization requirements would be applied to a volunteer repository site was never addressed.

Siting frameworks based on communities volunteering a site have been implemented or are under consideration in most countries with repository programs.[NWMO 2006] The most advanced examples are those of Sweden and Finland in which communities willing to host a repository have been identified. Japan began a voluntary process for siting a repository in 2002, but has not identified a candidate yet.

3.6.2. Lessons Learned Concerning Site Screening for a Voluntary Siting Process

1. The site evaluation criteria and procedure for a voluntary siting process need to accommodate the possibility of few volunteers, perhaps only one, in which case the focus would be to determine whether a specific site is suitable rather than whether it is the best of a substantial suite of candidates.
2. The site evaluation processes that were used in voluntary approaches in other countries merit evaluation for possible relevance to any US voluntary siting process.

3.7. Site Characterization

3.7.1. Cost of Site Characterization

When NRC's original repository regulations (10 CFR 60) were developed, the NRC expected that the in-situ site characterization required by the regulation would involve about 1000 feet of underground drifting and cost less than $60 million.[OTA 1985, p. 142] By the time the first three sites were recommended for characterization in 1986, the estimated cost of characterization had ballooned to over $1 billion per site, providing a major rationale for the decision to limit characterization to one site. By the time of the 1998 Viability Assessment was completed,[DOE 1998] which was before any major expenditures on detailed facility design and a license application had been incurred, the cost of work at Yucca Mountain had increased to nearly $6 billion, most of which was related to site investigations.

These cost escalations were an unpleasant surprise to key Senator J. Bennett Johnston, chairman of the two key Senate bodies with control over the high level waste program: the Committee on Energy and Natural Resources (with legislative authority) and the Energy and Water subcommittee of the Appropriations Committee (with funding control). At a hearing on the state of the program in 1987, during the turmoil following deferral of the second repository program, he said: "It was a great shock to me to learn that the cost of characterization of these sites has grown from what we were told in 1982 about $60 million a site to about $1 billion a site." [Senate 1987a] At a later session of the same set of hearings, he made an observation that presaged the legislation that was adopted at the end of the year: "If we can characterize one site instead of three, we save at least $2 billion. Now $2 billion is a lot of money in anybody's ballgame."[Senate 1987b]

At a March 31, 1992 hearing of a Senate Energy Appropriations Subcommittee on the disposal program's proposed budget, Subcommittee Chairman Johnston and his colleagues seriously questioned the viability of a disposal program whose costs continued to escalate without tangible results to show for it, or even the prospect of a favorable result. They were clearly disturbed at estimated costs of site characterization that had risen from $60 million in 1982 to $6.3 billion at the time of the hearing, and at the prospect that it would cost that much simply to find out whether Yucca Mountain is a suitable site. Senator Johnston commented: "The program is broke; it needs fixing."[DOE 1993]

By 1993, it had become clear that the program was no longer supportable in Congress, and a quicker, less expensive approach was needed. In response, OCRWM developed a new program approach that streamlined the site characterization effort and deferred some planned tests until after the site recommendation and license application.[DOE 1994] Recognizing the need for a significant milestone of repository progress earlier than the projected 2001 date for the license application, the Program Approach include a 1998 "Technical Site Suitability" decision—a formal assessment of the site against the Department's own site suitability guidelines.

The new program approach involved a major restructuring of the approach to site characterization. The previous approach called for extensive testing to obtain a comprehensive understanding of the Yucca Mountain site to allow decisions to be made simultaneously on site suitability, licensing and repository design issues. It was based on the anticipation that all of the tests outlined in the 1988 Site Characterization Plan (SCP) would be completed before determination of the suitability of the site for a repository.[DOE 1988] However, because the site characterization schedule did not call for definitive results until a license application was completed in 2001, progress was difficult to demonstrate or measure. In addition, due to continuing shortfalls in annual funding over the preceding five years, large annual funding requirements would have been needed under the existing Program approach for the next five years to maintain the schedule for disposing of waste in 2010. These requirements exceeded practical funding expectations.

The new program approach distinguished between tests required to evaluate site suitability, tests required to support licensing and define a cost-effective design, and tests required to confirm the safety of the repository before closure. This distinction permitted phasing of tests to achieve an earlier evaluation of whether Yucca Mountain appeared to be suitable and to preserve the schedule for licensing, constructing, and operating the repository if the site were found suitable. It also accommodated available resources.

During 1994, OCRWM developed a proposed technical site suitability evaluation procedure based on the existing siting guidelines, through public and stakeholder participation in the form of numerous public meetings, briefings, and workshops, and responses provided to OCRWM Federal Register Notices of Inquiry. The technical site suitability evaluation centered on a sequential evaluation of compliance with the Department's siting guidelines in 10 CFR Part 960 related to long-term waste isolation, radiological safety, and technical feasibility. The evaluation was to utilize site characterization data and analyses that would be documented or referenced in technical basis reports subject to external peer review, followed by assessments of compliance by Program technical staff against one or more of the siting guidelines, and finally, if appropriate, findings by the Director of compliance with the guidelines.

If the site appeared to be technically suitable, site characterization activities after 1998—including *in-situ* thermal testing—would focus on the development of a license application and more cost-effective repository and waste package designs. Results would provide input to the repository environmental impact statement in 2000, to the license application in 2001, to interactions with the Nuclear Regulatory Commission during the licensing process, and to an amended license application in 2008. Confirmatory testing—including tests in selected drifts of the expanding underground facility—would continue through the construction and operation of the repository to ensure that the repository performs as predicted. Testing to confirm the performance of the repository would continue until closure—a period of at least 50 years and possibly up to 100 years.[DOE 1994]

Congress funded one year of the new approach, with an FY 1995 appropriation of $512 million, a substantial increase over the previous year. However, the new majority taking office in 1995, preoccupied with deficit reduction, cut the FY 1996 appropriation sharply, with an effective funding level of $315 million compared to the $630 million requested to continue the 1994 Program Approach. These cuts necessitated an even more streamlined and less expensive approach that focused on a Viability Assessment in 1998 to provide a less formal near-term progress milestone to replace the Technical Site Suitability decision in the 1994 plan.[DOE 1998] The process for a sequence of partial findings of compliance against the siting guidelines, culminating in the technical suitability decision in 1998, was dropped. The budget cuts forced a careful assessment of the data that had already been collected and its implications for testing that remained to be done, leading to the conclusion that some of the tests included in the SCP no longer appeared necessary. To some extent, the reduced scope in the near term reflected a better recognition that the NWPA and the EPA and NRC regulations anticipated that not every scientific issue would have to be closed at the time of initial repository licensing, and that some of the contemplated tests would not have to be conducted until later, to confirm the analyses that supported the initial license.

Presumably, the Yucca Mountain licensing proceeding would have revealed whether the streamlined program was sufficient, considering the inflation of expectations about the degree of certainty required for the initial licensing decisions that appears to have occurred since NWPA was passed and the regulations were promulgated In other words, the expectations from both DOE and NRC appeared to have been (although not documented) that a large majority (greater than 75% and as much as 95%) of the achievable certainty about repository performance was necessary for authorizing construction of the repository even though this level of certainty was not the intent of the regulation when it was issued. As noted above, when the Act was passed, NRC expected that the in situ portion of site characterization would involve perhaps 1000 feet of tunnel. The ESF that was finally constructed involved on the order of 5 miles of tunnel.

3.7.2. Lessons Learned about Site Characterization

1. Considering that the sharp escalation of projected site characterization costs in the 1980s provided a major rationale for the decision to limit characterization to one site, continued high costs for site characterization may be an obstacle to the characterization of multiple sites in any new repository siting program.
2. Experience with characterizing the WIPP and Yucca Mountain sites showed that once a site is selected for detailed evaluation, the focus moves to uncertainties and the question becomes one of whether enough work has been done to resolve them. The data needs related to uncertainty become driving factors, leading to significantly increasing costs and schedules if unconstrained and could occur at every site that is identified for potential selection. Program scientists tend to propose a broad set of activities that could be done to address uncertainty. Program managers could have difficulty assessing whether they need to be done, particularly in the absence of established performance requirements and siting guidelines to guide the program.
3. The regulatory framework should be established in advance of the siting process to provide clear performance objectives.
4. Selection of multiple sites in similar media may provide both the regulator and the investigating organization a better perspective since relative uncertainties can be compared rather than abstract absolute uncertainties.
5. Use of performance assessment to prioritize data collection needs has proved useful both in the US and internationally. At WIPP, [Larson et al. 1999] "The key lesson learned is that as a project matures, it is not the perspective of experimental scientists, but rather the total-system PA methods (FEP analysis and screening, uncertainty analysis, modeling, and sensitivity analysis) that provide the context for evaluating the need for additional data."

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4. Non Site-Specific Research and Development

The schedule for siting and developing geologic repositories is undetermined, pending the recommendations of the *Blue-Ribbon Commission on America's Nuclear Future* and any subsequent Congressional action to provide the necessary legislative authority for a new repository program. It is important, however, to maintain progress in research and development (R&D) in repository science and technology development in the repository operations over the next several years while the US reevaluates nuclear waste management policies. Establishing the capability for high level waste management and disposal involves (1) developing the appropriate combination of engineered and natural barriers that will provide adequate long-term isolation, and (2) developing the capability to handle, transport, package, and emplace spent fuel at high annual rates (i.e., 1000s of metric tons per year).Both underground and surface test facilities can be used to support the development of the necessary capabilities.

Related to repository science, several international programs (e.g., Swedish, Swiss, and Japanese) maintain and fund research collaborations with individual US principal investigators. Broadening and formalizing these collaborations may be the most time and cost-effective method to initiate a new and formal R&D program to understand key repository processes in the alternative geologic media. As part of renewed US-International collaborations in alternative geologic media, it would be beneficial to review the large variety of tests that have been performed internationally in order to inform and guide future R&D that would require testing in an underground research laboratory (URL). Although consideration should also be given to international collaborations to develop and test the capability to handle, transport, and package UNF, collaborations with nuclear utilities and nuclear industry to develop operational test and evaluation facilities (TEFs) within the US is likely more beneficial and could be combined with studies on long-term storage discussed in §6.0 and studies integrating nuclear waste handling, storage, and transportation discussed in §7.0

Both the U.S. and International programs have recognized that repository development poses both technical and social challenges. URLs and operational TEFs may help meet the social challenges by contribution to the public confidence that nuclear waste can be feasibly and safely disposed of in geologic media. URLs and TEFs provide the setting needed to undertake repository scale process simulations, something that cannot be accomplished without underground access. URLs and TEFs could be a component of an overall waste management program by combining a long-term research facility and its associated benefits with a storage/disposal facility.

With the entire approach to repository development under consideration by the Blue Ribbon Commission, consideration might be given to use of the existing test and evaluation provisions of the NWPA, perhaps with some modifications, to allow interim steps towards full-scale operations that would support a "learn as you go" staged deployment concept.

Past work at URLs in the US and current international URLs are discussed below. Potential uses for a surface testing and evaluation facility (TEF) are also discussed.

4.1. Underground Research Laboratories

4.1.1. URL Purpose

Understanding the behavior of the natural and engineered barriers involves experimental studies at both the bench and field scale, while advances in construction and operational aspects of repository development will ultimately require repository (field) scale tests. Underground research laboratories (URLs) are critical to a more complete understanding of how radionuclides are transported within natural barriers while accounting for natural rock heterogeneity and coupled thermal, hydrological, and chemical processes.[Kickmaier and McKinley 1997] The NEA notes that "Importantly, relative to surface-based investigation techniques or laboratory research, a URL provides access to the geologic environment under realistic repository conditions.”[OECD-NEA 2001b]

The IAEA noted several roles for URLs that include[IAEA 2001]

1. Improving the methodology and tools for site characterization,
2. Assessment of geological and engineered barriers,
3. Demonstration of construction techniques and repository operations,
4. Building confidence and stakeholder acceptance, and
5. Fostering international collaborations.

International URLs and URLs in the U.S. have broadly fulfilled all of these roles for each of the major rock types considered internationally for geologic disposal. In terms of understanding the natural and engineered barriers, experimental studies at both the lab and URL scales are necessary to fundamentally understand radionuclide transport processes in potential geologic media for future repository development.

4.1.2. URL Experience in United States

Underground testing concerning high-level radioactive disposal began over 40 years ago in the US. URLs in the US have generally been site-specific and have operated for a limited time to meet a well-defined and limited testing scope.

URL Experiments in Salt

- *Project Salt Vault*: From 1961 through the early 1970s, Oak Ridge National Laboratory (ORNL) conducted radioactive-waste disposal experiments, most notably Project Salt Vault in an abandoned salt mine near Lyons, Kansas, from 1963 to 1967. The Salt Vault experiments involved emplacement in the floor of the mine of 14 irradiated fuel assemblies from the AEC’s Experimental Test Reactor to simulate solidified high-level waste. Electrical heaters were also installed in the central pillar to obtain information on its *in situ* structural response to heat. The results, showing no measurable radiolytic or excessive structural effects in the salt, led many in the AEC to believe that the assumptions about the suitability of salt for a high-level waste repository were generally valid. [OTA 1985, Appendix A-1, p. 210]
- *Experiments in Potash Mines and Salt Mines:* Sandia began to build a salt creep laboratory in 1974. Testing on specimens from mines and salt domes was in progress by 1975, and creep in salt from ERDA-9 cores was studied in 1977. Sandia initiated a 3-year program in 1979 to evaluate, through in situ and laboratory experiments, salt deformations around mine openings and the effects of heat on acceleration of salt creep. The in situ experiments were conducted in a nearby potash mine and at the Avery Island salt dome in Louisiana.
- *WIPP:* The WIPP included an experimental area that was used for evaluating salt creep, crushed salt consolidation, and to assess the thermo-mechanical effects of emplacement of hot HLW in salt.[Matalucci 1988]

URL Experiments in Granite

- *Climax Spent Fuel Test Facility*: This facility, located at the 1,400-ft depth in the Climax Stock granite formation on the Nevada Test Site, involved emplacement of 11 encapsulated commercial spent fuel assemblies and 26 auxiliary electric heaters in three parallel shafts to simulate repository conditions over 3 yr. The tests were intended to determine the generic behavior of granite under the influence of heat and radiation. This facility had a testing and operational phase that lasted for three years. Testing involved emplacement of spent nuclear fuel into boreholes placed in the floor of a canister drift for the purpose of assessing waste handling and retrievability operations, as well as assessing the technical suitability of granite as a host rock for spent fuel. The facility was shut down in 1985.[Patrick 1986]

- *Colorado School of Mines Experimental Mine* This facility, located in Idaho Springs CO hosted a number of URL experiments in granite in the early 1980s. In addition to hydrologic experiments in the fractured granite, this site was the location of the first heated block experiment undertaken; the purpose was to study the simulated behavior of a granite under controlled repository stress and temperature conditions.

URL Experiments in Basalt

- *Gable Mountain*: A near surface test facility (NSTF) involving a test room area was constructed in Gable Mountain on the Hanford site to explore the feasibility of utilizing basalt for nuclear waste disposal. *In-situ* tests in the late 1970s and early 1980s included experiments with electric heaters, followed by experiments with spent fuel where the combined effect of heat and radiation were examined.[DuBois 2010]

URL Experiments in Volcanic Tuff

- *G-tunnel*: From 1979 to 1990, tests were conducted in G-Tunnel (unused excavations from the weapons-testing program at the Nevada Test Site) to improve understanding of the thermal-hydrological process in an underground environment and to evaluate prototype instruments and test methods. Participants were Sandia National Laboratories, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, the USGS, and the U.S. Bureau of Reclamation.

- URLs at Yucca Mountain were represented by both the Experimental Studies Facility (ESF) and the Busted Butte Facility. These test facilities had critical roles in understanding repository processes and providing data to develop and validate process models for repository performance. The Busted Butte unsaturated flow and transport test, for example, was one of the key tests used to build confidence, provide data and model validation for unsaturated flow and transport modeling that supported the License Application. Although a large number of individual tests were performed over a several year period within the ESF, sustaining an integrated testing program was often challenging due to funding limitations and changes in program priorities. In the case of one of the longest lived underground tests for the Yucca Mountain Program (the Drift Scale Thermal Test), the cool down period was abbreviated significantly from the planned four years (by ventilating the drift) and planned mineralogical sampling to compare pre- and post-heating conditions was never completed.

4.1.3. International URLs

A tendency outside of the U.S. has been to build generic URLs (non-site specific and not intended to develop into repositories) with long operating histories and an evolutionary and sustained approach to R&D and testing. Several URLs in Europe have been operating for more than 15 years and are planned to operate for many more years. The flexibility in the testing schedules for these URLs allows staged and iterative testing programs and multi-year collaborative efforts with multiple international partners.[SKB 2009]

A number of other countries have developed, or are developing, underground research laboratories (URLs) as an important part of their repository development process (Table 4-1). In some, but not all, cases the URLs are at sites that are not expected to develop into repositories. The Department of Energy cooperated in some of these activities before work on crystalline rock was terminated following the 1987 amendments to the NWPA.

Table 4-1: Foreign underground research laboratories[NWTRB 2009, Table 9]

Country	Underground Research Laboratory
Belgium	Mol (clay)
Canada	Pinawa (granite)
Finland	ONKALO facility (granite)
France	Bure (argillite, a fine-grained sedimentary rock composed primarily of indurated [hardened] clay particles)
	Tournemire (argillite)
Germany	Gorleben (salt)
Japan	Mizunami and Tono (granite)
	Horonobe (sedimentary rock)
Republic of Korea	Korea Underground Research Tunnel (granite, shallow depth)
Sweden	Äspö (granite)
	Stripa (granite)
Switzerland	Mont Terri (clay)
	Grimsel (granite)

Field-scale natural analogue studies still have a potential role in repository science studies because they have the unique advantage of representing pertinent process over very long time periods. Along with participation in international URL, the US could increase collaboration on international natural analogue studies. The USGS has summarized natural analogue work conducted in the past for YMP, which could provide a foundation for future work.[Simmons and Stuckless 2010]

4.1.4. Test and Evaluation Facility Authorized in NWPA

Before the passage of the NWPA, DOE planned to construct an underground test facility to demonstrate the technology associated with routine repository operations. This facility, called a test and evaluation facility (TEF), was to be used to conduct experiments designed to address non-site-specific issues. The TEF objectives, based on general, program wide needs for repository design and construction, included equipment and waste handling confirmation, control of radiological exposure, confirmation of repository ventilation, and instrumentation. The TEF was to be located at one of the three candidate repository sites. Site selection for the TEF was to take place earlier than, and independent of, the site selection for the first repository in order to have TEF program results available to support the repository licensing process. Consequently, it was conceivable that the TEF might have been located at the site which proved not to be the site of the first repository.[DOE 1984]

The NWPA authorized an underground Test and Evaluation Facility (TEF) that broadened the concept of the TEF that had been contemplated by DOE. Title II of the NWPA provides for the construction, operation, and maintenance of a deep geologic test and evaluation facility to carry out research and provide an integrated demonstration of the technology for deep geologic disposal of high-level radioactive waste. The NWPA authorized the Department to set guidelines to be used in selection of test and evaluation sites, and it specified a site designation and approval process with interactions with States, Tribes, and other Federal agencies. A TEF can be located at repository site selected according to the repository siting provisions of the NWPA, but surface facilities for a co-located TEF cannot be constructed until the NRC has issued a construction authorization for the repository. Not later than one year after the date of the enactment, the Department and the Nuclear Regulatory Commission were to establish the procedures for review, consultation, and coordination for development of a test and evaluation facility.

The purposes of the TEF were to

1. Supplement and focus the repository site characterization process
2. Demonstrate a repository-like system
3. Provide a means of identifying and resolving potential repository licensing issues
4. Validate scientific models under actual conditions
5. Refine design and engineering of repository components and systems
6. Supplement siting data
7. Evaluate design concepts for waste packaging, handling, and emplacement.

These purposes were to be accomplished while using only the minimum quantity of high-level radioactive waste or other radioactive materials for testing. DOE was authorized to obtain up to 100 metric tons of high level waste or spent fuel for this purpose. Such materials were to remain fully retrievable. The Act required that the Department begin a testing program at the test and evaluation site within 88 months. Operation was to terminate 5 years after the beginning of repository operation, or when the Secretary determined that the facility was no longer needed.

Following the passage of the NWPA, the Department conducted an evaluation to determine the most beneficial role for a test and evaluation facility and to identify possible locations.[DOE 1984] From the evaluation, the Department determined that a test and evaluation facility could be part of a step-by-step program to gain experience with waste emplacement and to collect design information to inform decisions on constructing full-scale licensed facilities. The evaluation identified three areas where additional data acquisition could prove beneficial to the repository program:

1. Collection of geotechnical data for repository design optimization
2. Collection of data for site performance confirmation
3. Development and demonstration of technology for repository operations.

The Department considered several facility concepts in 1983 and 1984.[DOE 1984] One option was to use the exploratory shaft facilities being developed for site characterization at three candidate sites (the basalt flows at the Hanford site in Washington, volcanic tuff at DOE's Nevada Test Site, and a salt formation not determined until the next year, in Texas). The Department also considered construction of a surface or near-surface demonstration facility, which would not technically meet the definition of a TEF as a facility constructed "at depth" but could potentially provide data beneficial to the program. Co-location of a test and evaluation facility with the potential repository, and construction at a site remote from the repository site, were both considered.

As required by the NWPA, DOE submitted to Congress a report concerning the approach to siting a TEF.[DOE 1984] In that report, the Department concluded that a TEF—if one were constructed—should be co-located with the repository, but that the decision about the desirability of proceeding with a TEF would be deferred until 1987, when the program's data needs were well-understood. After the 1987 NWPAA terminated work on all sites but Yucca Mountain, the program focused on expeditious characterization of the site, and no further action was taken with respect to the TEF.

In 1991, at a time when construction of the at-depth Exploratory Studies Facility (ESF) for characterization of Yucca Mountain had still not begun, the Yucca Mountain Peer Review Team on Unsaturated Zone Hydrology issued a final report that stressed the need for initiation of prototype studies, offsite if necessary:[DOE 1991]

> It is imperative that the Yucca Mountain Research Teams gain access to suitable field sites on Yucca Mountain, or in similar terrain elsewhere, in order to carry out prototype studies required for equipment testing, concept hypothesis testing, fluid methodology development, and model validation. This recommendation is considered by the Peer Review Team to be the most important....

Once the Yucca Mountain ESF was constructed, it became the focus for practically all necessary testing. Work at the ESF was supplemented by the Busted Butte test facility, a URL constructed at a depth of 70 meters about 8 km SE of Yucca Mountain that operated between 1998 and 2000. Boring of the ESF had originally included a smaller TBM that would have excavated a portion of the underlying Calico Hills to field experiments. However, this excavation was eliminated because of budget cuts. Later, the Busted Butte test facility was added to obtain analogous data. A series of tracer tests (using non-radioactive ions as surrogates for radionuclides) were conducted at Busted Butte to better understand flow and transport processes in tuff units that lay beneath the repository, and to evaluate and validate site-scale 3D flow and transport models.[Bussod et al. 1999; Tseng et al. 2003]

4.1.5. Lessons Learned Concerning URLs

1. For the next several years, there is no clear need for the US to develop generic URLs for purposes of obtaining information about long-term repository performance unless they are in geologic media or technologies where one does not currently exist somewhere abroad, such as deep borehole research. Although URL data can provide supporting analog information, the current US regulatory framework requires site-specific information and it is difficult to translate general information gained in URL studies to specific sites. This is not expected to change in the future.
2. In the near term, domestic fundamental research and development needs can be met by gaining access to and collaboratively conducting experiments in URLs in other countries. DOE should further broaden and formalize existing collaborations between international programs and individual US principal investigators to initiate a formal R&D program to understand key repository processes in alternative geologic media in a time and cost-effective method.
3. In the near term, the US could also collaborate more on international analogue studies to maintain expertise.

4. If the U.S. foregoes repository siting for an extended period of time, studies in a domestic URL would help maintain repository development expertise. Such a URL does not have to be associated with a specific site under consideration.
5. Once geologic media and sites have been selected for detailed characterization within the US, URLs at the sites could be established as soon as possible. The insights gained from working in the real system are invaluable and can reveal unexpected conditions much earlier.
6. A potential ancillary benefit of URLs is that they might help improve public confidence about radioactive waste management by demonstrating fundamental understanding of disposal and operational concepts. URLs are also a vehicle to involve local universities and state oversight agencies in characterization efforts at the very beginning of site characterization. Such research facilities could also be part of a storage site.

4.2. Test Facilities for Evaluating Repository Operations

4.2.1. Development of Operational Experience

Whatever the path forward for management of spent fuel and high-level waste in the US, implementation of a national system will be needed for routine and reliable handling of those materials at unprecedented amounts and rates. These rates will be substantially higher than those facing other countries since the United States has twice a many operating reactors as either France or the former USSR and almost three times as many as the Great Britain. The US experience with the design and operation of WIPP and the effort to design the high-level waste management system provides valuable insights into how to develop the capability for the required scale of system operation. However, learning could continue while waiting for decisions on siting a large-scale waste management facilities.

The Test and Evaluation Facility was intended to provide pre-closure operational experience as well as information related to post-closure performance. Specifically it was "to evaluate the design concepts for packaging, handling, and emplacement of high level radioactive waste and spent nuclear fuel at the design rate; and to establish operating capability without exposing workers to excessive radiation." In addition, the Test and Evaluation Facility provisions of the Act authorized the Department of Energy to use its existing facilities for conducting "generically applicable tests regarding packaging, handling, and emplacement technology for solidified high level radioactive waste and spent nuclear fuel from civilian nuclear activities."

In March 1993, an OCRWM task force issued *A Proposed Alternative Strategy for the DOE Civilian Radioactive Waste Management Program* to fulfill a commitment made by DOE Secretary Watkins to Senator Bennett Johnston.[DOE 1993] The report's recommendations included early development of an offsite waste packaging R&D facility to resolve issues concerning package fabrication, closure, and handling, and produce confirmatory data for the repository licensing proceeding. The facility would also serve as a center for an ongoing R&D program during the operational life of the repository to improve on the initial waste package design or to develop special packages (if needed) for the many different types of spent fuel from defense activities that might ultimately require direct disposal.

Ultimately, the available statutory authorities for such offsite testing were not exercised, and under the reference plan for development of the Yucca Mountain repository, the first test of the integrated operation of the pre-closure elements of the repository system would occur only after issuance of the construction authorization and construction of the initial repository facilities.

4.2.2. Lessons learned about Test Facilities for Repository Operations

1. Implementation of a national system for management of spent fuel and high-level waste will require routine and reliable handling of those materials at unprecedented amounts and rates. If decisions about siting and operating large-scale waste management facilities are deferred, ways to continue developing the capability should be considered.
2. A technology development facility should be considered for deployment. The benefits of such a facility have been identified before as provisions of the NWPA concerning a test and evaluation facility TEF were intended to provide data on the operational aspects of a repository (waste packaging, handling, and emplacement). A technology development facility would allow for the development of first-of-a-kind operational techniques that under the current policy framework will not be tested until a repository facility was constructed and operating. A technology development facility could be generic and independent of any site being considered.
3. Collaborations with the nuclear industry to develop and operate facilities to test the capability to handle, transport, and package SNF within the US would be beneficial and could be combined with studies on long-term storage and studies integrating nuclear waste handling, storage, and transportation.
4. The TEF provisions of the NWPA that authorize DOE to use its existing facilities for conducting "generically applicable tests regarding packaging, handling, and emplacement technology for solidified high level radioactive waste and spent nuclear fuel from civilian nuclear activities" may serve as a model for future policy. These provisions, perhaps with some modifications, may allow interim steps towards full-scale operations that would support a "learn as you go" staged deployment concept.

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5. Staged Repository Development

Both Yucca Mountain and WIPP have moved through several phases of repository development. As discussed, in Appendix A characterization of the natural barrier moved through different phases for site selection, feasibility analysis, viability analysis, and compliance support. Repository design at WIPP originally envisioned a pilot phase that was abandoned, while the repository plan in the US program since the passage of the NWPA has involved developing a full-scale repository as soon as NRC granted a construction authorization and quickly ramping up to shipping and disposing waste at a high rate. While slower, more stepwise scenarios were explored later, that plan has never changed. Nonetheless, the evolution of the repository design, driven largely by the need to adapt to the expectation that annual funding for repository construction would be limited, ended up with a flexible modular design that could accommodate a wide range of development scenarios.

5.1. Repository Development Stages for WIPP and Yucca Mountain

The repository development scenario that was prescribed in the NWPA consists of (1) site selection after several extensive steps examining several alternative sites; (2) natural barrier characterization and engineered barrier design; (3) application and granting of NRC license to construct; (4) full-scale construction; (5) application and granting of NRC license to receive and posses radioactive waste; (6) full-scale operations and confirmation of repository behavior with option to amend receive and posses license; (7) application and granting of NRC license to close; (8) closure operations and any monitoring required by closure license.

The repository development scenario for the WIPP varied somewhat in that Steps 2 and 4 occurred simultaneously, Step 3 was omitted, and, most importantly, the state was actively involved in the Step 2 through the requirements of the Stipulated Agreement and Consultation and Cooperation Agreement (discussed in §9.4), rather than only indirectly through comments on documents during Steps 2 and 4 and through comments on rulemaking (or in the case of Yucca Mountain, contentions raised at a hearing on the license application to construct the repository. Also, none of the legislation related to WIPP dictated a schedule. The only time line specified was that EPA had one year to review a certification application.

5.2. Examination of Staged Development of Yucca Mountain

The repository development scenario that has long been used as the basis for analysis of geologic repositories in the US and the basis for the license application for Yucca Mountain consists of siting and construction of full-scale repository facilities and ramping up to shipping and disposing of spent fuel at a rate of 3000 tons per year as rapidly as feasible after NRC approval. This scenario was initially developed at a time when it did not appear that spent fuel would be reprocessed, and when it was assumed that disposal of spent fuel in the repository would be the way to meet the contractual obligation to accept spent fuel from utilities.

By 1987, the target date for beginning operation of the first repository had slipped from 1998 to 2003, [DOE, 1987] and in 1989 it slipped again to 2010. [DOE 1989b] As a result, it had become clear that Yucca Mountain could no longer serve as the basis for accepting spent fuel from utilities by 1998 as required by the NWPA. Attention then began to focus on the use of storage capability to meet the acceptance requirements (based on the hope that the Nuclear Waste Negotiator could find a site for an MRS facility), and to concentrate more on an initial demonstration of disposal capability at a repository rather than large-scale disposal operations. Drawing on stakeholder input from several Strategic Principles Workshops, OCRWM issued a Draft Mission Plan Amendment in 1991 that defined the objectives of the program as follows:[DOE 1991]

- Timely disposal capability: to establish as soon as practicable the ability to dispose of radioactive waste in a geologic repository licensed by the Nuclear Regulatory Commission.
- Timely and adequate waste acceptance: to begin the operation of the waste management system as soon as practicable, obtaining the system-development and operational benefits that have been identified for the MRS facility.
- Schedule confidence: to establish confidence in the schedule for waste acceptance and disposal such that the management of radioactive waste is not an obstacle to the nuclear energy option.
- System flexibility: to ensure that the program has the flexibility necessary for adapting to future circumstances while fulfilling established commitments.

This draft was never finalized and thus full-scale deployment remained the YMP objective.

In January 1993, responding to a letter from Sen. Bennett Johnston, DOE Secretary Watkins promised to "provide a conceptual revised program strategy for public review..." To prepare the strategy, OCRWM created a task force that considered past discussions of program options with stakeholders and recommendations from such external groups as the NWTRB, the NAS Board on Radioactive Waste Management, and the NRC Advisory Committee on Nuclear Waste (ACNW). The report of the task force, *A Proposed Alternative Strategy for the DOE Civilian Radioactive Waste Management Program*, was issued in March 1993,[DOE 1993] The report recommended a fundamental redirection of the program to shift the program goal from rapid full-scale disposal to the early licensed demonstration of the capability for disposal, consistent with the statement of objectives in the 1991 draft Mission Plan Amendment. The report cited two key reasons for this change:

- There was no urgent safety reason for rapid large-scale permanent disposal, and some stakeholders opposed premature irreversible action.
- The proposed new approach would give maximum flexibility by providing the option for disposal without foreclosing other options.

The report recommended a phased development plan for a licensed full-scale repository to allow earlier, smaller steps:

> Early licensed demonstration of small-scale disposal using a conservative system design: begin design tests with a small amount of waste (packaged in an offsite waste packaging R&D facility) soon after construction authorization, while building a small pilot packaging facility at the repository
>
> Optimize repository design using information from characterization, licensing, and small-scale operation; then construct and operate full-scale facilities when needed
>
> Design to allow extended open operation and monitoring to confirm that the repository is performing as expected

The report also recommended that waste acceptance be clearly separated from emplacement in the repository for disposal, pointing out that "[t]he more gradual repository loading plan in the proposed strategy requires additional surface storage after disposal begins in order to meet acceptance obligations." The report noted that surface storage at the repository after licensing (using multi- purpose containers) could allow adequate waste acceptance if monitored retrievable storage (MRS) capacity were not available. As with the recommendations in the draft Mission Plan Amendment, these recommendations were not adopted and continued full-scale deployment remained the objective.

Alternative development scenarios that involve staged construction and operation of the repository were considered in the beginning in the mid-1990s, primarily as a means of coping with the reality of annual funding constraints that would not support the construction of large, multi-purpose surface facilities, rather than providing the sorts of benefits for a staged approach that had been identified earlier. DOE also sponsored a study of staged development by the NAS, as discussed in the next Section.

5.3. Staged Development for a Future Repository

The charter for the *Blue-Ribbon Commission on America's Nuclear Future* says that it will consider "Options for decision-making processes for management and disposal that are flexible, adaptive, and responsive." The management approach called "adaptive staging," recommended in the 2003 report from the National Academies (*One Step at a Time: The Staged Development of Geologic Repositories for High-Level Radioactive Waste)* as "a promising means to develop geologic repositories for high-level waste such as the proposed repository at Yucca Mountain, Nevada,"[NAS 2003a] appears relevant to this aspect of the Commission's task.

5.3.1. Concept of Staged Development

The NAS described adaptive staging as "a learn-as-you-go process that enables project managers to continuously reevaluate and adjust the program in response to new knowledge and stakeholder input" and defined two approaches to staging:[NAS 2003b]

- Linear staging, involving a single, predetermined path to a well-defined end point, with stages viewed as milestones at which cost and schedules are reviewed and modified as needed.
- Adaptive staging, which emphasizes deliberate continued learning and improvement and in which the ultimate path to success and the end points themselves are determined by knowledge and experience gathered along the way.

The report recommended that "adaptive staging should be the approach used in geologic repository development," which was expected to lead DOE to do the following:

- Highlight the goal of ensuring safety and security at all times more prominently than the specific milestone of emplacing 70,000 MTHM in Yucca Mountain.
- Focus more strongly on achieving the degree of technical and societal consensus needed to begin waste emplacement, rather than on the emplacement of all waste.
- Introduce stages that explicitly focus on what can be learned about safety (i.e., re-evaluating the safety case) and about concerns by the regulator, stakeholders, and the general public.
- Start conservatively in design and operations, with the opportunity to reduce conservatism as new knowledge allows.
- Plan for early pilot and test facilities along with possible demonstration facilities; clarify with the USNRC how the use of these facilities could affect the licensing process.
- Focus specifically on assuring and demonstrating retrievability.
- Focus on explicit thermal load management alternatives.
- Plan for sufficient buffer storage at or near the site, with transparency about its policy implications, and decouple the rate of waste acceptance from the rate of waste emplacement underground.
- Place high priority on defining and securing funding for the monitoring and the science (including social science) programs with the intention of modifying and improving the programs as learning progresses.

The report explained its recommendation of Adaptive Staging as follows:

> Every first-of-a-kind, long-term, and complex project develops in stages. With time, stages and schedules are inevitably revised in light of experience and knowledge gathered along the way.

> However, many national repository programs, including the U.S., have so far set rigid milestones to full-scale waste emplacement and repository closure.
>
> The report recommends implementing adaptive staging, a flexible approach where the ultimate path to success and the end point themselves are outlined at the beginning of the program and all parties, including stakeholders, acknowledge that the program can be revised as it progresses. Adaptive staging is therefore less "error-prone" than a rigid approach and ensures that early decisions do not commit the project to a path that later proves inappropriate or unsafe. Adaptive staging also allows the current generation to manage waste using the best available knowledge without foreclosing options if future generations decide to manage waste otherwise.
>
> A central feature of adaptive staging is a series of assessment periods, or "decision points," when project managers actively collect and evaluate information, including stakeholder input, to develop options for the next stage of the project. At these points, managers reassess the safety of the repository, make their findings public, and engage in dialogue with affected communities and other stakeholders.

The NAS stated adaptive staging is characterized by the simultaneous presence of the following seven attributes:

1. **Commitment to systematic learning**. Project managers intentionally seek, are open to and learn from new knowledge and stakeholder input. Stages are designed specifically to increase available scientific, technical, societal, institutional and operational knowledge.
2. **Flexibility**. Project managers are able and willing to reevaluate earlier decisions and redesign or change course when new information warrants.
3. **Reversibility**. Project managers are able to abandon an earlier path and reverse the course of action to a previous stage if new information warrants.
4. **Transparency**. The decision-making process and the basis for decisions are documented and accessible in real-time and plain language to all stakeholders
5. **Auditability**. Documentation for the basis of decisions is complete and made available to all interested party for review purposes.
6. **Integrity**. Technical results are accurately and objectively reported and all uncertainties, assumptions, and indeterminacies are identified and labeled.
7. **Responsiveness**. Project managers seek and act on new information in a timely fashion.

The Nuclear Energy Agency (NEA) reported in 2004 that the concept of staged development, or "adaptive staging" (the term used by the National Academies), is attracting increasing attention internationally as a means of increasing the societal acceptability of waste management activities.[OECD-NEA 2004] As described by NEA, "The key feature of these concepts is development by steps or stages that are reversible, within the limits of practicability. This is designed to provide reassurance that decisions can be reversed if experience shows them to have adverse or unwanted effects."

Now that the advisability of rapid disposal of the nation's inventory of UNF is under increasing question, developing and demonstrating the capability to dispose UNF and HLW may be a more important near-term objective than rapidly implementing that capability. Hence, an adaptive staging approach for stepwise repository development appears more suited to current needs. Stepwise processes allow sequential repository development in a manner that:

1. Allows decisions to be made/reversed consistent with the most recent technical findings on an as-needed basis rather than requiring all decisions to be made at the beginning of a decades-long process repository development;

2. Allows modular deployment compatible with changes such as separate disposal of defense and commercial wastes, expansion of waste inventory/forms, and annual capacity increases;
3. Allows demonstration (using both non-radioactive and radioactive material) for both surface facility and underground material handling techniques prior to investing in the full-capacity-rated facilities; and
4. Allows continuous regulator involvement that might enhance their confidence in the program, with each decision step being smaller in scope.

Several caveats about a staged approach must also be considered:

1. The funding mechanism must accommodate the fact that staged development can increase undiscounted total costs at the same time as it reduces annual costs.
2. Both the regulator and the licensee must maintain the technical capability and administrative capacity to continuously evaluate and approve changes rather than planning for large peaks and valleys in staff resources for both the regulator and licensee (but as with other aspects of staged development this can be an advantage with limited annual budgets).
3. When setting up the incremental steps, there needs to be a clear rationale for each step that serves the needs of the operator or regulator. The WIPP pilot phase was characterized by opponents as a pretext to get waste into the ground, a criticism that was strengthened by the conclusion of the NAS that there was no clear technical justification for the test emplacement of waste in WIPP
4. To legitimize a stepwise process involving interactions with the regulator, it must be clear to the public that the program seeks to learn from these interactions.
5. The value of staged development is more in maintaining and enhancing credibility though a sensible development process; its value as a means to increase the initial societal acceptability of waste management activities can easily be overstated. From anecdotal evidence, the elimination of WIPP's pilot phase in 1993 did not decrease acceptability (unfortunately survey data was not available in 1993, see Fig. 9-5).

The current statutory structure appears to be consistent with at least some forms of staging, e.g. constructing the repository facilities in a stepwise manner beginning with pilot scale facilities after a construction authorization is granted. For example, in promulgating 10 CFR 63, NRC stated that it expected the repository operations area to be substantially complete and sufficient underground storage space for initial operations available before it would consider granting a license to receive and possess. Yet, it would be helpful for new legislation and regulations to explicitly recognize and facilitate staged development. Furthermore, it would be helpful for new repository regulations to be crafted to ensure that such interactions with the regulatory can take place as an important part of a staged development process. For example, pre-licensing interactions between DOE and NRC on the Yucca Mountain project, such as the interactions on key technical issues, the criticality topical report, and an NRC review of a dry spent fuel transfer system, showed the value of such interactions as an indicator of progress during repository development even though they do not constrain the NRC in its formal licensing review.

5.3.2. Impact of Program Funding

The clear intent of Congress was that the funding mechanism created by the NWPA (the nuclear waste fee and the Nuclear Waste Fund) would free the program from the normal competition for funds within the federal budget process. With the passage of budget deficit control legislation that affected expenditures from the Nuclear Waste Fund (starting with the *Gramm-Rundman-Hollings Act* passed in 1985), this mechanism has not worked as originally intended. Annual appropriations have been unpredictable and generally have fallen short of the levels the waste program indicated were needed to maintain steady progress. This had adverse impacts on the program schedule and caused deferral of some design issues that led to problems later. Staged repository development would be better able to accommodated changes in funding.

5.3.3. Lessons Learned about Staged Development

1. Developing and demonstrating the capability to dispose of spent fuel and HLW may be a more important near-term objective than rapidly implementing that capability at large scale. Hence, an adaptive staging approach for stepwise repository development appears potentially more suited to current needs.
2. The modular, flexible design for surface and underground facilities for Yucca Mountain may provide a useful model for a repository design that is compatible with staged development.
3. It would be helpful for new legislation and regulations to explicitly recognize and facilitate staged development by ensuring that appropriate interactions between the regulator and repository developer can take place as an important part of a staged development process.
4. The experience of the high level waste repository program underlines the necessity of providing funding that is stable, predictable, and available as needed to meet peak demands, e.g. for repository design and construction. To provide confidence in the development of repositories over the periods of decades involved, the funding mechanism needs to assure availability of the level of funds required by the program implementation plan, instead of having funding constraints determine the achievable program.
5. If uncertainty about the stability and predictability of funding remains, a modular design such as that developed for Yucca Mountain can provide flexibility to allow continued progress nonetheless.

5.4. Flexible Decisions and Implications of Repository Design

5.4.1. Flexible Decision-Making

The experiences with WIPP and Yucca Mountain underlined the importance of flexible decision-making, including the ability to stop and make significant design changes and development of designs that facilitate flexible responses to changing conditions. Key contingencies that require flexible planning and decision-making that have been identified include:

1. Uncertainty in the availability and timing of new waste management facilities and any operational constraints (e.g. capacity limits) that may be imposed on them.
2. Potential need for design or operating mode changes after a repository has received an initial license.
3. Constrained and/or uncertain funding.
4. Uncertainties about future fuel cycles and the associated amounts, types, and timing of waste forms requiring storage and disposal.
5. Uncertainties about the ability to retrieve, transport, and handle UNF after extended storage periods (as discussed further in §6.0).

An important aspect of flexibility is the ability of the regulatory process to address and make decisions about proposed changes. Sufficient resources are needed for the waste manager to develop the scientific and technical basis for proposed changes and for the regulators to review and decide upon such proposals in a timely manner. Continued support is needed to maintain these capabilities in the waste management program and the regulators during the operating period following initial facility licensing.

5.4.2. Repository Design Approach for Enabling Adaptive, Flexible Decisions

The approach to the design of the repository's surface and underground facilities will significantly affect the ability of any decision-making process to adapt to changing circumstances. The evolution of the design of the Yucca Mountain repository may provide useful insights into both the flexibility of the decision process and the way in which considerations of flexibility were incorporated into that process.

Whenever it is decided to proceed with a repository, many uncertainties affecting the future development and operation of the repository will likely not be resolved at the time decisions about the design for a license will have to be made. Some uncertainties may remain even at the time a repository starts operating. Therefore, attempting to develop a design that is "optimized" for a particular postulated reference operating scenario might produce a design that does not perform as well as expected if actual conditions deviate significantly from the reference scenario. To reduce this risk, flexibility to function at some level no matter how these uncertainties are resolved is an important criterion in evaluating both surface and subsurface designs. More details of the many changes in the YMP repository design are described in Appendix A.

An example of this potential risk can be found in the reference design concept used at the time of the Viability Assessment in 1998. That design included one large integrated waste handling surface facility designed primarily for receiving and packaging 3000 tons a year of bare UNF and an underground repository with a single large emplacement area for the 70,000 MTHM inventory that required construction of large underground infrastructure (i.e., perimeter drift and full ventilation system) before any emplacement operations could begin. This system design assumed direct disposal of all commercial used fuel, with no reprocessing—consistent with general expectations at the time—and was optimized for that scenario, offering little flexibility to accommodate future changes of mission. This non-modular design concept tended to minimize the undiscounted total system lifecycle cost if the reference program scenario, which included an assumption of unconstrained funding, materialized. However, constrained funding or substantial changes in the expected operating scenario that necessitated design changes would lead to delays, increased overall costs, and adverse policy impacts.

OCRWM used flexibility as a key design evaluation criterion in the evolution of the repository from the Viability Assessment reference design. For example, flexibility was an important explicit consideration in the License Application Design Selection (LADS) study that led to selection of the current reference underground design.[TESS 1999] The approach to evaluating "flexibility" used in the LADS process was to identify a set of contingencies (e.g. the need to dispose of more than the nominal 70,000 MTHM) and to assess how each Enhanced Design Alternative (EDA) would perform when faced with these contingencies. "Flexibility" was used as a measure of the degree to which a design would be capable of remaining viable and/or able to change in the face of future regulatory or other changes. Possible changes considered during the LADS process were:

1. Increased disposal capacity (87,000 or 105,000 MTHM), if expanded capacity is authorized
2. A longer preclosure period (100 or 300 years following emplacement)
3. A shorter preclosure period (10 years following end of emplacement)
4. Receipt of 5-year-old spent nuclear fuel
5. Late design changes that were assumed to occur just prior to the start of construction (e.g., change from high to low areal mass loading, or vice versa, and adding or removing blending)

6. Unanticipated natural features or findings (volcanism, seismicity, water table rise, flooding)

The LADS process led to a lower temperature design with thermally-decoupled emplacement drifts with substantially greater thermal flexibility (i.e. ability to operate below or above boiling) than the high-temperature reference design that it replaced. Subsequent value engineering studies led to a flexible modular underground design with a number of smaller emplacement zones instead of the single large zone assumed in LADS. The license application design involves five smaller independent waste emplacement panels, reducing the front-end investment required before emplacement begins and allowing for changes in the design and layout, if required, during the operational period. For example, this approach could accommodate a change to zoned disposal of different waste forms similar to the French approach, if that proved to be desirable.

More recently, the final revisions to the Yucca Mountain repository surface facility design that led to the 2008 license application design involved use of a comparison of alternatives in which "flexibility to respond to changing circumstances" was a key criterion.[BSC 2006] Flexibility was defined in terms of ability to adapt to specific postulated contingencies:

1. Ability to be developed under different funding scenarios
   - Ability to achieve timely operation under constrained annual funding
2. Ability to accommodate uncertainties in the waste stream (types, timing, quantities)
   - Ability to accommodate increases in the quantities of commercial SNF that require uncanistered handling above the quantity expected in a primarily canister-based system
   - Ability to accommodate alternative operating scenarios
   - Compatibility with early commercial SNF receipt option
   - Compatibility with future design changes
   - Compatibility with early start using DOE waste
3. Compatibility with phased development
   - Maximize the ability to respond to changing funding levels and incorporate experience from initial operations or future technology improvements.

The result was a surface design with various functions distributed among a suite of modules with different capabilities that could be added at different times as needed to accommodate future developments. These modules offer flexibility to adjust to changing circumstances or policies, since they can be combined as needed to meet any desired sequence of receipt, aging, and disposal, and the design of later modules can be modified prior to construction to accommodate different waste streams, subject to revised safety analyses and approval by the NRC.[Kim and Cotton 2007]

Overall, the design process was able to accommodate an evolution from large "non-modular", inflexible surface and subsurface designs, with large front-end costs, to the highly modular design concept in the License Application, with smaller front-end costs that provided flexibility for future decision makers to adapt to a wide range of possible waste management scenarios within the historical funding constraints; specifically,

- The surface facilities are highly modular, so receipt and disposal capabilities can be added as needed, and later modules can be adapted to a changing waste mix and waste management strategy, and

- The underground repository is developed sequentially in separate zone (which does not require excavation of a perimeter drift and complete ventilation system) to accelerate initial receipt of some waste, and facilitate disposal of different waste types.

5.4.3. *Lessons Learned about Flexible Design*

1. While the current reference plan for a Yucca Mountain repository presented in the license application is not one of "adaptive staging" as recommended by the NAS, it does incorporate a highly modular repository surface and subsurface design and phased construction plan that enhances the opportunity for implementing lessons learned (e.g., to optimize later phases based on operating experience) and enhances flexibility to adapt to new information or circumstances.
2. This design and construction approach could provide a useful starting point for a more explicit staged development plan for a future repository. At a minimum, the flexible modular concept for surface and underground facilities should be portable to another repository site.

5.5. Role of Storage in Providing Flexibility

5.5.1. *Storage Flexibility*

The NAS *Adaptive Staging* report noted that a flexible staged development approach for a repository has significant implications for buffer storage requirements: [NAS 2003a]

> Adaptive Staging's flexibility and reversibility may require a higher buffer storage capability located at or near the repository site to keep open various options for emplacement schedules. Sufficient buffer storage provides the flexibility to choose among waste types (thermal blending), for managing emplacement and for ensuring a place to which waste can be credibly retrieved, should the need arise. Such buffer storage also provides a flexible mechanism to separate waste acceptance from waste disposal. Increased buffer storage allows for flexibility in the system, and affects the need for at-reactor storage and transportation capacity. A cost- and schedule-driven Linear Staging approach tends to minimize buffer storage and aims for 'just-in-time' delivery of waste.

The report went on to note:

> In many programs there is reluctance to implement a high-capacity buffer storage, especially if the storage facility operates before the repository is functional, out of societal fears that the buffer storage facility could become a permanent surface storage facility. This concern can be alleviated if the regulator grants the repository construction authorization before the surface facility is built and if the regulator grants the licenses to receive and emplace waste in the repository before the buffer storage facility is operational.

The tension between the desire to include substantial storage capacity as a way to provide system flexibility for decision makers and the concern that such capacity could delay availability of permanent disposal capability has been a constant theme in the U.S. waste program since before the NWPA was passed. The Atomic Energy Commission's proposal in the mid-1970s for a Retrievable Surface Storage Facility (RSSF) to allow a more deliberate pace for development of repositories was rejected because of this concern.

The NWPA deferred the decision about whether larger, longer-term storage facilities (Monitored Retrievable Storage, or MRS, facilities) were needed, directing the DOE to come back to Congress with a design and site for such a facility so that a decision about authorizing its construction and operation could be made. As with the earlier RSSF proposal, the debate was dominated by concerns that the availability of a long-term, large-capacity Federal storage facility would reduce the incentive for continued work on a geologic repository, and that the storage facility would become a de facto permanent solution. In response to this concern, the NWPA directed that disposal in repositories would proceed whether or not an MRS facility was provided.

In 1986, the Department submitted a proposal to locate a monitored retrievable storage facility at a site at Clinch River in Oak Ridge, Tennessee, with two alternative sites in Tennessee. The proposal included a recommendation that the total storage capacity be limited to 15,000 MTHM to allay concerns that the MRS would supplant the repository.

The 1987 Nuclear Waste Policy Amendments Act (NWPAA) nullified the Department's proposal, but authorized the construction of an MRS facility, pending examination of the need for an MRS facility by a Monitored Retrievable Storage Review Commission before the DOE could proceed. Congress acted to prevent an MRS facility from becoming a *de facto* permanent repository by linking its siting, construction, and operation tightly to the development of the repository.[8] Finally, the NWPAA established the Office of the Nuclear Waste Negotiator to seek a volunteer host site for a repository or monitored retrievable storage facility.

Following enactment of the 1987 amendments, the DOE issued a formal position supporting development of an MRS facility "as an integral part of the waste-management system because an MRS facility would allow the DOE to better meet its strategic objectives of timely disposal, timely and adequate waste acceptance, schedule confidence, and system flexibility. This facility would receive, store, and stage shipments of intact spent fuel to the repository and could be later expanded to perform additional functions that may be determined to be beneficial or required as the system design matures."[DOE 1989a] DOE stated that it "prefers an MRS facility that is sited through the efforts of the Nuclear Waste Negotiator, especially if the siting negotiations lead to linkages that allow the advantages of an MRS facility to be more fully realized." In 1989, the Secretary of Energy sent a message to Congress reporting that the repository was not expected to be available until 2010,[DOE 1989b] and stating that "the DOE plans to work with the Congress to modify the current linkages between the repository and the MRS facility and to embark on an aggressive policy to develop an integrated MRS facility for spent fuel."

Efforts were made by both houses of Congress in the latter half of the 1990s to enact legislation directing the DOE to develop a storage facility at or near Yucca Mountain. None were successful.

In 1996, the Nuclear Waste Technical Review Board added its voice to the argument that storage capacity is needed to provide flexibility:[NWTRB 1996]

> The Board believes that federal storage capacity will be needed in the future for two reasons. First, when a repository begins operating, a centralized storage capability will be needed to provide added flexibility to handle the waste. For example, storage would provide a buffer between the repository and the rest of the waste management system if waste emplacement rates in the repository are less than spent fuel acceptance rates. Storage capacity also offers technical advantages, such as allowing spent fuel to be mixed and matched to optimize the thermal loading of the repository to improve repository performance.[9]
>
> The Board concluded that storage at the repository would be preferable: "The construction of a federal centralized storage facility should be deferred until after a decision has been made about the suitability of the Yucca Mountain site for repository development. If Yucca Mountain proves suitable, the centralized storage facility should be located there.

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[8] DOE was prohibited in the NWPAA from selecting an MRS site (which could not be in Nevada) until a repository site was recommended, from commencing MRS construction until NRC issued a construction authorization for a repository, from storing more than 10,000 MTHM in the MRS before the repository begins operation, and from storing more than 15,000 MTHM in the MRS at any time.

[9] The second reason was the need to avoid build up of fuel in dry storage at reactors: "A centralized facility will relieve utilities of the need to build new dry-storage capacity at shutdown reactors while accommodating any future institutional or technical uncertainties associated with the long-term storage of spent fuel."

With the failure of efforts to provide legislative authorization for a centralized storage facility, the OCRWM program remained focused on the repository. To provide the flexibility that was foreseen for storage facilities, the Yucca Mountain repository design includes an onsite surface aging facility that would handle up to 21,000 MTHM of spent fuel. DOE described the functions of the aging facility as follows:[DOE 2009, §1.2.7]

> As demonstrated in the Application, DOE's proposed Aging Facility is not intended merely for storing waste; it is necessary for, and designed to serve, other critical functions that are integral to the logistics of waste handling for the purposes of permanent storage in the repository. SAR §1.2.7 At its core, the Aging Facility is designed to be a buffer facility, to "uncouple waste receipts from waste emplacement operations to accommodate repository temperature and thermal limits, operations workflow (differences in acceptance and emplacement rates), and maintenance outages.

These functions are essentially the same as the functions for at-repository buffer storage described by the NAS *Adaptive Staging* report.

In the contentions filed on the Yucca Mountain license application, Nevada argued that this plan violates the NWPA, as amended, by making Nevada the site of both a repository and a retrievable storage facility (forbidden by §141(g)). The Department responded that the contention should be rejected, on the grounds that the NWPA and associated regulations contemplate that a proposed geologic repository design may include a surface aging facility.[DOE 2009] DOE pointed out that NRC Staff recognized that DOE's geologic design may include surface facilities for receiving, handling, packaging and storing waste, and cited an NRC staff letter that stated:[Reamer 2004]

> Part 63 contemplates that a proposed repository design may include surface facilities for the receipt, handling, packaging, and storage of waste…A surface aging facility will likely not be designed merely for temporary storage, but will serve other functions, which are integral to the logistics of waste handling for the purposes of permanent storage in the repository.

With the proposed termination of the Yucca Mountain licensing proceeding, the arguments about the applicability of the NWPA's restrictions on interim storage facilities to what is done with used fuel at a repository before it is emplaced underground will continue to lack a formal legal resolution.

5.5.2. Lessons Learned Concerning the Role of Storage

1. Some centralize storage capacity – whether at an independent storage site or at a repository – is needed to provide a variety of functions that are integral to the logistics of waste handling prior to emplacement in a repository.
2. Storage capacity can enable receipt of waste to be decoupled from emplacement in a repository, facilitating a stepwise repository development process.
3. The current linkages in the NWPA between operation of a central storage facility and the construction and operation of a repository severely limit the value of such a storage facility.
4. Flexibility for the waste management system would be enhanced if future legislation and regulations explicitly facilitate co-location of needed storage capacity at a repository site once it has been selected and approved.

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6. Storage and Transportation of Used Nuclear Fuel

The decision not to pursue the licensing and development of a repository at Yucca Mountain for disposal of UNF has resulted in the lack of an identified disposal path for UNF. This has a significant impact on the current once-through fuel cycle and also impacts the other three fuel cycles being considered by the DOE in its Fuel Cycle Technology Program plan. These fuel cycles include: an optimized once-through open cycle, a modified open cycle, and a fully closed cycle. The production of used fuel is common to all three cycles, and its storage is an integral part of each fuel cycle. The time period for storage will vary and depends on the availability of a disposition path or a geologic disposal option. Without Yucca Mountain, long-term storage of used fuel will be required past the current regulatory threshold of 60 years, possibly for an indefinite period of time. Such long time periods raise technical, regulatory, and policy questions that have not been addressed to date.

6.1. Technical Considerations

6.1.1. Commercial Used Nuclear Fuel

Retrieval of UNF from surface storage followed by transportation will be needed for either subsequent processing or disposal. The overriding technical issue is the ability to safely retrieve UNF after very long-term storage. The UNF container must be retrievable to be transported for either reprocessing or disposal. Furthermore, handling degraded fuel at a repository could have costly impacts on surface facility design and on safety analyses required for licensing. Planning and development of storage systems for eventual retrieval without resorting to a processing facility on site might provide future generations more flexibility and reduce the costs and exposures when retrieval is required. Before regulations for long are contemplated, the technical issues to consider are the condition of the UNF (commercial and defense) after long term storage and degradation of storage casks and inner canisters.

Operating reactors are discharging fuel with increasingly higher burnups (>45 GWd/MT); the pressurized water reactors (PWR) will begin discharging only high burnup UNF in 2012 in the US.[EPRI 2003] This new situation raises questions about physical and chemical reactions in storage over the long term integrity of cladding (e.g., creep, fracture toughness, ductility under impact, hydriding, corrosion) and UNF (fission and He gas pressures) that could lead to fuel assembly deterioration potentially affecting subsequent removal from storage, transportation, handling, and reprocessing or disposal. Therefore, analysis of possible changes to fuel design that might reduce concerns about degradation in long-term storage may be useful.

Also, retrieval from dry casks may be difficult without adequate planning. Some on-site reactor storage locations might experience flooding and seismic activity over a 300 to 500 yr period. Though these disruptive events may not cause substantial damage to the cask itself, the residual effects of flooding and seismic activity could complicate retrieval schemes. Also, several dry cask storage designs use reinforced concrete overpacks for dry surface storage of UNF. While they have proven to be stable and able to retain their integrity in the 24 years since dry surface storage of UNF began, there is less than a century of experience with modern cements, the binder compounds for modern concrete, and the interaction of cement and reinforcing metal structures. The possibility of storage for periods on the order of a century or longer suggests a need for additional investigation regarding the long-term performance of reinforced concrete.

Fuel may be canistered for storage, simplifying transportation and ultimate disposal if no access to the fuel is needed. However, a welded canister creates an obvious problem if one wishes to assess the condition of the fuel after long-term storage. Analysis of changes to storage casks and canister designs to mitigate against any degradation that does occur may be useful. Spending more time and money now on fuel and/or storage systems could provide insurance against unanticipated higher costs for dealing with the consequences of fuel or cask degradation in the future.

6.1.2. Defense Used Nuclear Fuel and High-Level Waste

During the last four decades, DOE and its predecessor agencies have generated approximately 250 varieties of spent nuclear fuel from weapons production, nuclear propulsion, and research missions. In addition, a variety of forms of spent fuel have been accepted from other sources. The vast majority of DOE UNF is currently stored at three existing DOE sites; Hanford Site in Washington, the Idaho National Laboratory in Idaho, and the Savannah River Site in South Carolina. The storage configurations vary for each of the sites and include both dry and wet storage, but DOE plans to place the UNF in sealed canisters with no expectation of removal later. The existing technical basis for storage of commercial UNF for up to 60 years is not directly applicable to storage and subsequent retrieval and transportation of the DOE UNF inventory (with the exception of the small quantity of commercial UNF in the inventory). DOE will need to develop this technical basis.

DOE HLW is in the process of being vitrified or otherwise solidified and loaded into canisters for disposal. All of the HLW existing and planned canisters at Savannah River, Hanford, and INL (about 22,000) are to be stored on site in storage designed for 100 years, pending final disposition. DOE sees no significant near-term technical or safety impacts for long-term storage.

6.2. Regulatory Considerations

The term of an NRC license for surface storage is 20 years. The NRC has allowed license extensions for up to 40 additional years for a total of 60 years. However, these licenses are valid only for low burnup fuels (i.e., <45 GWD/MTHM). Currently, the technical basis is incomplete for extension of storage times for low burnup fuels past 60 years. In addition, there is no technical basis for long term storage of high burnup fuels (i.e., > 45 GWD/MTHM) for any time duration.

NRC is already addressing the question of updating storage regulations in light of the increase in projected storage time length to ~500 years. Transportation regulations have not been redrafted since the terrorists attacks on 9/11, but NRC is prepared to revise these regulations, drawing upon on technical information provided by DOE and its own studies. EPA regulations may also need updating, since 40 CFR 190 was developed in 1977 based on short-term storage. It may be appropriate to reexamine the need for dual regulation of facility operations by NRC and EPA.

Current storage and disposal regulations allow reliance on administrative controls to guarantee safety and security for no more than 100 years. The role of administrative controls will need to be reconsidered while revising storage regulations to accommodate longer storage times. Similarily, a long term disposition option that has considerable is use of heavily engineered above ground facilities for multi-century storage. Either a more traditional or heavily engineered storage concept would likely raise new regulatory issues related to how to address human intrusion and whether institutional controls can be relied upon over long time periods to prevent human intrusion or repair damage or deterioration.

Uncertainties about the likely state of UNF after an extended period of storage raise questions about whether the waste management system will be able to transport UNF loaded into a container today at the end of such a period without knowing the actual state of the fuel and the canister. In a few extreme cases, the UNF might be in the form of damaged assemblies with some rubble or granular fuel loose in the canister. Hence, questions exist as to how the regulations will want a licensee to deal with extreme cases, and whether the waste management system should anticipate the development of storage regulations for such long time frames that will be similar to those developed for disposal and thus probabilistic.

Long term storage raises issues concerning self protection and security. Radiation from UNF falls below the "self protecting" level after approximately 100 years of storage, and this period is only slightly longer (120 yr) for high-burnup fuel. Under current regulations, this could require more stringent and expensive provisions for safeguards and security. This might affect calculations about when it is cost-effective to remove fuel from reactor sites. Obviously, however, the use of massive storage casks, mitigates against easy diversion and, to some extent, sabotage. Hence, adoption of some form of "attractiveness" rankings like the DOE's as a basis for security requirements may be needed.

With the exception of a small amount of commercial fuel owned by DOE that is stored in NRC-regulated facilities, DOE UNF is stored under DOE safety regulations (10 CFR 830).[66 FR 1810] The DOE regulations may need to be reviewed and possibly revised to address much longer storage periods than originally contemplated. The ongoing review of the technical bases and NRC regulations for long-term storage of commercial UNF should be monitored and evaluated for possible implications for DOE's regulations as they affect such storage.

6.3. Policy Questions

A key policy question is where long-term storage should occur – at current sites, regional sites, or a centralized site. A 2009 GAO Report evaluated centralized and regional storage compared to on-site storage and concluded that centralized storage is favorable.[GAO 2009] However, The long history of resistance to efforts to site central storage facilities beginning with the Atomic Energy Commission (AEC) proposal for a Repository Surface Storage Facility (RSSF) in 1970, the Away from Reactor (AFR) Facility proposal by President Carter, the initial siting of the MRS, the volunteer siting process for the MRS, and the PFS storage facility, which was licensed by the NRC but blocked by rulings by the Department of Interior that have recently been remanded by a federal court), strongly indicates that gaining acceptance of a facility solely for storage will still be difficult.[NAS 2005; Huntsman 2006; Matheson 2009]

Experience suggests that any transportation of UNF requires a clear and convincing reason. A key objection that was raised to the Yucca Mountain Project was that no compelling reason had been given for moving UNF from existing sites any time soon, in view of the safety of continued onsite storage. On the other hand, it is clear that permanent storage at reactor sites is not a sustainable solution. Development and articulation of a defensible long term plan for UNF management is needed to provide a clear context and rationale for the movement of UNF from existing sites to other facilities for long-term or permanent disposition when such movements are justified.

So called "orphan" sites (i.e., sites that no longer have an operating reactor and may have no facilities at all other than dry storage systems for UNF) raise special issues with respect to the rationale for movement of the UNF stored there. Past conclusions concerning the suitability of at-reactor storage have not addressed orphan sites. Fuel/canister degradation and decreasing self-protection could be drivers for moving fuel from such sites earlier rather than later. With no operating reactor at a site, the full costs of security are attributable to the continued presence of UNF onsite. If any technical difficulties arose after extended storage that necessitated reopening and recovering fuel from storage containers, new facilities would have to be built and licensed at each site. These considerations could significantly affect the cost/benefit analysis of removing fuel from these orphan sites to centralized facilities. Further analysis of the issues affecting storage at orphan sites is needed as a basis for both regulatory and policy development. Without action, the US will have orphaned waste with no ability to repackage or transport if problems occur after 100 yr or more of storage.

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7. Integrated Waste Management System Design

The pre-closure aspects of the waste management system—storage, transportation, and waste packaging, handling and emplacement at the repository—involve significant challenges because of the large scale of operations required to manage and dispose of existing and projected US inventories of UNF and HLW. It is important to consider these pre-closure impacts now. Without a clear long term plan, the US will remain where we are now, without regard to overall costs and complexity in future transportation and repository operations. The situation includes: (1) little standardization of storage and transportation casks with many inner canister sizes optimized for each reactor site based on their own immediate needs; (2) a contract that allows UNF of various ages to be sent from each reactor site without coordination with transportation and repository operations, based their own immediate needs site; (3) little integration of storage, transportation, and disposal regulations; and (4) orphaned waste with no ability to repackage or transport in the future (as already mentioned in the previous section)

7.1. Integration between Storage and Disposal

The NWPA provides that waste owners are responsible for storage of their waste until it is accepted by the Federal government for disposal. When the NWPA was passed, it was expected that a repository would begin operating in the 1998 time frame, and therefore that storage needs would be limited to the spent fuel that accumulated until the repository began operation. With an assumed repository receipt rate of 3,000 MTHM/year – about 50% higher than the annual rate of generation of UNF – it was anticipated that operation of the repository would soon stop the buildup of spent fuel in storage and begin working off the backlogs that had accumulated.

Dry storage casks were first licensed for use in 1986, as a result of a dry storage demonstration program authorized by §218 of NWPA. Since then, dry storage systems have become the technology of choice for additional on-site storage at reactor sites, although other technologies (e.g., dry vaults) are also available. Most of the canisters in use are dual-purpose, designed for storage and subsequent transportation, while some fuel is contained in single-purpose storage canisters. In the absence of any guidance from the DOE to bring standardization to the process, each utility made incremental decisions about what storage system of those available at the time would be best for their particular circumstances. Utilities understandably sought to continue to seek the most cost effective storage systems for their UNF. Simple economic considerations provided an incentive for vendors to develop casks with higher capacities.

The Electric Power Research Institute described the storage situation to the Blue Ribbon Commission as follows: [EPRI 2010]

- As of the end of 2009, the utilities had the following stored at their sites:
    - In-pool ("wet") storage: 170,000 assemblies
    - Dry storage: 52,000 assemblies in 1200 storage casks
    - Over 20 different dry storage cask designs are in use, most of which will require different handling for transport and re-opening
    - About 63,000 MTU (metric tons of uranium)
- Projected on-site spent fuel inventories by the end of this century
    - No new nuclear plants, 60-year plant lifetime:
        - 133,000 MTU at ~70 sites

        - ~11,000 dry storage casks
        - Spent fuel will be “stranded” at decommissioned sites (probably no spent fuel pools in operation at any site)
    - “Limited” nuclear expansion (add 1000 MWe/yr starting in 2015):
        - ~180,000 MTU at >70 sites
        - ~12,000 dry storage casks
    - “Larger” nuclear expansion (total capacity growth of 3% per year starting in 2015)
        - ~11,000 dry storage casks ~750,000 MTU at >>70 sites
        - ~47,000 dry storage casks

Many of these storage casks use an inner canister that is welded, rather than bolted, shut. Hence, the inner canister may need to be cut open later for either reprocessing or disposal of the UNF. Under the terms of the contracts between DOE and the utilities, UNF in such canisters is not considered standard fuel, and does not have to be accepted by DOE on the schedule implied by the oldest-fuel-first principle. However, the proposed surface facility designs for the Yucca Mountain repository included a Wet Handling Facility with a pool in which these casks could be cut open, allowing the fuel to be transferred to Transportation-Aging-Disposal (TAD) handling canisters, however, throughput would be limited.

The more different-sized canisters there are, the more transportation overpacks have to be designed, certified, and constructed, and the more complex is the front-end designs for repositories or reprocessing plants that have to accept, open, and unload them—with concomitant impacts on the total cost and complexity of waste management.

If UNF storage at reactor sites is going to play an increasingly important role in the waste management system for the foreseeable future, it could be advisable to expeditiously determine whether some standardization of storage systems going forward could reduce the total life-cycle costs and the technical impacts of storage in the long run. This analysis could consider measures such as specification of standard interfaces and sizes for storage systems, and the potential for standardized canisters suitable for storage, transportation, and disposal (discussed further below). In this context, it is worth noting that Private Fuel Storage (PFS), the multi-utility enterprise that obtained an NRC license for a 40,000 MTHM dry storage facility on land owned by the Goshute tribe in Utah, specified a single cask system for use at the facility, although the member utilities had already been using a variety of systems.[PFS 2002]

The successful development of a specification for a TAD canisters for storage and eventual disposal at a Yucca Mountain repository, through interactions with the utilities and vendor community (discussed below), suggests that development of a standardized storage system might be achievable through a similar interactive and cooperative approach.

7.2. Integration between Storage and Disposal Canister Designs

One particularly important area of investigation for the potential to integrate utility storage decisions with the rest of the waste management system concerns the possible use of UNF canisters that can be used for storage, transportation, and ultimate disposal (if the spent fuel is disposed of directly.) The challenges of designing licensable waste packaging buildings at Yucca Mountain that would handle bare fuel at very high rates led to a decision to minimize the problem by integrating the UNF management system using TAD canisters loaded at reactors and never reopened later. Because the large emplacement drifts and gently-sloped access ramps enabled by the Yucca Mountain site allowed use of very large waste packages, the TADs were able to have a high capacity that was consistent with the utilities' desire to load UNF into large containers for storage and transportation. However, other repository sites and designs (e.g. using small boreholes and vertical access shafts) might require use of much smaller canisters if a similar integrated waste management system design is desired. For example, a single small canister design under consideration in the early 1980s could be used in salt, shale, granite, and tuff.[Gregg and O'Neal 1983]

As part of a system integration analysis described above, DOE should initiate and coordinate analysis to determine whether UNF canisterization and the size of the current canisters still makes sense in the face of uncertainty about the size of waste package that would be feasible for other repository sites or conceptual designs (which strongly affects the economics of canisterization) as well as the uncertinaty about how much spent fuel might be reprocessed. The analysis will need to evaluate the implication for caniterization based on a range of alternative repository media, waste package designs, and facility designs.

7.2.1. Proposed Multipurpose Handling Canister

In the early 1990s, the concept of a multipurpose handling canister (MPC) became a focus of attention in the OCRWM program. An MPC would be loaded at the reactors and then placed in an appropriate overpack for storage, moved to another overpack for transportation, and finally placed a disposal overpack (waste package). An MPC system minimizes the handling of bare spent fuel, thereby, simplifying the operation of the waste management system, and improving overall system integration.

The MPC system concept met with a favorable reaction by some utilities and other stakeholders; the Edison Electric Institute (EEI) was a leading supporter. Proponents believed a MPC system would simplify facilities in the Federal system. Claimed benefits included:

1. Reduced handling of individual spent nuclear fuel assemblies;
2. On-site storage at utilities compatibility with the waste management system;
3. Reduced number of shipments;
4. Near-term relief for utilities by 1998;
5. Standardized design;
6. Reduction in low-level radioactive waste generation;
7. Facilitation of early spent fuel pool decommissioning;
8. Presumed lower overall system life cycle cost; and
9. Offsets to utility costs for at-reactor storage.

The Nuclear Waste Technical Review Board (NWTRB) spoke favorably about the MPC concept in its Annual Report for 1993.[NWTRB 1994] The Board concluded:

1. If developed properly, the MPC has the potential of (1) enhancing safety in the waste management system by substantially reducing handling, (2) fostering a systems approach to the management of the nation's spent fuel and high-level waste, and (3) introducing a level of standardization into a system that currently is evolving in an *ad hoc* fashion.
2. A systems analysis that assesses the trade-offs of alternative concepts for the major parts of the system – storage, transport, *and* disposal – and that would provide a technical basis for decision-making has not been completed.

The Board also expressed concerns that the proposed accelerated schedule for MPC development and deployment gave too little priority to the disposal function, and could lead to premature specification of a suboptimal design. The report included several recommendations:

> The Board recommends that the DOE complete the systems analysis necessary to support decisions about MPC development. This analysis should determine if the various potentials of the MPC concept can be achieved in a practicable way.
>
> To avoid prematurely dropping the disposal function, the Board recommends that DOE begin to address in a technically substantive way the issue of how a true multipurpose container can evolve and be implemented given what is known today and the technology that is practical today, despite all of the uncertainties associated with repository design, has important, positive implications for system safety as well as for the consideration of extended retrievability.

The MPC system was incorporated into the OCRWM baseline in February 1994 and OCRWM began the next phase of the development program for MPCs, including the acquisition of designs for submission to the Nuclear Regulatory Commission. In 1994, the Department issued the Multi-Purpose Canister System Evaluation based on a number of MPC studies performed by the waste program's management and operating (M&O) contractor, TRW Environmental Safety Systems (TESS).[DOE 1994a] Those studies included comparisons of the reference bare-fuel only system with three canister-based options: an MPC, transportable-storage casks, and a multi-purpose unit that could serve as the disposal package without an overpack. Key assumptions, findings and recommendation of that report included:

1. The MPC system was the most suitable alternative because it provided a triple-purpose function at lower cost than the other canister systems, with a cost comparable to the individual-assembly handling system.
2. The MPC system would include two sizes: 125-ton MPC (21 PWR/40 BWR), assumed to be used at 88 facilities, and 75-ton MPC (12 PWR/24 BWR), assumed to be used at 14 facilities. Burnup credit would be required for the 21 PWR MPC. The MPCs were expected to be usable at all but 19 facilities that were assumed to ship bare assemblies in truck casks.
3. The MPC system would simplify operations throughout the waste management system, and would standardize SNF storage and introduce overall system compatibility at utility sites. It would also decouple utility operations for retrieving SNF from on-site dry storage from operations in the spent fuel pools, potentially allowing earlier decommissioning of pools.
4. The MPC system was projected to reduce overall spent fuel management costs cost for both DOE and the utility by $550 million compared to the reference case with no MRS, which was small enough to be within the level of uncertainty in the analysis. The net reduction resulted from an estimated $1.5 billion increase in the CRWMS system (driven mainly by a $5 billion increase in container costs and a $3 billion decrease in repository costs), offset by a $2 billion reduction in utility costs primarily from a reduction in storage costs.
5. The MPC system increased routine worker radiation exposures from 27% to 35% compared to the reference bare fuel handling system (primarily because of lid welding and weld inspection).
6. The implementation plan provided for having the first MPCs and transportation casks available in 1998.

The December 1994 CRWMS *Program Plan* stated that one main aspect of the new "Program Approach" was to "Ensure that multi-purpose canisters are available in 1998 for possible at-reactor storage, waste acceptance, transport, and ultimately for disposal," and included an MPC system deployment schedule. According to the *Program Plan*:[DOE 1994b]

> The availability of multi-purpose canisters for use at reactors starting in 1998 would facilitate standardization of interim storage and integration with the rest of the waste management system. Supply of these canisters by the Department could, to some extent, offset the direct site-specific costs to utilities of at-reactor storage until the spent nuclear fuel is accepted by the Federal Government for disposal.

In June 1994, TESS issued a request for proposals (RFP) with performance specifications for the design and initial fabrication of the MPC system. Five qualified offers were received in response, and in April 1995 TESS awarded a contract to Westinghouse for development of Safety Analysis Report designs and Safety Analysis Reports (SARs) for the MPC System (Phase I) with options for certification of the SAR designs, scale model and prototype fabrication and regulatory testing (Phase II) and fabrication of MPC canisters and welding equipment in 1998 and 1999 (Phase III). In August 1995 a preliminary draft EIS on implementation of the MPC concept in the waste management system was completed. Because utilities had concerns of about costs for purchasing, handling, and transportation of the new canisters and how these costs would be recouped and because vendors thought that Westinghouse had an unfair advantage in bidding since it had been involved in early analysis of the MRC, Congress eliminated funding for the MPC in the Fiscal Year 1996 appropriation. The DOE had to terminate funding for Phase II of the MPC program and bring the program to an orderly close.[DOE 1996] Westinghouse completed the Preliminary Design Report (PDR) and Safety Analysis Report (SAR) in August 1996. With termination of the MPC effort, OCRWM proceeded with the design of a repository system based on acceptance and handling primarily of bare SNF at the repository.

DOE also halted preparation of the MPC EIS (*Environmental Impact Statement for a Multi-Purpose Canister System for Management of Civilian and Naval Spent Nuclear Fuel*) that was being prepared with the Navy participating as a cooperating agency. However, the Navy chose to proceed with that part of the MPC EIS covering naval spent nuclear fuel, with DOE as a cooperating agency. Based on evaluation of a range of factors, the Navy decided to utilize a dual-purpose canister system for the management of naval spent nuclear fuel and the management of naval special case low-level radioactive waste. A dual- purpose canister system would be used for the loading, dry storage, transport, and possible disposal of naval spent nuclear fuel following examination at INL. The primary benefits identified for a dual-purpose canister system were efficiencies in container manufacturing and fuel reloading operations, and potential reductions in radiation exposure.[Navy 1996] Spent naval fuel has been loaded into these dual-purpose canisters for storage at INL pending shipment to a repository for direct disposal in a waste package overpack.

7.2.2. Proposed Transportation, Aging, and Disposal Canister

The Nuclear Waste Technical Review Board reiterated its interest in canister systems in an April 19, 2005 letter to OCRWM:[NWTRB 2005]

> …the Board recommends that the DOE evaluate the costs and benefits of using dual-purpose (transportation and storage) or multipurpose (transportation, storage, and disposal) casks for transporting, storing, and disposing of spent fuel at Yucca Mountain. The use of such casks has the potential to limit the number of times that spent-fuel assemblies must be handled and, thus, the risks and radiation exposures associated with such handling.

The challenges of designing licensable waste packaging buildings at Yucca Mountain that would handle bare fuel at very high rates led to a decision to minimize the problem by integrating the UNF management system using transportation-aging-disposal canisters loaded at reactors and never reopened later. In October 2005, the DOE announced a redirection for the YMP to a primarily clean-canistered approach to spent nuclear fuel handling operations. For this approach, multipurpose transport, aging, and disposal (TAD) canisters were to be used to minimize handling of uncanistered SNF by sealing commercial SNF in TADs at reactor sites. The same TADs were to used for transportation, aging (or staging), and disposal. In all three modes, a TAD was to be placed inside another vessel (overpack) that provides other necessary functions such as shielding, heat dissipation, structural strength, and corrosion resistance. For the repository, the disposal overpacks for TADs were the waste packages. The relatively small amount of uncanistered SNF that arrived at the repository would be packaged into TADs there.

The TAD was intended to[Kouts 2007]

1. Support the standardization of SNF storage, transport, aging and disposal packaging, allowing integration of SNF handling operations,
2. Use utility fuel handling experience in packaging SNF,
3. Simplify DOE operations and minimize redundant handling of bare SNF assemblies at the repository, leading to cleaner facilities,
4. Reduce low-level waste production and worker radiation exposure at DOE facilities, and
5. Reduce complexity and cost of DOE facilities.

TAD canisters would be the key interface component that facilitates system functions for temporary storage of spent nuclear fuel at utility sites, transport to the repository, aging at the repository and ultimate disposal. The TAD canister system would comply with regulatory requirements of 10 CFR 71 for Transport, 10 CFR 72 for Storage, and 10 CFR 63 for Disposal.

In November 2005 DOE directed the M&O contractor to use a performance-based approach in developing performance specifications that would stimulate a market driven approach to implement the development and deployment of the TAD system. The TAD system includes the TAD canister, aging overpack, site transporter, shielded transfer cask, transportation overpack, transportation shipping skid, and transportation ancillary equipment. Development of the TAD specification received substantial input from industry and from the transportation and repository components of the program. DOE issued the TAD system performance specification in November 2006.[DOE 2006] The TAD specification delineated the requirements that DOE relied upon in the repository License Application to demonstrate compliance of the TAD system with 10 CFR 63, both pre-closure and post-closure. The capacity of the TAD design is 21 PWRs/44 BWRs, with dimensions of 212.0 inches long and 66.5 inches in diameter, and a maximum weight of 54.25 tons. The TAD design uses borated stainless steel as the required neutron absorber for disposal, and prohibits the use of any organic, pyrophoric, and or RCRA materials. The TAD canisters are to be seal welded.

As discussed above, the Navy has designed a spent fuel handling system—the multi-purpose canister and associated storage and transportation components—that is designed for a Yucca Mountain repository. With the TAD, OCRWM adopted an approach similar to the Navy system. In fact, the TAD is similar in size to the naval long multi-purpose canisters, and the waste packages for the TADs are similar in size to the naval long waste packages.

TAD proof-of-concept designs were developed by four vendors (Energy Solutions, Holtec International, NAC International, and Transnuclear), and the TAD is included in the Yucca Mountain license application. Unlike the naval MPCs, no TADs have been fabricated or deployed.

The requirements established for the TAD significantly affected the repository design. For example, one of the requirements is that the repository must be designed to receive as much as 90% to 95% of 63,000 MTHM of commercial SNF in TADs. This requirement in itself was associated with a fundamental change in the previously-approved repository design. The new design includes three principal nuclear facility modules for handling spent nuclear fuel and high level waste on the surface before emplacement underground: a Canister Receipt and Closure Facility (CRCF) that receives TAD canisters of waste and loads and seals them into waste packages for disposal, a Wet Handling Facility (WHF) with a spent fuel pool for receiving and handling individual spent fuel assemblies and loading them into TADs for aging or disposal packaging at a CRCF, and a Receipt Facility (RF) that receives TADs and dual-purpose canisters and sends them to a WHF, an on-site aging facility, or a CRCF for disposal packaging. The surface facilities also include an expandable aging area for TADs in storage overpacks, and a relatively small, low throughput, Initial Handling Facility that processes only DOE glass waste and Naval canisters.

The Yucca Mountain TAD design is based on a large, high-capacity waste package (21 PWR assemblies) that is much larger than waste packages being considered in other countries for repositories in different media. Because the large emplacement drifts and gently-sloped access ramps enabled by the Yucca Mountain site allowed use of very large waste packages, the TADs were able to have a high capacity that was consistent with the utilities' desire to load spent fuel into large containers for storage and transportation. Specifically, the standard SNF waste package in the license application is a drift-emplaced design holding 21 intact PWR assemblies or 44 intact BWR assemblies, with dimensions of 77.3 inch diameter and 230.3 inch length. The total number of SNF packages in the license application is 7,796, and the total including defense waste packages is 11,629.

However, other repository sites and designs (e.g. using small boreholes and vertical access shafts) might require use of much smaller canisters if a similar integrated waste management system design is desired. For example, the Site Characterization Plan Conceptual Design Report included waste package types (called disposal containers) designed for emplacement in boreholes in the repository tunnels.[Scully et al. 1987] The SNF waste package could be used for 6 consolidated PWR assemblies, 18 consolidated BWR assemblies, 3 intact PWR assemblies (6970 lb), or 6 intact BWR assemblies (6440 lb). Package dimensions were 26-in diameter and 187.5-in length. The total number of defense and commercial waste packages projected to be emplaced was ~40,000. More recently, the German disposal package contains 12 PWR assemblies (the largest package being considered for a repository in which the packages are lowered vertically to the disposal horizon), while the Swedish and Swiss designs for crystalline rock repositories contain 4 PWR assemblies. Further analysis is needed to determine whether spent fuel canisterization still makes sense in the face of uncertainty about the size of waste package that would be feasible with other repository sites and designs (which strongly affects the economics of canisterization) and about how much spent fuel might be reprocessed. If smaller canisters than the TAD are adopted in the US multiple canisters could be placed in overpacks to reduce costs and maintain the current approximate dimensions of dry storage overpacks and shipping casks.

If analysis shows that use of standardized canisters would be cost-effective for the waste management system, the question of how to provide incentives for utilities to use such canisters will need to be addressed. The utilities now appear to have little incentive to implement changes in canisterization that might increase initial storage costs while reducing long-term system costs because the federal Judgment Fund will increasingly be paying for storage at reactor sites, and assurances may be required that increased costs incurred because of changes in storage practices would be eligible for compensation.

7.3. Waste Stream Integration

Radioactive waste disposal planning currently assumes separate disposal facilities for highly radioactive waste and low-level waste, and integrated disposal in a single facility for high-level waste and spent fuel from both defense and civilian activities. Both merit reconsideration.

7.3.1. Integrated Disposal of Radioactive Waste

Currently the statutory and regulatory basis for radioactive waste disposal anticipates separate disposal pathways for different wastes:

1. HLW/UNF in a mined geologic disposal facility,

2. LLW for classes A,B, and C in shallow land burial, and
3. GTCC LLW using mined geologic disposal unless another method is approved by the NRC

These disposal pathways are anticipated based on the waste hazard (e.g. LLW requires the lowest degree of isolation). In general, the highest degree of isolation results in the highest cost of disposal.

Experience with design of repositories for HLW and SNF suggests that opportunities might exist for cost-effective co-disposal of these waste forms in a single repository. (For example, the flexibility to dispose of LLW generated during HLW/SNF repository operations in the repository rather than shipping the LLW off site would be advantageous.)

The design of HLW/SNF repositories, specifically the density at which waste can be disposed, will be constrained by thermal limits. Generally the final layouts have a fairly low areal heat loading resulting in disposal rooms or drifts being spaced relatively far apart. The total excavated underground area is therefore dictated by the heat generating waste. Integrated waste type disposal concepts can take advantage of the excavated volume required for emplacing the HLW/SNF but not available for high heat waste disposal by emplacing GTCC and LLW in these areas. For example, it may be possible to utilize rooms or drifts constructed to provide access to the HLW/SNF disposal areas for low- or non-heat generating wastes (LLW or GTCC) without requiring significant additional underground excavation. Such integrated disposal concepts might be able to reduce total fuel cycle waste disposal costs, since the front-end costs of developing a high-level waste repository will have to be borne in any event and the incremental cost of disposing of other wastes in the unused areas may be low. Integration of the LLW and HLW regulations to avoid dual regulation by the state compacts and federal government would facilitate implementation.

7.3.2. Decoupled Disposal of Defense and Commercial HLW/UNF

The NWPA presumed that radioactive waste from atomic energy defense activities would go to a civilian repository developed under the Act. The Act defines the term "atomic energy defense activity" as any activity of the Secretary performed in whole or in part in carrying out any of the following functions:

1. Naval reactors development;
2. Weapons activities including defense inertial confinement fusion;
3. Verification and control technology;
4. Defense nuclear materials production;
5. Defense nuclear waste and materials by products management;
6. Defense nuclear materials security and safeguards and security investigations; and
7. Defense research and development.

The NWPA placed the responsibility on DOE (acting for the President) to justify a separate defense waste-only repository. The Act did not preclude a defense-only repository, but made no provisions for siting one and made it clear that such a repository would be subject to full NRC licensing. In 1985, President Reagan determined that a separate repository was not needed, based on analysis that showed that there would be large cost savings (~$1.5 billion) to using the civilian repository for the defense wastes, and that no other factors distinguished significantly between the options.[DOE 1985] Since then the DOE has planned for disposal of its high-level wastes from defense nuclear activities in a repository developed by OCRWM.

Subsequent to President Reagan's decision, the DOE established a policy to allocate ninety percent (90%) of the first repository capacity (in MTHM) to civilian SNF and ten percent (10%) of the repository capacity to Department-managed SNF and HLW. (The NWPA does not specify any allocation.) As a result, 63,000 MTHM of the 70,000 MTHM statutory limit is allocated to civilian waste and the remaining 7,000 MTHM is allocated to national defense waste. The reference plan for operation of the Yucca Mountain repository now calls for carefully synchronized co-emplacement of defense and commercial waste packages in the same disposal drifts, as part of the thermal management strategy that uses the lower heat output of interspersed defense waste packages to dilute the higher heat output of the commercial used fuel packages.

7.3.3. Integration between UNF Contract and Repository Operations

The current contract between the utilities and DOE does not allow DOE, the operator of the repository, much control as to the type and age of UNF sent to the repository. Instead the repository operations must plan for a variety of receipt scenarios. Although designing and constructing operations facilities with flexibility is desirable, the inability to plan an operating receipt schedule is challenging. Planning at the storage/disposal facility would benefit greatly if the facility could manage the types and age of fuel received. The facility could combine fuel types and ages to maintain high radiation during transportation for enhanced security, maintain more uniform heat loads within the repository without the need for extensive aging at the repository. Control of the age and type of fuels would also be necessary if the storage/disposal facility were to be combined with reprocessing facilities as might occur in the future.

7.3.4. Lessons Learned about Waste Stream Integration

1. Revisions to HLW and LLW regulations may be required to allow implementation of such co-disposal options.
2. A technical evaluation of such concepts by DOE would contribute to the reconsideration of HLW/SNF and LLW disposal regulations.
3. Less tightly coupled disposal plans warrant consideration in view of the current uncertainties about the production of the defense high-level waste forms for disposal and about the timing and relative amounts of commercial used fuel and high-level waste to be disposed of. Other options include (1) disposal in the same repository but (a) sequential emplacement of defense waste followed by portions of the commercial waste or (b) decoupled emplacement of defense and commercial waste in designated areas of the same repository, or (2) use of separate repositories for defense and commercial waste developed at different times. Early and separate initiation of defense waste disposal could provide a demonstration of disposal capability, and might find greater acceptance in addressing a national problem related to defense, rather than commercial facilities.
4. No statutory or regulatory obstacles to such options have been identified, although disposal in separate defense and commercial repositories would require revisiting the 1985 Presidential determination that separate repositories are not required. Repositories solely for defense wastes (subject to NRC regulation) are allowed by the NWPA, but that approach might preclude future use for non-defense wastes.
5. Sequential or decoupled emplacement of defense and commercial waste in the same repository could be part of a stepwise development plan, in which disposal begins with materials having little or no prospect of future reuse. This approach can be accommodated within the current legal structure since NWPA allows NRC to consider an application for “all or part of a repository.”

7.4. Integration of Regulations

7.4.1. Regulations for transportation, Storage, and Disposal

At present there are separate legal and regulatory frameworks for reactors, storage, transportation, and disposal that were developed over time around the current once-through fuel cycle. Having to design and operate the waste management system under multiple regulations (i.e., 10 CFR 71 for transportation, 10 CFR 72 for storage, and 10 CFR 63 for disposal) poses challenges. For example, the 10 CFR 63 requirement to evaluate the consequences of events with a frequency as low as 10^{-6}/year had a significant impact on the design of the TAD canister that was not otherwise required under 10 CFR 71 or 10 CFR 72. The NRC is currently undertaking an integrated review of its storage, transportation, and disposal regulations.

7.4.2. Lessons Learned on Regulatory Integration

1. Integration of regulations would facilitate integration of the design and operation of the waste management system,
2. The DOE should encourage the regulator to develop in the near future a single set of uniform regulatory requirements for spent fuel casks that spans the storage, transportation, and waste disposal phases,
3. Integration of LLW and HLW regulations to facilitate disposal of low volumes of GTCC LLW in a geologic repository might be advantageous,
4. The DOE may need to provide specific examples of where uniform requirements would help where costs savings might be substantial.

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8. Compatibility with Alternative Fuel Cycles and Disposal Systems

When the current statutory and regulatory structure was developed, it was widely anticipated that commercial waste management would primarily involve direct disposal of light water reactor (LWR) spent fuel in a geologic repository. With renewed interest in reprocessing, possible advanced separations and transmutation, advanced reactor types, and the potential for alternative disposal systems, reconsideration of the current legal and regulatory framework is appropriate to determine whether modifications would be needed to ensure compatibility with such changes and/or to ensure that alternative fuel cycle decisions are not unwittingly biased by unforeseen effects of legislative or regulatory requirements. While discharged fuel and waste materials could be managed and disposed of in a legal and regulatory framework similar to that in place today, changes/modifications could allow for further optimization while continuing to protect safety.

8.1. Compatibility with Alternative Fuel Cycles

8.1.1. Impact of Nuclear Waste Fee Structure

One of the potential advantages of reprocessing and recycling is the possible reduction in the impact of disposal resulting from multiple high level waste forms compared to spent fuel because of the reduction in radionuclide content and subsequent decay heat output of the waste. Decay heat output is one of the principle design attributes of any repository; thus, reductions in the decay heat disposed may lead to a decrease in the cost of the repository (or allow a higher waste emplacement for the same cost). Because reprocessing also generates LLW, the net savings would be the difference in costs between disposing UNF and HLW and LLW from reprocessing the UNF. Estimating the actual differential disposal costs for different waste forms will require knowledge of the waste forms, the disposal system site and design, and the disposal performance requirements.

Although reprocessing may reduce the costs of disposal of the HLW compared to direct disposal of the commercial UNF, the current statutory fee structure does not allow any such cost reductions to be reflected back specifically to the owners and generators of the HLW resulting from those activities. The NWPA establishes a single, uniform fee (per kilowatt-hour of electricity generation) to be charged to all contract holders, independent of which type of waste (HLW or UNF) that they deliver for disposal. The amount paid by each contract holder each year is tied to the amount of electricity generated that produced the waste, not to any specific characteristics of that waste. The NWPA requires the adequacy of the fee to be reviewed regularly, and that the fee be adjusted as needed to ensure recovery of the full costs of management and disposal activities. As a result, any substantial reduction in projected disposal costs resulting from a shift towards disposal of HLW instead of SNF would benefit all contract holders paying the fee, rather than only those who are deliver HLW instead of UNF for disposal. Since any disposal cost benefits from disposal of HLW cannot be fully recaptured by the generators of the UNF that is reprocessed to produce that HLW, their economic incentive for bearing the costs of reprocessing is thereby reduced.[Kim and Cotton 2007]

8.1.2. Lessons Learned about Nuclear Waste Fee Structure

1. Providing fee adjustments or rebates for any actions taken by waste owners/generators that reduce the disposal burden merit consideration.

2. Additional technical analysis is needed to determine (1) the potential reduction in disposal burden both (a) on repository performance (if any) and (b) operational waste handling costs; and (2) how such rebates/reductions would be calculated.
3. The possibility that some waste forms (e.g. pebble bed reactor fuel) might increase disposal costs should be evaluated.
4. If analysis show costs differences are measureable and significant, explicit statutory language may be needed to enable or direct an approach that would link disposal charges to the actual cost of disposal.

8.2. Compatibility with Alternative Disposal Systems

DOE's generic EIS on commercial radioactive waste management considered three alternatives:[DOE 1980]

1. Emphasize mined repositories. In this alternative, "The program would concentrate on identifying specific locations for the construction of mined repositories."
2. Parallel Technology Development. In this alternative, "the research and development program would be structured to bring the knowledge and development status of two or three disposal concepts to an approximately equal level." The likely candidate technologies would be
    - Geologic disposal using conventional mining technology
    - Placement in sediment beneath the deep ocean subseabed
    - Disposal in very deep holes
3. No Action. Under this alternative, the Department's research and development programs for radioactive waste disposal would be eliminated or significantly reduced and a decision to plan to dispose of commercially-generated wastes would be deferred indefinitely.

In the Record of Decision (ROD) following completion of the EIS,[40 FR 26677] DOE announced that it had decided to "(1) adopt a strategy to develop mined geologic repositories for disposal of commercially-generated high-level and transuranic radioactive wastes (while continuing to examine subseabed and very deep borehole 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."

Passage of the NWPA in 1982 enacted this decision to proceed with the development of geologic repositories into law. At the same time, §222 of NWPA directed DOE to continue with research on alternative disposal technologies:

> The Secretary shall continue and accelerate a program of research, development, and investigation of alternative means and technologies for the permanent disposal of high-level radioactive waste from civilian nuclear activities and Federal research and development activities except that funding shall be made from amounts appropriated to the Secretary for purposes of carrying out this section. Such program shall include examination of various waste disposal options.

Under §302(d) of NWPA, the use of the Waste Fund for research and development is limited to "nongeneric research, development, and demonstration activities under this Act," and DOE interpreted that as requiring that research on alternative disposal methods under §222 be funded by general appropriations instead.

8.2.1. Subseabed Disposal

Consistent with the ROD and NWPA, DOE continued work on subseabed and borehole disposal following passage of the NWPA. In 1983, the DOE conducted an engineering study of borehole disposal up to depths of 6 km in granite, and concluded that the option was credible from an engineering standpoint and compared favorably with cost of a mined repository using technology thought to be available by 2000.[ONWI 1983] In addition, DOE continued participation in an ongoing international research program on subseabed disposal. However, in fiscal year 1986, the DOE terminated the subseabed disposal program because budget appropriations for generic research and development not funded from the Nuclear Waste Fund had been greatly reduced.[DOE 1987]

In 1987, the NWPAA added a new Section 224 (Subseabed Disposal) that required a report to Congress on the technical, institutional, and cost aspects of subseabed disposal including a recommended R&D program, and established an office of subseabed disposal research within the DOE. However, these provisions were never funded. The Seabed Working Group of the Nuclear Energy Agency conducted joint research on subseabed disposal for 11 years and concluded in a 1988 report that subseabed burial disposal of high-level radioactive wastes or spent fuel was a technically feasible option but further research was needed to reduce the uncertainties in ts long-term safety assessment before it is used.[Calment 1989]

8.2.2. Deep Borehole Disposal

While interest in subseabed disposal is dormant because is it prohibited by the London Dumping Convenction, the same is not true of borehole disposal.[Brady et al. 2009] Development of technology for drilling deep boreholes for geoscientific purposes has continued, and in 1994 a National Research Council report on disposition of surplus weapons plutonium suggested deep boreholes as a possible disposal method.[NAS 1994] More recently, interest in deep borehole disposal concepts in the US has risen with the increasing emphasis on the future role of nuclear power.[MIT 2003] A recent Sandia report concluded that "the dramatic advances in drilling technology since completion of the geoscientific boreholes have decreased the costs and increased the probability of successfully implementing a deep borehole disposal program for low-volume, highly radioactive waste," and that "Preliminary evaluation of deep borehole disposal of high-level radioactive waste and spent nuclear fuel indicates the potential for excellent long-term safety performance at costs competitive with mined repositories."[Brady et al. 2009]

8.2.3. Lessons Learned about Deep Borehole Disposal

1. Deep boreholes may be an attractive option for disposal of low-volume, highly radioactive waste that could be produced by advanced fuel cycles.
2. The potential for stepwise decision-making raised by the prospect of deploying boreholes one at a time or in small numbers could be an advantage.
3. At present there is no statutory or regulatory framework governing siting, construction, and operation of any long-term disposal systems other than geologic repositories.
4. Deep borehole disposal systems might not be consistent with the Assurance Requirements in 40 CFR 191 related to the ability to retrieve material placed into a disposal facility (as discussed in §2.4).

5. Use of borehole disposal would likely require supporting NEPA analysis of the approach and any disposal regulations developed for that technology.

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9. Enhancing Acceptability and Maintaining Credibility of Repository Development

9.1. The Challenge in Managing the Backend of Nuclear Fuel Cycle

Although significant public support exists for continued reliance and expansion of nuclear power (as discussed below) this support does not translate into support for siting storage and disposal facilities because increased perceptions of benefits of nuclear power in general drive the current support while the perceived risk of nuclear facilities has remained fairly constant. Philosophically, the country as a whole benefits from nuclear power in that emissions from alternative sources of power are eliminated and thus potential adverse effects from CO_2 and the potential for global climate change are reduced. However, the challenge of managing the backend of the nuclear fuel cycle has been that a state and many of its citizens typically attribute to a generic storage/disposal facility only risks without seeing any benefits. Thus, the debate on siting a storage and/or disposal facility focuses on the magnitude of these risks. Furthermore, remotely siting a storage/disposal facility means fewer citizens become familiar with local, immediate benefits; hence, only a small fraction of the state population will advocate for the facility.

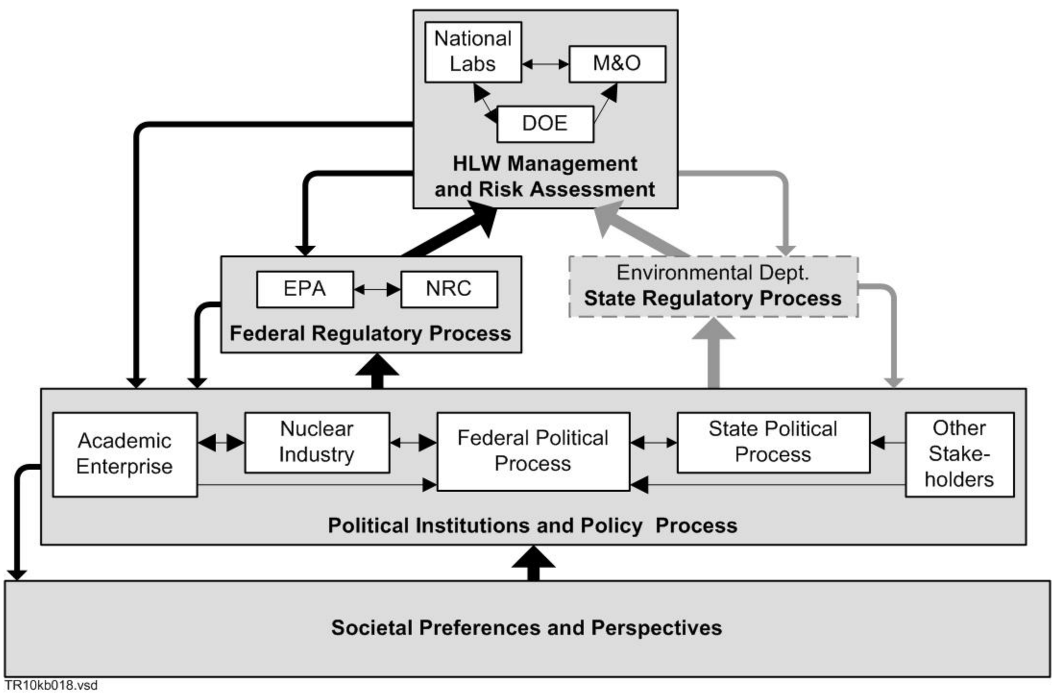

Figure 9-1: Layers of societal and governmental institutions influencing regulatory and nuclear waste management

Although this situation is intuitively understood, the process of siting a storage and/or disposal system is too easily thought of in isolation from the interaction between governmental institutions of the United States. In a conceptual sense, the various layers of the political process are nested and coupled with feedback (Fig. 9-1). The situation is quite complex when interactions between components of each of the layers are examined. For example, a complex interaction occurs between the states and the federal government (see the example related to WIPP in Appendix A). The situation becomes even more complex when interactions within each of the components are explored. For example, within the federal political policy process, the Congress allows for multiple decision points and multiple avenues for interest groups to influence agency decisions. Furthermore, the Congress, itself, allows for multiple decisions points since the process is divided between two bodies that must reach an agreement on authorization and then annually agree on a budget. The end result is a siting process with significant hurdles to overcome and requiring decades to execute.

Although the interaction between the federal and state government is a major policy aspect of nuclear waste management (components within the second layer of Fig. 9-1), the topic is beyond the scope of this report except to occasionally refer to its importance herein. Resolution of this policy aspect is a necessary condition for a successful waste management program. However, resolution of this policy aspect is not necessarily sufficient to ensure the ease of implementing a nuclear management policy. Some changes at the interface between the regulatory process and the high-level radioactive waste management institutions (i.e., the top two layers of the nested governmental institutions of Fig. 9-1) may also be necessary to promote successful implementation. This regulatory interface is the primary topic of this report. However, this section looks at some societal preferences and perspectives related to the more technical aspects of the storage and/or disposal facility (e.g., number, depth, and type) that may filter through to the regulatory process that could enhance acceptability and maintain credibility.

Constructive use of improvements in the regulatory framework discussed in prior sections of this report will be accomplished only if public confidence and acceptance for UNF and HLW storage and disposal facilities can be attained in appropriate host communities, and the affected state and local governments support the siting of those facilities. This section examines lessons learned about public acceptance of nuclear storage and disposal facilities in the United States over the past several decades.

One important question among professionals is where they can contribute to debates about UNF management policy and implementation. Drawing on the examples of WIPP and YMP as guidance for the case of siting of nuclear waste facilities in general, it appears that scientists and engineers contribute most by assuring the credibility of technical evaluations of a facility once sufficient support has developed for a community, state, or tribal organization to entertain the idea of hosting a facility. Past experience suggests that scientists and engineers, or the organizations primarily composed of these professionals cannot overcome initial resistance to a facility by presenting scientific arguments as to the small magnitude of the risks from a facility. Rather, the facility must have policy attributes that a community, state, or tribal organization find compelling. Only after the policy attributes of the facility are sufficiently compelling for a plurality of citizens and members of the governing body to entertain hosting a facility, do the scientists, engineers and their organizations have a more prominent role in evaluating the feasibility and acceptability of the facility as regards public health and safety such that the initial acceptability of the facility can be broadened. To elaborate, some policy and technical attributes of a facility are more important in garnering initial acceptance and some policy and technical processes are more important in maintaining credibility and broadening support. The discussion below is separated into two sections to distinguish between these two aspects after discussing the current public perceptions related to nuclear power and UNF management.

9.2. Current Public Perceptions

Public attitudes concerning the management of UNF and HLW are coupled with attitudes about nuclear energy more generally. Understanding how perceptions and preferences concerning nuclear energy have evolved in recent years provides necessary context for making sense of the beliefs, concerns and preferences for managing UNF.

9.2.1. Public Perceptions of Risks and Benefits of Nuclear Energy

The degree of public acceptance for nuclear facilities is linked to individuals' intuitive balancing of the perceived risks and benefits associated with those facilities.[Slovic, Krause et al. 1991; Jenkins-Smith and Kunreuther 2001] In the case of civilian nuclear energy, the US public perceives the balance to be generally positive. In ongoing survey research,[Herron and Jenkins-Smith 2010; Jenkins-Smith and Heron 2009] using data from the Sandia National Security Survey (SNSS)[10], the overall balance of perceived risks and benefits of nuclear energy among the public has been tracked since 2005. After considering a number of specific risks (releases of radiation due to accidents at plants or in transport of nuclear fuel; terrorist attacks; diversion of materials from UNF for nuclear weapons) and benefits (reliable production of base energy; reductions in reliance on energy imports; reductions in greenhouse gas emissions) of nuclear energy, representative samples of respondents were asked to give their assessments of the overall balance or risks and benefits, ranging from a value of 1 (risks greatly exceed benefits) to 7 (benefits greatly exceed risks). The mean values for the 2006-2010 time-period are shown in Fig. 9-2 (sampling error in each year is <3%). These data make clear that, over the past decade, Americans have consistently viewed nuclear energy as producing greater benefits than risks.

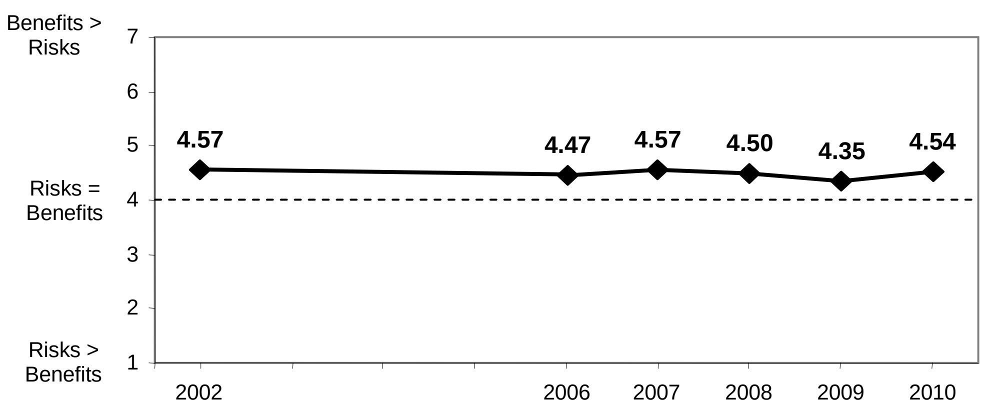

Figure 9-2: Americans' assessment of the balance of risks and benefits from nuclear energy

Perceived risks of nuclear energy – like those for any energy source – are necessarily relative to the risks of other sources of energy. When placed in a comparative context, the risks posed by nuclear energy are seen as equivalent to, or slightly lower than, those posed by fossil fuels over the past several years.[Herron and Jenkins-Smith 2010, p. 84] One result of these considerations is that, on average, members of the public would prefer to see a substantial increase in reliance on nuclear energy in the overall energy supply mix over the next 20 years. Fig. 9-3 shows the mix of US energy supplies that the public would prefer in twenty years, after having been informed about the current mix (fossil fuels – 85%; nuclear energy – 8%;

[10] The Sandia National Security Surveys are sponsored by Sandia National Laboratories and the University of Oklahoma. The surveys are collected annually, in May and June. Internet surveys are collected every year. Companion telephone surveys are collected periodically to allow for assessment of the mode of collection on responses.[Herron and Jenkins-Smith 2010; Jenkins-Smith and Herron 2009; and Jenkins-Smith and Herron forthcoming 2011]

renewables – 6%).[11] The public would like to see the fraction of US energy from nuclear energy rise from 8% to 22%, or a 275% increase, over the next two decades.

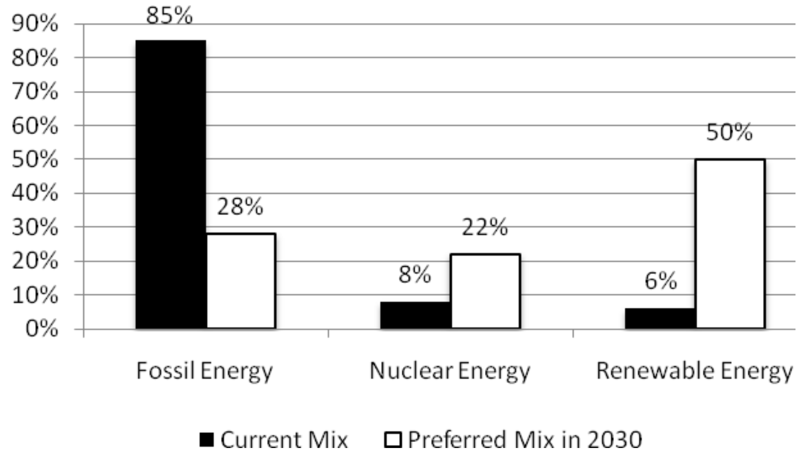

Figure 9-3: Preferred mix of total energy sources in 2030

Assessments of risks and benefits, and preferences for increased reliance on nuclear energy, are borne out by expressed preferences for construction of additional nuclear reactors. When asked for their preferences for construction of new reactors at existing plants, and new reactors at *new* sites, on a scale from 1 (strongly oppose) to 7 (strongly support), the public's average level of support for both has grown significantly since 2002 (the earliest year in which the SNSS included this question). The average level of support by year is shown in Figure 9-4. From 2002-2010, the average level of support has increased approximately 10% for adding reactors at the site of existing nuclear power plants, and by 15% for adding reactors at new sites.

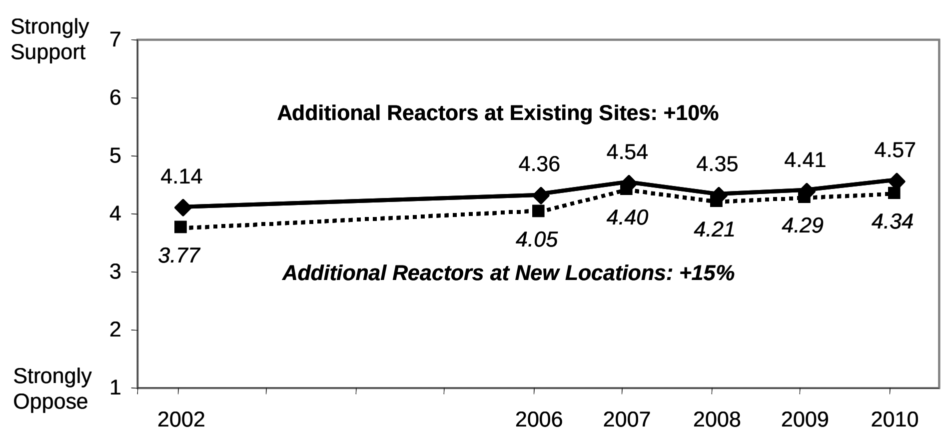

Figure 9-4: Preferences for construction of new reactors at current and new sites

[11] The proportions shown are the averages from the SNSS taken over 5 years, from 2006 to 2010. The yearly averages have fluctuated very little over time.

It is in this context that public acceptance of policy options for managing UNF and HLW will evolve. Public acceptance of management options for UNF will be conditioned by the current environment of increasing support for reliance on nuclear energy, including support for constructing new nuclear energy reactors.[12]

9.2.2. Public Perceptions of Risks and Benefits of Used Nuclear Fuel

In contrast to perceptions of nuclear energy, members of the public in the US and elsewhere have tended to view both used nuclear fuel and HLW as wastes with dreaded risks and little in the way of offsetting benefits.[13] While UNF storage and disposal policies may seek to provide inducements to accept UNF, measures designed to provide compensation to potential host communities to offset perceived risks of UNF storage and disposal facilities can backfire, and be seen by the public as confirmation that the risks are dire.[Kunreuther and Easterling 1998; Jenkins-Smith and Kunreuther 2005] Beyond the perceived physical risks from such wastes, other research has suggested that "perception-based impacts" may stigmatize and impose social and economic losses on host communities and states.[Easterling and Kunreuther 1993; Gawande and Jenkins-Smith 2001] The sustained public and state-level opposition to the siting of the Yucca Mountain repository,[Slovic, Layman and Flynn 1991] coupled with DOE's decision to withdraw the license application and terminate the project in 2010, would seem to confirm the difficulty of finding communities and states willing to host facilities designed to manage and dispose of UNF and HLW.

Recent successes at finding willing host communities for spent nuclear fuel disposal in Sweden and Finland have stimulated new thinking about the possibilities of siting UNF management facilities.[Mark Elam and Sundqvist 2009] Within the US, the successful licensing and ongoing operations of the Waste Isolation Pilot Plant (WIPP) near Carlsbad, NM, has also generated some reason for optimism that nuclear materials disposal facilities can attain acceptance in host communities. Studies of public attitudes about UNF disposal, and experience with WIPP and the proposed YM repository, provide important lessons for future nuclear materials facility siting efforts. This report makes extensive use of lessons learned from studies of the beliefs and preferences of the US public, based on the SNSS program initiated in 1993.[14] Experience and social science research applied to the YMP and WIPP are also utilized.

9.2.3. Public Understanding of UNF and Related Policies

While members of the public are broadly capable of developing reasoned policy preferences in complex policy domain. [Herron and Jenkins-Smith 2006; Lupia and McCubbins 1998] public understanding of such issues tends to evolve from inchoate and variable opinion toward stable judgment as policy debates mature.[Yankelovich 1991] Evidence collected by the SNSS Project indicate that public opinion on the UNF issue has yet to fully mature. In part this is evident from widespread misunderstanding of current UNF practices in the US. Until very recently, a plurality (one third) of survey respondents believed that UNF was already being shipped to Nevada for permanent disposal. Although the long-running debate over the Yucca Mountain repository has often been in the news, [15] this is not surprising, given that much of the public neither seeks

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[12] The results from the SNSS are consistent with the findings of other, less comprehensive, measures of attitudes toward nuclear energy.[Jones 2009] Also consistent with other findings, the SNSS data show that support for nuclear energy is greater among males, and those with higher incomes and education levels.

[13] One of the more powerful examples of issue framing in public debates has been the widespread reference to used (or spent) nuclear fuel as "nuclear waste", and of repositories as "nuclear waste dumps". Designation as a waste implies no further use or purpose other than disposal; hence, there are only risks to be considered.[Slovic, Flynn, and Layman 1991]

[14] For the most recent published summary of the Sandia National Security Survey Project, see Herron and Jenkins-Smith (2010). The analysis of the 2010 data will be published in Jenkins-Smith and Herron (2011).

[15] The pattern of news coverage since 2004, as well as the volume of internet search activity, for Yucca Mountain can be readily seen by using "Yucca Mountain" as the search term at Google Trends, accessible at http://www.google.com/trends.

nor continuously monitors information on UNF management practices. Nevertheless, there has been a modest trend toward broader public understanding that UNF is most often stored at or near civilian nuclear reactors. Over the 2006 to 2010 period, the fraction of respondents who correctly responded that UNF is stored in special containers at nuclear power plants throughout the US has risen from 1 in 5 to nearly 1 in 3 (31% in the 2010 iteration of the survey, slightly more than the 30% who still believe it is sent for deep geologic disposal in Nevada). When asked whether UNF was stored at any site in their own states, only 12% could answer correctly. Thus, while public understanding appears to be growing modestly over time, there is some distance to go before opinion will evolve to form a clear and stable aggregate public judgment about UNF policy.

Given the current level of public understanding of the issue, measuring public preferences to analyze prospects for acceptance of UNF management facilities requires that a basic level of background information be provided to survey respondents. Even on complex issues of this kind, once balanced background information is provided, members of the public are able to express differentiated and stable opinions that are grounded in their broader systems of beliefs.[Herron and Jenkins-Smith 2006] The SNSS project has used this approach to track public assessments of current policies and to evaluate variations in public acceptance of UNF management options across alternative design elements for policy and facility characteristics (e.g., number, depth, and type).

9.2.4. Public Evaluation of Current UNF Management Practices

Evaluations of current UNF storage practices requires that the survey participants be apprised of the primary points of view of both proponents and opponents of continued on-site storage, in a manner that does not privilege one argument over another.[16] The following background was provided with the 2010 SNSS:[17]

> Spent nuclear fuel is highly radioactive and must be safeguarded for thousands of years or chemically reprocessed. If it is reprocessed, the uranium can be separated from the waste and reused to make new fuel rods for generating electricity, but the remaining elements are highly radioactive for a very long time and must be safeguarded and isolated from the environment for thousands of years.
>
> In 2010 the government halted construction of a deep underground facility inside Yucca Mountain in Nevada that had been intended for long-term disposition of spent nuclear fuel, and very little spent nuclear fuel is being reprocessed in the U.S.
>
> Currently, US spent nuclear fuel is being temporarily stored at over 100 sites in 39 states. Most of it is stored at nuclear power plants where it is placed in secure cooling pools. In some cases, the spent fuel is transferred to specialized concrete casks stored above ground near the nuclear power plant. At each site, the cooling pools and storage casks are protected at all times by security forces.

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[16] The objective in survey design of this kind is to provide, in brief and accessible form, the range of arguments that the public is likely to encounter in public debate on the issue.

[17] The public usually understands (often through direct experience from home construction) that the construction process involves a number of steps that includes seeking several permits and, for large construction, exploratory drill holes for foundations etc. However, because seeking a construction authorization was such a major step for Yucca Mountain, those intimately involved with the YMP have commented that "halted construction" in the question would give the impression to the public that the NRC had issued a license for construction of the surface handling facilities and disposal drifts. However, the general public is not that familiar with the specific steps of repository construction and operation. A full explanation that construction of 5 miles of tunnel and numerous alcoves was not construction of the repository but rather construction of an exploratory studies facility that would become part of repository, and that DOE chose to withdraw the application seeking authorization to convert the exploratory studies facility into part of the repository and construct additional disposal drifts and surface handling facilities would easily distract the reader from the intent of the question.

Some people think this is an acceptable solution for the foreseeable future, while others think such practices are risky and other options need to be adopted.

The following arguments were then presented in randomized order:

Opponents argue that some nuclear power plants where spent nuclear fuel is stored are near rivers, oceans, and large population centers. On rare occasions spent fuel has leaked radiation into the cooling pools. Moreover the cooling pools and containers are located at ground level, and therefore might be vulnerable to terrorists. They note that these storage practices do not provide a permanent solution for managing spent nuclear fuel.

Supporters argue that transporting spent nuclear fuel by train or truck to consolidated storage facilities is risky, that storing spent nuclear fuel at nuclear power plants is less expensive than consolidated storage, and that it buys time for finding future solutions. Moreover, storage at nuclear power plants has not caused any accidents that have exposed the public to radiation.

Survey respondents were then asked: "Using a scale from one to seven, where one means *strongly oppose* and seven means *strongly support*, how do you feel about the current practice of storing spent nuclear fuel at or near nuclear power plants?" The mean responses from 2006-2010 have consistently been below mid-scale (3.3 – 3.7). In 2010, 40% of respondents opposed indefinite on-site storage and 34% were undecided. The remaining 26% favored continuing the current practice. These responses indicate that, while the public is decidedly uneasy about indefinite on-site storage, there remains significant latitude (with a third of the public undecided) for continued policy development.[18] However public support for variations in UNF management strategies is shaped significantly by policy design options.

9.3. Considerations for Enhancing Initial Acceptability of Repository Development

9.3.1. Retrievability

Analysis of results from the most recent SNSS data, and of the policy debate concerning UNF in Europe, suggests that two related considerations currently underlie public acceptance of UNF management strategies. These include the question of defining UNF as a waste or a resource, and whether society should retain the capacity for future amelioration or enhancement of the safety of the materials in the storage/disposal facility. Both of these considerations directly bear on retrievability in UNF repository design.

The issue of retrievability has become a central factor in public debates over initial acceptance of UNF disposal siting in Europe.[OECD-NEA 2001c; 2009] In the Finnish debates over facility siting, the addition of the requirement for integrating retrievability into the design of disposal facilities for UNF was one of the few concrete results of very extensive public engagement on the issue,[Hokkanen and Kojo 2003] and subsequently Finland was the first country to successfully site a permanent repository, near the host community of Eurajoki. In the US the issue of retrievability of UNF has received little public consideration, though focus group discussions undertaken in the late 1990s suggested that members of the public believed that

[18] Another indicator of latitude for continued policy development is that less than 20% of the responses fall on the scale endpoints ("strongly oppose" or "strongly support").

future generations should be given the option to remove UNF from disposal facilities if new knowledge or changed circumstances warranted such action.[19]

The SNSS project queried the implications of retrievability in repository design for public acceptance of UNF facility siting by presenting balanced arguments for and against. The wording was as follows:

> Now we want you to consider the issue of whether stored radioactive materials should be managed in a way that allows authorized personnel to gain access to them and retrieve the materials in the future, or that seeks to permanently block access to them. One option is to build facilities where the stored materials are continuously monitored and can be retrieved for reprocessing, or possibly to make them less dangerous using future technological developments. This option requires greater security efforts and may be more vulnerable to attack or theft. Another option is to attempt to seal off storage sites in such a way that people cannot readily gain access to the materials in the future. This option is more secure, but does not allow reprocessing or treatment by future technological advancements.
>
> Using a scale from one to seven, where one means *strongly oppose* and seven means *strongly support*, please indicate how you feel about each of the following two options.

The two options were presented to the respondent in random order:

> Construct sites so that stored materials are monitored and could be retrieved for reprocessing or further treatment in the future.
>
> Construct sites so that stored materials are permanently sealed away and cannot readily be retrieved in the future.

Overall, 67% of respondents supported the retrievable facility design (with a mean response 4.98), while 38% expressed support for the non-retrievable design (mean response 4.14). When asked to rank the two options, 69% preferred the retrievable option. In sum, though neither option generates strong opposition, inclusion of retrievability in repository design is preferred by a two-to-one margin.

Waste or Resource?

Available evidence suggests that broad public support for retrievability stems from two distinct considerations. The first is the matter of whether UNF is understood by the public to be a waste or a potential future resource, via reprocessing. The SSNS project asked respondents to indicate their preferences for reprocessing beginning in 2008.[20] The responses have been consistent since measuring attitudes about reprocessing began; a substantial majority has expressed support for the reprocessing option (ranging from 59-67% in favor). Less than 20% have expressed opposition in any year (those opposed made up 13% of all respondents in 2010). Note that these results were obtained despite reminding respondents that the uranium and plutonium, when separated in the reprocessing, could be used to make nuclear weapons. The public thus broadly perceives UNF to be a potential resource.

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[19] These focus groups were conducted in Nevada, New Mexico and Illinois as part of a research project undertaken by the University of New Mexico's Institute for Public Policy in 1998. The results were summarized in Bassett et al (1998).

[20] The reprocessing option was described as follows: "Next we want you to consider the issue of reprocessing, which involves the chemical separation of radioactive materials in spent nuclear fuel. After reprocessing, most of the uranium and plutonium can be captured and reused to generate electricity, reducing the amount of uranium that must be mined in the US or purchased from other countries. Remaining materials are radioactive and must be safeguarded and isolated from the environment. However, reprocessing may also separate the plutonium which, like uranium, could be used to make nuclear weapons." Respondents were then asked to register their support or opposition to "the option for reprocessing spent nuclear fuel".

Future Options Retained

The second consideration made by members of the public that militates toward a retrievable UNF repository design is that of potential future improvement in safety. In the European debate over UNF disposal, the retrieval issue has distinguished between *retrievability*, which is restricted to physically retrieving the UNF from the repository, and *reversibility*, which can be taken to mean retaining the option to change the disposal policy should better options become available.[OECD-NEA 2001c, p. 11] In the American context, focus group findings suggest a substantial technological optimism that future developments in science and engineering will lead to new options that current technologies do not now support,[21] and hence permanent closure of a repository would preclude taking advantage of those options.[Bassett et al 1998] More conclusive evidence of a public preference for retaining the option to employ future learning is available from the SNSS project, which in 2010 asked whether support for siting a repository would change if the repository was co-located or combined with a research laboratory that focused research on finding ways to more safely and efficiently manage UNF. Inclusion of such an option substantially increased support for the facility, even among those initially opposed to siting the facility, as discussed in more detail later in this section.

9.3.2. Design Factors of Waste Management Facilities

Given the broad public sensibilities concerning retrievability, how do specific design factors shape public support for UNF management facilities? Given that current administration has decided to withdraw the license application for the repository at Yucca Mountain and terminate the project, it is possible to consider a wide range of options. Primary policy design features that may have significant implications for public acceptance include (a) the number of sites to be considered, (b) the type of storage and storage depth for the UNF at the sites, and (c) whether the repository function is combined with other activities at the facilities. The SSNS project investigated the implications of each of these design features for public acceptance in 2010.

How Many Storage Sites?

While the range of options for the number of UNF storage/disposal facilities is broad, three options appear to capture that plausible range for consideration; (a) continued dispersed, on-site storage, chiefly at operating nuclear reactors; (b) a number of regional facilities, perhaps designed to optimize UNF transport routing; and (c) one or two centralized facilities. The 2010 SSNS questionnaire measured the relative public preference for a characterization of each. Respondents first were asked to consider the preferred number of facilities:

> While nuclear power plants will continue to store some spent fuel in their cooling pools, much of the radioactive materials currently at temporary storage sites in 39 states might be consolidated at a smaller number of regional or central facilities. Once it is consolidated, the spent nuclear fuel can more easily be secured and protected from attack. The fewer the number of regional or central storage facilities, the less complex are the political and legal obstacles for finding communities willing and able to host the facilities. At the same time, a larger number of regional storage facilities would reduce the distances radioactive materials must be transported by train or truck, and would also reduce the number of communities through which the transport routes would pass.

[21] One such example is deep-borehole disposal, which has become more promising over the last decade with advances in deep drilling.

Respondents were asked to rate their preferences for each of three options on a scale from one to seven, where one means *strongly oppose* and seven means *strongly support.* They were also asked to rank the options from most to least preferred. The options were then presented in random order:[22]

> After spent nuclear fuel is removed from the cooling pools, continue the current practice of temporarily storing it above ground at designated nuclear power plants. This option does not require additional transportation of radioactive materials by train or truck, and it presents few additional political or legal obstacles.
>
> Construct six to eight regional storage sites that can be more easily secured and can provide longer-term storage. This option requires transporting spent nuclear fuel by train or truck over moderate distances and is likely to generate political and legal opposition.
>
> Construct two large centralized storage sites (one in the west and one in the east) that can be most secure and provide permanent storage. This option requires transporting spent nuclear fuel by train or truck over longer distances and is likely to generate political and legal opposition.

The average respondent level of support on the 1-7 scale for (a) continued on-site, (b) 6-8 regional sites, or (c) 2 centralized storage sites were 4.15, 4.18, and 3.91, respectively. Mean preferences for continued on-site storage and the multiple regional storage facilities are statistically indistinguishable; both are preferred over the two centralized storage/disposal sites option.

Several points are evident from these results. Strong preferences for the number of sites where UNF might be stored temporarily or permanently have yet to develop, suggesting that there remains considerable latitude for determining an acceptable option. For each of the options considered, the modal response was the scale mid-point (indicating uncertainty or lack of preference); strongly held positions (either in support or opposition) remained near or below 20% in each case. At the same time, support for a larger number of sites – whether regional or continued at reactors – was greater than support for 2 centralized sites. This suggests that the public would not rule out multiple storage/disposal facilities, in concept. The prospective difficulties with obtaining acceptance from those nearby, because of a not-in-my-backyard (NIMBY) reaction are discussed later.

At What Depth?

Another critical design issue concerns the depth of storage, which can plausibly range from storage at ground level to disposal miles below the surface in "deep borehole" repositories. The SNSS respondents in 2010 were asked to consider their preferences for three possible designs; storage on the surface storage, storage/disposal in deep geologic mined storage, and disposal in deep boreholes. The question was posed as follows, where the ordering of the options was random:

> Next we want you to consider the issue of storage depth. There are three general options.
>
> One option is to store spent nuclear fuel at or near the surface in hardened structures of concrete and steel. This allows monitoring and retrieval, but it is considered to provide a safe means to manage the material for only about a hundred years.

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[22] Those involved with repository programs are familiar with the definition of storage as "retention…of radioactive material with the *intent or capability to readily access* or retrieve such material. [emphasis added]"and disposal as "emplacement of waste in the repository with *no intent of recovery,* whether or not the design of the disposal system permits the ready recovery of the waste [emphasis added]" and where repository is the "mined portion of the facility constructed underground…" Rather than switch words in the last option of the question and thereby risk confusion and thereby some aversion to this choice (since dispose can imply further processing such as with a garbage disposal unit), the question purposefully changes the adjective proceeding storage in each option to allow the reader to quickly understand the intent of the question, that is, *temporary, longer-term* and *permanent*.

> One option is to build mine-like storage facilities that are thousands of feet underground. These can be constructed to allow materials to be retrieved, or they can be designed to permanently block assess in the future. They are suitable for storage over thousands of years.
>
> One option involves drilling multiple boreholes of about 1.5 feet in diameter and up to three miles deep. Spent nuclear fuel would be stored in the deepest parts of the boreholes that are in bedrock. There is almost no chance that the materials could migrate into the surface environment over thousands of years, and they would be extremely difficult to retrieve.

SNSS respondents indicated their support for each option on a scale from one to seven, where one meant *strongly oppose* and seven meant *strongly support*. Support for the mine-like geologic storage scored highest (4.92 on the 1-7 scale). Support for the ground-level and deep-borehole options was statistically tied (4.16 and 4.08, respectively). When asked to rank the options, the deep geologic storage option was the first choice of 49% of the respondents; the ground-level and deep-borehole options were the preferred choice of 27% and 25%, respectively.

Among the SNSS respondents the mine-like repository option is the clear preference for depth. However the characterization of the options placed emphasis on the implications of each choice for retrievability and suitability for long-duration of storage. The survey respondents' preference for the mine-like repository may well reflect the characterization of that option as affording *both* retrievability and the option to seal the materials for "thousands of years". This is consistent with the more general preference for retrievability discussed above.

Storage/Disposal Combined with other Facilities?

The selection of the design features of a storage/disposal repository may have large implications for the acceptance of the facility by prospective host communities. The Yucca Mountain repository, for example, was designed (and presented to the public) exclusively as a disposal facility, to be permanently sealed after a monitoring period. It was to have minimal long-term scientific research activity, and was not designed to include non-disposal functions for nuclear waste management (e.g., an MRS, research, or reprocessing). The combination of features of the proposed facility (including those absent) shapes the way an observer understands the combination of risk and benefits of the facility, as discussed above. For that reason the combination ofdesign features of a facility may have large implications for public acceptance when siting UNF facilities.

Given the large number of permutations of possible facility design features, the SNSS focused on the effects of two variations in design features: combining the repository with a research laboratory and/or with a UNF reprocessing facility. To evaluate the effect of these options, two variations on a "base" repository were considered: one option was for two centralized mine-like repositories, the other was for seven regional repositories employing deep-borehole disposal. Respondents were randomly assigned to consider only one base option.[23] The description of the base repositories for one half of the respondents was as follows:

> For the next few questions, assume that construction of two underground mine-like storage facilities is being considered for the storage of spent nuclear fuel. One would be in the eastern U.S., and the other in the west. Each of these sites would include secure surface storage buildings and a mine several thousand feet deep where radioactive materials could be isolated from people and the environment and could be designed to allow retrieval or to permanently seal away the materials. The facilities and the mines would be designed to meet all technical and safety requirements set by the U.S. Nuclear Regulatory Commission, the U.S. Environmental Protection

[23] The random split resulted in 1,177 respondents receiving the deep-borehole repository option, and 1228 receiving the mine-like deep geologic repository option.

Agency, and applicable state regulatory agencies. Using a scale from one to seven where one means *strongly oppose* and seven means *strongly support*, how do you feel about this option?

The other half of the respondents received this alternative base option:

> For the next few questions, assume that construction of about seven regional sites across the U.S. are being considered for the storage of spent nuclear fuel. Each of these sites will include secure surface storage buildings and a number of deep boreholes drilled up to three miles deep into bedrock where the radioactive materials could be isolated permanently from people and the environment. The facilities and boreholes would be designed to meet all technical and safety requirements set by the U.S. Nuclear Regulatory Commission, the U.S. Environmental Protection Agency, and applicable state regulatory agencies. Using a scale from one to seven, where one means *strongly oppose* and seven means *strongly support*, how do you feel about this option?

Note that both of the alternative base cases stipulated that the repository would have secure surface storage, and would be in compliance with relevant regulatory safety requirements.

The inclusion of the more complete descriptions resulted in moderate public support for both options. The deep-geologic mine option received an average initial support of 4.82 on the one ("strongly oppose") to seven ("strongly support") scale. Fifty-eight percent of the respondents who were presented with this option expressed support, while 16% were opposed (26% were neutral). The other half of the sample gave the deep-borehole option a mean support score of 4.49. Fifty-one percent of those who received this option supported it, while 21% were opposed (28% were neutral). Given these starting points, what happens to support for the facility if the repository function is combined with the laboratory and/or reprocessing function?

To evaluate the effects of a combination of facilities, respondents were asked the following questions:

> Now we want you to consider how your support would be affected by more specific information. Please respond to each of the following questions on a scale from one to seven, where one means the information would *greatly decrease* your support and seven means it would *greatly increase* your support.

The following two questions were posed in random order:

> What would happen to your level of support if you learned that each of the sites also would contain a national research laboratory for studying ways to more safely and efficiently manage and dispose of nuclear materials?
>
> What would happen to your level of support if you learned that each of the sites also would include facilities for reprocessing spent nuclear fuel for reuse in generating electricity?

The effect on support for a base repository when combined with a hypothetical national research laboratory is shown in Table 9-1. Changes in support due to addition of the laboratory are shown for those who initially supported, were neutral, or opposed the base facility (as described above).

Table 9-1:Change in support for repository when combined with research laboratory

	2 Mine-Like Geologic Repositories			7 Deep Borehole Repositories		
Initial Preference	**Support (58%)**	**Neutral (26%)**	**Oppose (16%)**	**Support (51%)**	**Neutral (28%)**	**Oppose (21%)**
Support Increased	70%	55%	48%	72%	61%	50%
Support Unchanged	20%	37%	21%	19%	33%	23%
Support Decreased	10%	8%	31%	9%	6%	26%

Of greatest policy relevance are those who initially opposed or were neutral to siting the facility. Among those initially opposed, approximately half said their support for the repository would increase if it was combined with the national research laboratory. The numbers are larger (55-61%) for those who were initially neutral. This is consistent with the findings of earlier studies of public support for facility siting, in which it was found that modifying the function of a facility in a manner that addresses the initial risks—both reducing the risks and providing benefits germane to those risks—will do the most to increase acceptance of the facility.[Jenkins-Smith and Kunreuther 2005] In this case, co-locating a UNF repository with a national research laboratory that would study "ways to more safely and efficiently manage and dispose of nuclear materials" both serves to reduce the relevant risks and provides high-prestige employment and other economic development benefits. Based on the broad increases in levels of support, such a facility may be less susceptible to the kind of stigmatizing imagery that adheres to a stand-alone repository.

The effects of combining a repository with a reprocessing facility are shown in Table 9-2. Again, the changes in support are shown for those who initially opposed, were neutral, or supported each of the base repository options.

Table 9-2: Change in support for repository when combined with reprocessing facility

	2 Mine-Like Geologic Repositories			7 Deep Borehole Repositories		
Initial Preference	**Support (58%)**	**Neutral (26%)**	**Oppose (16%)**	**Support (51%)**	**Neutral (28%)**	**Oppose (21%)**
Support Increased	66%	47%	48%	66%	56%	50%
Support Unchanged	21%	43%	16%	21%	35%	25%
Support Decreased	13%	10%	36%	12%	9%	26%

As with co-locating a repository with a national research laboratory, combing a repository with reprocessing facilities increases support.[24] Among those who either initially opposed the repository or were neutral, about half said the addition of the reprocessing capability would increase support for the repository. Relatively modest percentages said that the combination would reduce support. Given the consistent and generally supportive view that most Americans have toward reprocessing (as discussed

[24] A more accurate description of this option is where the waste disposal function is not separated from other functions related to fuel fabrication and reprocessing.

above), this increase in support for the repositories when combined with reprocessing is not surprising, and could be policy-relevant.

The implications are that public acceptance of a UNF repository will be sensitive to the *overall* design attributes of the facility. When the facility is exclusively for disposal, the perceived risks and associated negative imagery will tend to dominate perceptions (especially when UNF has been designated a "waste"). When the facility is more heterogeneous, including design elements that address offsetting risk/benefit activities (such as a laboratory or reprocessing facilities), prospects for public acceptance are increased.

9.3.3. Compensation and Public Acceptance

Studies of hazardous facility siting have shown that providing compensation to host communities can increase public support, but may only be effective if the overall balance of risks and benefits attributed to the facility is within acceptable ranges.[Kunreuther and Easterling 1998; Jenkins-Smith and Kunreuther 2001, 2005] To what extent does compensation play a role in acceptance? The SNSS posed the following question in 2010:

> What would happen to your level of support if you learned that each of the states hosting the sites would receive several billion dollars a year, paid for by revenues from nuclear energy, that could be used for hospitals, roads, and schools in that state?

The pattern of changes in expressed support is shown in Table 9-3, which again shows changes within the groups of those who supported, were neutral, or opposed the repository siting prior to introducing the compensation option.

Table 9-3: Change in support for repository designs with state compensation

	2 Mine-Like Geologic Repositories			7 Deep Borehole Repositories		
Initial Preference	**Support (58%)**	**Neutral (26%)**	**Oppose (16%)**	**Support (51%)**	**Neutral (28%)**	**Oppose (21%)**
Support Increased	62%	42%	39%	59%	52%	41%
Support Unchanged	20%	43%	23%	24%	30%	22%
Support Decreased	18%	15%	37%	17%	18%	37%

Although overall increases in support in response to compensation are evident, the changes are more modest than was the case for bundling positive attributes into the facility design. Among those who initially opposed the siting, the fraction for which compensation *decreases* support is nearly as large as that for which it *increases* support. Among those initially neutral however the effect of compensation on increasing support is substantial; between 42% and 52% of those neutral to the repository expressed increased support when compensation was added to the mix. The conclusion is that compensation is likely to have the effect of increasing support only among those for whom the facility design does not generate strong opposition. For that reason it appears that primary emphasis should be on specification of other facility attributes that generate initial public acceptance. Compensation should be considered as a means to maintain and broaden approval after the facility attains sufficient support .

9.3.4. Proximity of Nuclear Facilities and Public Acceptance

Used nuclear fuel disposal repositories long have been viewed to be one of the most difficult-to-site facilities.[Slovic, Flynn and Layman 1991] The recent administrative decision to withdraw the license application for the Yucca Mountain facility and terminate the project would seem to confirm this judgment.[25] What are the lessons about proximity in the US case? Two kinds of evidence seem relevant. The first consists of systematic measures of the sensitivity of the US public's level of support for repository siting to the distance of the prospective repository from the respondent's residence. These data can be used to reveal initial preferences, prior to the onset of policy debates over a specific repository proposal. The SNSS data are used here for that purpose. The second kind of evidence comes from cases in which measures of public acceptance for an actual repository can be related to distance from the facility. While no UNF repositories have been constructed and operated in the US, and no systematic data are available on public support for UNF repository siting outside Nevada,[26] measures of public support for the Waste Isolation Pilot Plant (WIPP) in southern New Mexico provide an important case for evaluating the effect of proximity on support for repository siting over the course of an extended and ultimately successful effort. The data from both the SNSS and the study of WIPP are therefore used to draw lessons about proximity and public acceptance for nuclear materials facility siting.

The SNSS data collected in 2010 permit analysis of the change in support for two broad repository designs (Mine-like Deep Geologic and Deep Borehole) as the stipulated distance of the repository site is increasingly close to the respondent. All respondents were asked the following question:

> What would happen to your level of support if you learned that one of these sites is to be located in your state?

Responses were coded on a one to seven scale, where one means the information would greatly decrease support for siting the repository and seven means greatly increase support. Respondents were then were asked:

> What would happen to your level of support if you learned that one of these sites is to be located (randomly assigned: 50, 300) miles from your principal residence?[27]

For this analysis, the percentages of respondents who support, are neutral, or oppose the repository are shown for each of three categories of distance: (a) within the respondent's state of residence, (b) within 300 miles of the respondent's principal residence, or (c) within 50 miles of the respondent's principal residence.[28] Results are shown in Table 9-4.

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[25] See the relative level of opposition to the potentially hazardous facilities analyzed in Jenkins-Smith and Kunreuther (2001).

[26] The Nevada case, which was singled-out as the nation's only HLNW repository site to be evaluated over the strong and persistent objections of most Nevada elected officials, provides evidence of "worst case" conditions for garnering public support.

[27] Respondents in the telephone sample were randomly divided into the 300 and 50-mile categories, while those in the Internet survey were divided into 300, 100, and 50-mile categories. In order to use the combined telephone/Internet responses, we omitted the 100-mile category from this analysis.

[28] The number of respondents randomly assigned to each subgroup was 857 for the 50-mile group, and 900 for the 300-mile group.

Table 9-4: Change in support for repository by proximity

Repository is within…	Mine-Like Geologic Repository			Deep-Borehole Repository		
	Increased Support	No Change	Increased Opposition	Increased Support	No Change	Increased Opposition
Respondent's State	44%	30%	26%	45%	27%	28%
300 miles of residence	42%	27%	31%	40%	27%	33%
50 miles of residence	30%	31%	39%	40%	20%	40%

The results from the SNSS analysis confirm the broader finding, consistent with the not-in-my-backyard (NIMBY) hypothesis, that closer proximity appears to decrease public support for siting a repository. But note that substantial fractions of respondents indicated that their support for the facility is *increased* by closer proximity. Even at the closest (50-mile) distance, 30% of those respondents considering the mine-like repository, and 40% of those considering the deep-borehole repository, indicate that the location will increase support. At the same time, the percentage of respondents who oppose the facility increases at closer proximities. In the context of a survey concerning a hypothetical repository, significant fractions of the public appear to increase as well as decrease support as the prospect of the siting is moved closer to their place of residence.

In the context of an actual siting debate, then, we would expect to see some fraction of the respondents closest to the proposed site increase their level of support. In the case of WIPP, data collected in New Mexico by the University of New Mexico permit analysis of the effect of proximity on support for opening the WIPP facility. These data measured New Mexicans' views on WIPP, including support for opening the facility, using statewide random telephone surveys conducted in the spring and fall of each year over the 1990 to 2010 period.[Jenkins-Smith, Silva, Nowlin and deLozier et al. 2010] Analyses of these data show that support for opening the facility increases significantly, on average, the closer the respondent's residence (as mapped by residential zip codes) is to the WIPP facility. Fig. 9-4 illustrates the estimated level of support for WIPP, based on distance of the population from the facility.[29]

[29] The effects of proximity were modeled using time series regression models with polynomial expressions for distance.[Jenkins-Smith, Silva, Nowlin and deLozier et al. 2010]

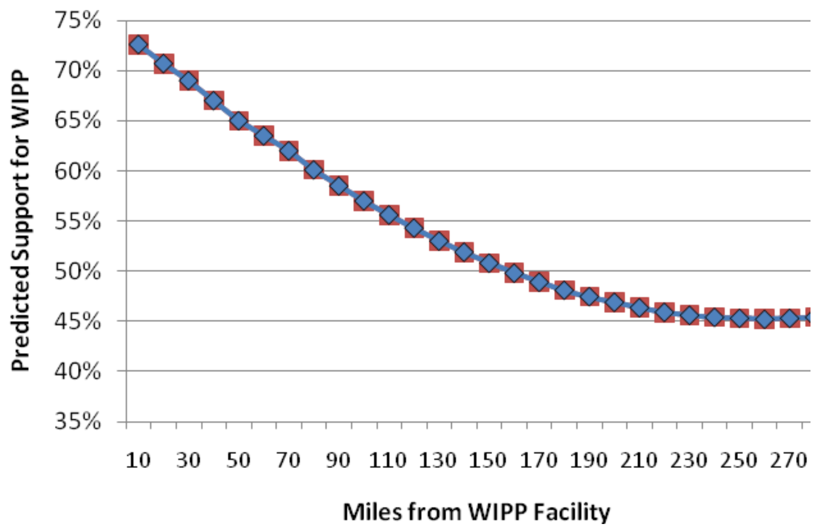

Figure 9-5: Predicted support for WIPP, by distance from facility, among New Mexico residents

As indicated by Fig. 9-4, the interpretation of the results from a sample of New Mexico citizens indicates that the estimated level of support for the facility is over 60% of those living within 80 miles of the WIPP facility, whereas estimated level of support drops to 50% or less for residents more than 160 miles distant.

The New Mexico data show that, in the context of a long-term debate over repository siting, the actual relationship between proximity and policy acceptance can be positive. The WIPP case is not entirely analogous to prospective UNF repository siting in several respects; the materials range from low-level waste to highly radioactive remote contact-handled materials, and all of the materials at WIPP are deemed wastes without provision for ready retrieval without incurring substantial expense. Given that the materials at WIPP are identified solely as a waste, and that the facility is nearly exclusively designed for disposal,[30] the WIPP case would seem to be a difficult case for which to obtain public support. In the early years of the policy debate over WIPP, New Mexicans by a 2 to 1 margin opposed opening the facility. Support grew over time but still did not reach a majority six months before the repository was approved in May 1998. Only after EPA approval and WIPP began receiving waste in 1999 did a majority of New Mexicans consistently express support for the operation of WIPP. Fig. 9-5 illustrates that trend, in which the vertical dashed line indicates the date WIPP opened.

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[30]There is a research program based at New Mexico State University in Las Cruces, New Mexico, focused on monitoring the environment around the WIPP facility. The extent to which association with this program increases support for WIPP has not been systematically measured.

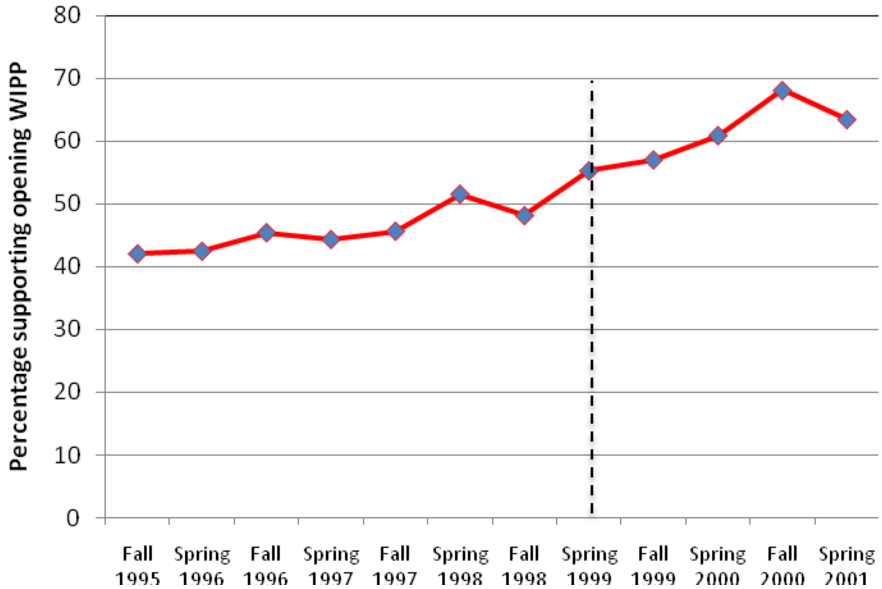

Figure 9-6: Percentage supporting opening WIPP

The WIPP case indicates that initial abstract opposition of those closest to a proposed repository can be reversed in the context of a sustained siting initiative. Although data on this aspect were not collected in this study, one may hypothesize that those closest to the repository are interested enough to seek out information directly through data provided by the project or indirectly through those with some association with the project (e.g., emergency responders trained along the WIPP transportation routes.)

9.4. Maintaining Credibility and Broadening Support

As discussed above, measures such as combining a repository with long-term research laboratory, associating it with an important national function (national defense) as in the case of WIPP may help gain initial support for the facility. However, that initial support must be sustained and expanded over the long time period involved in developing and operating a repository. The experience with WIPP shows that that it is indeed possible for the acceptability to be maintained and even enhanced once a local community and state or tribal organization has initially entertained the idea of hosting a storage facility, repository, or other nuclear facility (Fig. 9-5). The increased support over time, and the strong support for WIPP by those closest to the facility, suggest that familiarity and localized benefits (such as economic development) can play a role in garnering local support. We are unaware of any systematic quantitative analysis of these relationships and the SNSS has not attempted such a study. Rather, what follows is a qualitative account based on discussions in the May 2010 Workshop, knowledge of other qualitative accounts,[McCutcheon 2002] and reference to a scientific credibility/trust survey conducted for the WIPP.[Jenkins-Smith and Silva 1998]

9.4.1. Experience at WIPP

Organizational Structure

The WIPP had a stable organization structure, with only slow turnover in the leadership of the science advisory group. Stability is of itself conducive to maintaining credibility and a craftsman-like culture, and the slow turnover in leadership avoided many of the issues that can befall organizations with rapid turnover. The structure was also important in that it ensured that the science advisory leadership would be in prominent roles within the organization. Although the search for a site began earlier, the WIPP formally began in January 1975 with two main participants: ERDA (later DOE) and SNL. SNL served as the scientific advisory group in charge of four tasks: selecting and characterizing the site, drafting a conceptual repository design, writing the EIS, and initiating scientific studies. Engineering firms that had been involved with conceptual designs oversaw some of the initial shaft construction. Once the decision to construct the repository was made, the US Army Corps of Engineers managed the construction as the third main participant. At this point the basic structure of WIPP had been established with DOE as owner and engineering and science sharing significant roles. In preparation for operations, a Management and Operating (M&O) contractor was let that replaced the Corps of Engineers (see Appendix A). Although a more hierarchical structure might seem more business-like and efficient, siting and obtaining approval for repository construction require an emphasis on relationships with Congress, the state, the local community, scientific review groups, and the workforce, for which a flat organizational structure was more appropriate.

Specifically, having a visible science advisory group that had an identity separate from the DOE and the M&O was important at the WIPP in maintaining trust with the public and state. [Jenkins-Smith and Silva 1998] This science advisory role was supported by the organization structure. Also, direct interactions of the technical staff with the National Academy of Sciences and other external peer review groups, the State of New Mexico Environmental Evaluation Group (EEG), and the public; collaboration with the host state university system; and the engagement with the EPA regulator were important aspects of the openness and transparency that proved to be beneficial in the repository siting and development process. All of these interactions were conducted by, or with strong support of, the science advisory group. The EPA process for certifying WIPP’s compliance with the performance standard via an open rulemaking process rather than a litigated adjudicatory licensing process was also conducive to open and continued external interactions by project scientists, facilitated by the science advisory group, all the way to the end of the certification process.

State and Scientific Review

In the case of WIPP, DOE funded establishment of the independent Environmental Evaluation Group (EEG) in 1978 within the New Mexico State government to provide technical review of the project, and in 1981 entered into a Consultation and Cooperation agreement with the State of New Mexico that provided a detailed process for state oversight and involvement. In the *National Defense Authorization Act* for Fiscal Year 1989, Congress assigned the EEG to the New Mexico Institute of Mining and Technology University.

WIPP convened two types of peer review panels: Expert Review Panels and Expert Elicitation Panels. Expert Review Panels were used to confirm the use of professional judgment in experiments and model development. Expert Elicitation Panels were used to develop scientific judgments on topics requiring disparate scientific fields were integration of information may not have occurred in the normal course of scientific publications. The EPA required Expert Review Panels to review 24 conceptual models of the WIPP performance assessment supporting the Compliance Certification Application (CCA). In addition,[Larson et al. 1999]

> The WIPP team convened expert review panels for many topics prior to the preparation of the CCA license application (more than sixteen external peer review panels are identified in the CCA). For example, since 1978, the National Research Council Committee on the Waste Isolation Pilot Plant has published at least 13 reports, providing broad oversight of policy and science issues on the WIPP. Expert review panels were convened for specific topics, for example: using geostatistics for aquifer characterization (WIPP Geostatistics Expert Group); developing models of hydrofracture in bedded evaporites (WIPP Fracture Expert Group); PA methods (WIPP PA Peer Review Panel); and conceptual model uncertainty (WIPP Conceptual Model Uncertainty Expert Group). Furthermore, in late 1996 a joint IAEA/NEA WIPP International Review Group was chartered to review the WIPP Compliance Certification Application.

WIPP used an expert elicitation to provide the particle diameter of degraded waste. Prior to development of the CCA, expert elicitation was conducted to develop information to support data collection or design activities in the topics of inadvertent future human intrusion, site markers, radionuclide source term, and chemical retardation. The use of expert elicitation was more limited, possibly because of some regulatory limits for the CCA:[Larson et al. 1999]

> In WIPP experience, regulatory constraints on the use of expert elicitation are profound: it may not be allowed if a phenomenon is observable; and it may be required if a phenomenon is unknowable. Although the general procedure for convening an expert elicitation panel is similar to that for an expert review panel, there are two significant differences under WIPP regulations. First, the panel must be administered independently from nominations to conclusions. Second, the panel must be carefully focused on a single problem, and must know in advance the desired format and use of the results.

Finally, publication of scientific results in the peer-reviewed literature was an important way to enhance scientific credibility and transparency and, indirectly, public credibility. Publication of scientific results in the peer-reviewed literature was emphasized as a result of the fact that a science advisor was a key visible role at the top of the WIPP organization.

State Agreements

The WIPP benefited from a formal and binding Consultation and Cooperation Agreement between the state of New Mexico and DOE that help garner the initial support to go forward with the project. The agreement included discrete points where issues of concern to the State were addressed prior to moving forward such that trust could be maintained between the DOE and the State of New Mexico. When unexpected situations arose, the program was able to back-up, change the design, and move forward in a manner that maintained credibility with the state. This experience suggests that a process for siting developing a facility that includes contractual arrangements that are not easily altered and state monitoring/oversight of facility operations can develop trust and maintain credibility with a state. The consultation and cooperation agreement provisions in the NWPA, modeled on the WIPP agreement, would allow negotiation of such a stepwise and consultative decision process for a repository or storage facility developed under that Act. The WIPP experience suggests that it would be helpful for future legislation to retain provisions allowing for such agreements as part of an adaptive staging process.

9.4.2. Experience at YMP

Participation

The NWPA stated "State and public participation in the planning and development of repositories is essential in order to promote public confidence in the safety of disposal of such waste and spent fuel." The importance of public participation was also a theme of the 2003 report from the National Academies that recommended "adaptive staging" as "a promising means to develop geologic repositories for high-level waste ..." [NAS 2003a] According to the Academies, adaptive staging as "a learn-as-you-go process that enables project managers to continuously reevaluate and adjust the program in response to new knowledge and stakeholder input."[NAS 2003b] The report concluded that "stakeholder input to the decision-making process is of paramount importance for effective implementation of Adaptive Staging" and that involving stakeholders and the public at key decision points "holds the potential for advancing social science knowledge and for enhancing public trust," while recognizing that "[e]ngaging stakeholders and the general public does not, however, guarantee success."[NAS 2003a] Most recently, the charter of the Blue-Ribbon Commission on America's Nuclear Future calls for the Commission to consider "Options to ensure that decisions on management of used nuclear fuel and nuclear waste are open and transparent, with broad participation."

In the area of direct consultations on high-level radioactive waste management policy issues with stakeholder groups at the national level, DOE conducted a number of activities in the first half of the 1990s:

1991 to 1992 - Three Strategic Principles Workshops discussed strategic principles for guiding the program; these principles were used as the core of a draft Mission Plan Amendment, and they addressed a wide range of potential program modifications then under consideration.

1992 - Director's Forum meeting to follow up on the Strategic Principles Workshops

1992 - Workshop on contingency plans for Yucca Mountain unsuitability.

1994 - Several workshops on criteria for evaluating alternative "system architectures" for the waste management system.

1995 - Secretary O'Leary's meeting with stakeholders.

During 1994, OCRWM developed a proposed technical site suitability evaluation procedure based on the existing siting guidelines through public and stakeholder participation in the form of numerous public meetings, briefings, and workshops, and responses provided to OCRWM Federal Register Notices of Inquiry.[DOE 1994] The technical site suitability evaluation centered on a sequential evaluation of compliance with the DOE siting guidelines in 10 CFR Part 960 related to long-term waste isolation, radiological safety, and technical feasibility. The evaluation was to use site characterization data and analyses that would be documented or referenced in technical basis reports subject to external peer review through a process independently managed by the National Academy of Sciences, followed by assessments of compliance by Program technical staff against one or more of the siting guidelines, and finally, if appropriate, findings by the Director of compliance with the guidelines. This process was never established because of budget cuts in the FY 1996 appropriation for the program.

Independent State Investigations and Scientific Review

The NWPA provided authorization and funding for state and local oversight activities including conduct of independent scientific investigations such as the Nye County Early Warning Drilling Program (NC-EWDP), and repository-related research at the University of Nevada system funded by the DOE. While the NWPA also included provisions for negotiated Consultation and Cooperation agreements modeled on the WIPP example, none of the states involved chose to enter into such an agreement.

The report of a blue-ribbon panel on Alternative Means of Financing and Management (AMFM) of the OCRWM program, required by the NWPA, included establishment of a Scientific Peer Review Board as one of the features recommended for all organizational options that were considered.[AMFM 1985] Along these lines, the DOE and the National Research Council discussed establishing panels similar to the Council's WIPP oversight committee to oversee work on the three sites to be characterized for the first repository, but the effort was not continued after the passage of NWPAA in 1987. The NWPAA created a standing Nuclear Waste Technical Review Board (NWTRB) to assess the scientific validity of DOE's activities.

OCRWM also supported a number of independent peer reviews, including a review of the consequences of igneous intrusions into the repository,[Detournay et al. 2003] and a review of the performance assessment under the joint aegis of the OECD Nuclear Energy Agency and International Atomic Energy Agency.[OECD-NEA 2002] In addition, the M&O contractor established a Repository Design Consulting Board as a standing panel of external design and construction experts that reviewed the Viability Assessment design work and SNL convened an independent peer review of the final performance assessment to support the license application.[Apostolakis et al. 2008]

Peer reviewed publication of scientific work is another important way to enhance credibility. In addition, as a result of Supreme Court decisions related to the admissibility of scientific evidence in federal court, one of the criteria judges are to use in deciding whether scientific testimony is valid and admissible is whether underlying theory or technique supporting the testimony has been subjected to peer review and publication.[43 F.3d 1311] Peer reviewed publications were used in Yucca Mountain projects, but obstacles to publication were encountered: lack of funding, tight time schedules to produce work needed by the program, and perceived legal constraints associated with the Yucca Mountain licensing process (particularly towards the end of the preparation of the license application). The desirability of facilitating peer-reviewed publication of key results related to repository performance should be given careful consideration in designing future institutional arrangements for maintaining credibility of a repository program.

9.5. Lessons Learned on Acceptability and Credibility

1. The US public generally is supportive of nuclear energy and in recent years has consistently expressed support for expanded reliance on nuclear energy.
2. Average US residents generally do not seek the information and thus remain uninformed about the the current policies in place for managing UNF, though trends suggest that awareness is growing.
3. Retrievability is generally preferred, both because the public views UNF as a possible future resource and because the public prefers to retain the option to revise UNF storage strategies in light of new learning.
    - The public favors retaining the option for reprocessing UNF by a two-to-one majority.
4. Survey research shows that specific design and policy elements substantially alter the level of initial public support for repository siting.
    - Expressed public support for a UNF repository is increased substantially if it is combined with a national laboratory focused on increasing safety of UNF storage/disposal or reuse.
    - Combining a repository with capacity for reprocessing UNF increases public support for siting the facility.
    - Compensation to states tends to increase support primarily among those who are not initially opposed to siting the facility.
5. The effects of proximity to repositories on public acceptance is mixed.
    - Responses to survey questions generally show that support changes with closer proximity to a hypothetical repository; some respondents increase support and other respondents increase opposition
    - However, responses related to an actual repository show support to be positively associated with proximity; closer proximity led significant fractions of survey respondents to *increase* support for the WIPP repository.
6. Direct interactions of the technical staff with peer review groups, the State, and the public is an important aspect of the openness and transparency that is a key need in the repository siting and development process.

7. Publication of scientific results in the peer-reviewed literature is an important way to enhance credibility and transparency. The desirability of facilitating peer-reviewed publication of key results related to repository performance should be given careful consideration.
8. Having a visible science advisory group that had an identity separate from the DOE and the M&O was important at the WIPP in maintaining trust with the public and state.
9. A process for siting developing a facility that includes contractual arrangements that are not easily altered and state monitoring/oversight of facility operations can develop trust and maintain credibility with a state.
10. The experiences of WIPP and Yucca Mountain show that scientists and engineers and their work products alone cannot resolve initial state and public concerns about accepting nuclear waste storage or disposal facilities.
11. At the same time, the credibility of the science and engineering underlying waste management program is a necessary condition for maintaining and enhancing acceptability once a State or Tribal organization has entertained the idea to host a UNF management facility.

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Appendix A: Summary of Events for WIPP and YMP

The process of defining the concept of safe disposal of defense TRU in the United States took 17 yr, from 1976 to 1993 concurrent with implementing a disposal program over 25 yr, from 1974 and 1999. The process of defining safe disposal for SNF and HLW has already taken 34 yr from 1976 to 2010 concurrent with implementing a disposal program over 32 yr, from 1978 to 2010, and will involve further refinement as a new repository program is initiated. This Appendix presents general background information about the U.S. program for managing high level waste and UNF. Summary histories and timelines for legal passage and regulatory actions as well as selected other relevant events are presented for WIPP and YMP. Although the YMP timeline of events is new, the WIPP timeline and much of text related to WIPP is similar to previously published work.[Rechard 2000]

A-1. Background on Radioactive Waste Management in US

The US went through an extensive review of all available options for disposal and management during the 1970s, culminating in the 1980 *Environmental Impact Statement on Management and Disposal of Commercially Generated Radioactive Wastes*.[DOE 1980c] This review considered a full range of alternatives to mined geologic repositories, including deep boreholes, subseabed disposal, space disposal, and ice sheet disposal. Mined repositories were the favored option, but subseabed disposal and deep boreholes were retained for further consideration. Subseabed disposal remained technically a promising option, but was precluded by international treaty in the 1990s. Deep boreholes were considered to require further technological advances.

As part of this review, in 1979, the Interagency Review Group for nuclear waste management, formed by President Carter with representatives from 14 federal agencies, completed its report on radioactive waste management and disposal and concluded that[IRG 1979] (1) responsibility for managing nuclear waste resides with the current generation, and in particular, the federal government; (2) mined geologic disposal was the most promising method for disposal of SNF, HLW, and TRU and repository development should not be delayed waiting for alternatives; (3) the federal government should consider a number of sites in a variety of geologic media and select at least two, preferably in different regions of the US (e.g., one in western and one in the eastern half of US); and (4) safe interim storage should not be used as a reason to delay opening the first repository. A year later in the final EIS, DOE affirmed the IRG recommendation that a mined geologic repository was the best option for the disposal of commercial SNF and resulting HLW Hence, the US (and many other countries) made the commitment to mined geologic disposal in 1980.

A-2. Background on Waste Isolation Pilot Plant

The search for permanent disposal for radioactive waste began in 1955 when the Atomic Energy Commission (AEC), precursor to DOE and the NRC, asked the National Research Council of the National Academy of Science and Engineering (NAS) to examine the disposal issue. In 1957, the NAS reported that deep geologic disposal in salt formations was the most promising method to explore for disposing of high-level waste (HLW) resulting from reprocessing of used nuclear fuel (UNF). NAS reaffirmed that position in 1961 and 1970 (NAS, 1970).[Rechard 2000] Positive attributes for salt disposal include: (1) salt is easily mined, (2) salt has high thermal conductivity, (3) salt is plastic (readily deforms and flows), (4) salt fractures self heal, (5) salt has very low permeability and porosity, (6) salt has existed underground for millions of years, (7) salt deposits are often in stable tectonic regions, (8) salt deposits exist in many locations with wide geographic distribution in the US. With these positive attributes and technology available in the 1950 and 1960s, the AEC gave mined disposal in salt high priority, especially for defense-related radioactive waste, and selected a site for a repository in an existing mine near Lyons, KS in 1970.

Although salt has many advantages, a disadvantage is the coexistence of economically valuable minerals and hydrocarbons. In 1971, pre-existing boreholes for mineral exploration and solution mining were discovered to have a potential to compromise the proposed repository. In May 1972, the AEC abandoned the Lyons Project and announced plans for a Retrievable Surface Storage Facility (RSSF) on the Hanford Reservation. However, nuclear opponents and the EPA, through comments on the Environmental Impact Statement (EIS) issued in 1974, said that the RSSF proposal put too much emphasis on interim storage at the expense of permanent disposal, while nuclear proponents felt it would distract the AEC and take pressure off finding a disposal site.[Carter 1987, p. 76; Walker 2009, p. 93-94]

The criticism prompted the Energy Research and Development Administration (ERDA), the successor to AEC, to search again for permanent disposal sites. Local citizens, with the tacit approval of Governor King, invited the AEC to New Mexico to consider the thick bedded salt deposits in southern New Mexico. The search for a specific site in the Delaware basin occurred between 1973 and 1976. The site for the Waste Isolation Pilot Plant (WIPP) was characterized in support of the draft and final Environmental Impact Statements (EIS), which were completed in 1979 and 1980.

In December 1979, Congress authorized the DOE to construct the WIPP repository for disposal of defense waste contaminated with TRU radionuclides (mostly Pu) and hazardous chemicals generated during the production of nuclear weapons. The first shaft was excavated in 1981; full construction began in 1983; and construction was substantially complete by the end of 1988. Along with construction, an underground research laboratory was deployed to the north of the disposal area.

The WIPP Project conducted a preliminary analysis in 1989 to demonstrate the feasibility and three analyses (1990, 1991, and 1992) to demonstrate the viability of the WIPP. In 1996, the Compliance Certification Application (CCA) was completed. In 1998, the Environmental Protection Agency (EPA) certified that the WIPP disposal concept complied with its regulations. After dismissal of several lawsuits, the WIPP repository received its first shipment of waste in 1999; 25 years after the area in New Mexico was first identified and 20 years after authorized by Congress.

A-2.1 Legal Framework for WIPP

In the late 1960s, environmental hazards, such as radiation and radioactive waste disposal, became part of the national and world agenda. For example in May 1969, the Rocky Flats Plant, built by the AEC in 1951 to machine plutonium and other metals for nuclear weapons, caught fire. Located only 16 miles from Denver, Colorado, the fire and subsequent cleanup attracted public attention. That same year Congress passed the *National Environmental Policy Act of 1969* (NEPA),[Pub. L. 91-190] which required federal agencies to consider the environmental consequences of any major action through an EIS (environmental impact statement). The EIS process exerted it influence during the 1970s as the AEC, then ERDA (formed in 1974) and finally the DOE (formed in 1977) formulated waste management plans and searched for suitable disposal sites through an administrative process. Also, in 1970, Congress established EPA to set standards to limit impact to the environment.

Although the purpose of the WIPP as a general disposal site for radioactive waste was clear, decisions about what kind of waste would be sent there fluctuated throughout the 1970s. Quoting from the *Historical Background on Performance Assessment for the Waste Isolation Pilot Plant*:[Rechard 2000]

> …Under consideration were three kinds of waste—TRU waste, high-level waste from reprocessing spent nuclear fuel, and direct disposal of spent nuclear fuel—and whether the waste originated from defense or commercial activities. The initial focus of the AEC in the 1950s and 1960s with regard to disposal was on nuclear waste from reprocessing spent nuclear fuel (or high-level waste as it came to be called), because uranium was thought to be in such short supply that it would be necessary to recycle commercial fuel. The initial screening analysis of scenarios for the WIPP assumed 75,000 canisters of high-level waste, enough to accommodate the anticipated volume of high-level waste from all commercial reactors through the year 2000. However by 1975, the emphasis of the WIPP was disposal

of TRU defense waste because of the prominence of the latter as a result of the Rocky Flats Plant fire, and the WIPP was removed from the commercial repository program within ERDA.

…During the 1970s, the lack of a proven waste disposal scheme was presented by the public, through comments on the EIS and at licensing hearings, as an argument against construction of nuclear plants. Furthermore, California passed a law in 1976 banning construction of nuclear power plants until disposal of nuclear waste was demonstrated. The Rock Flats fire in Denver and the California moratorium clearly placed nuclear waste disposal on the national agenda. In response, President Ford requested that the ERDA accelerate the demonstration of permanent disposal and for EPA to develop disposal standards. Also, the DOE seriously considered disposal of commercial waste at the WIPP between 1977 and 1979, at least as a means of demonstrating the disposal concept. Conceptual drawings of the WIPP repository in 1977 showed two levels: one for the cooler contact-handled TRU waste, 640 m below the surface, and the other for remote-handled TRU waste and the hotter high-level waste, 790 m below the surface.

In March 1979, the Interagency Review Group of 14 federal agencies formed by the President Carter suggested that the WIPP be a candidate for commercial spent fuel and President Carter endorsed their recommendation. However, the State of New Mexico and the House Armed Services Committee strongly opposed commercial waste disposal at the WIPP. Congress responded in 1979 by defining the mission of WIPP as a research and development facility for disposal of only defense TRU (preventing commercial SNF disposal and, because of the HLW controversy, even defense HLW). The Congress also exempted WIPP from NRC licensing and required DOE to sign a Consultation & Cooperation Agreement with the State of New Mexico.

In 1978, the DOE asked the NAS to form a WIPP Panel to review the scientific aspects of the WIPP. Also, the DOE contracted with the State of New Mexico to set up the Environmental Evaluation Group (EEG) to provide a state assessment of the WIPP, since at the time DOE was self regulating. Still, a lack of trust existed between the State and the DOE, and the decision to proceed to construction in 1981 drew lawsuits by the State of New Mexico. The Secretary of Energy Edwards and Governor King worked out a Stipulated Agreement with a Consultation and Cooperation Agreement as an appendix. Based on the Stipulated Agreement, the U.S. District Court judged stayed the lawsuits. This administrative process under DOE, with amendments to Stipulated Agreement and Consultation and Cooperation Agreement, guided the WIPP up through 1992 (i.e., site selection, site feasibility, and site viability).

In the *Waste Isolation Pilot Plant Land Withdrawal Act* (WIPP LWA) in 1992,[Pub. L. 102-579] Congress established legislative procedures that assigned EPA as the regulator for the WIPP, required EPA to repromulgate 40 CFR 191 to address the aspects that had been remanded by a federal court in 1987 (discussed further below), required recertification every 5 years, ratified the previous Stipulated Agreement and Consultation and Cooperation Agreement, required continued DOE cooperation with the EEG, and gave the State of New Mexico $600 million over 30 years along with the legislation that transferred land from the Bureau of Land Management (BLM) in the Department of Interior to the DOE. The EPA conducted the certification process using a standard rulemaking process under the Administrative Procedures Act. In 1997 EPA issued a draft of the rationale for its determination that WIPP met each of the requirements of 40 CFR 191 and the implementation rule 40 CFR 194. After receiving and considering public comments on the draft, EPA then issued a final rule certifying WIPP in May 1998.

A-2.2 WIPP Legal and Regulatory Timeline

966 Jan: B52 collides with refueling tanker at 30,500 ft; three nuclear weapons crash into Spanish soil; fourth parachutes into ocean. Question raised as to quantity of Pu contaminated soil (transuranic or TRU waste) to return to US.

1969 Congress passes *National Environmental Policy Act* (NEPA), which requires federal agencies to write an environmental impact statement (EIS) on any major action.

1970 Congress forms Environmental Protection Agency (EPA) and transfers to it research, monitoring, standard setting, and enforcement activities related to environment.

1971 Appeals Court requires Atomic Energy Commission (AEC) , formed in 1946 by *Atomic Energy Act* (AEA) to look at all environmental impacts in EIS for nuclear reactors.

1974 Oct: Congress splits AEC into Energy Research and Development Administration (ERDA) and Nuclear Regulatory Commission (NRC).

1975 ERDA removes Bedded Salt Pilot Plant (BSPP) in southeastern New Mexico from commercial repository program.

1976 Jan: BSPP Project is officially named the Waste Isolation Pilot Plant (WIPP) for defense transuranic (TRU) and high-level waste (HLW).

1976 Oct: President Ford orders EPA to develop standards for radioactive waste disposal. **Dec:** EPA announces intent to develop standards for spent nuclear fuel (SNF) and HLW disposal.

1977 Jan: Congress forms Department of Energy (DOE) from ERDA. **Feb:** EPA conducts public workshop to understand public concerns and technical issues of waste disposal. **Nov:** Although role of NRC at WIPP unclear, DOE tells NRC it plans to seek license for WIPP based on policy of Carter Administration.

1978 DOE Deputy Sec. Jerry O'Leary promises NM Congressional delegation that New Mexico "could veto the plan" for WIPP. DOE General Counsel states O'Leary powerless to grant "state veto."**Jan:** EPA announces public forum to develop disposal criteria for radioactive wastes. **Jun:** In response to DOE request to review scientific aspects of WIPP Project, NAS forms WIPP Panel and holds first meeting. **Oct:** Deutch Report (Lead by MIT Chem. Prof. Deutch) recommends disposing TRU waste at WIPP without planning for retrieval, and demonstrating SNF and HLW disposal at WIPP. DOE Deputy Sec. J. O'Leary presses 2nd recommendation as way to satisfy California law banning nuclear power plants until SNF disposal demonstrated. **Nov:** DOE contracts with NM to establish Environmental Evaluation Group (EEG) to provide an independent state assessment of WIPP. EPA publishes *Criteria for Radioactive Wastes* as guidance for federal agencies and seeks comments.

1979 Mar: Interagency Review Group (IRG), formed by President Carter in response to Deutch Report, recommends disposal of SNF, HLW, and TRU in mined geologic repositories, suggests making WIPP candidate for commercial SNF **Apr:** DOE completes draft EIS that describes WIPP as defense/commercial repository. **May:** House Armed Services Committee cuts WIPP funding in response to DOE expansion of WIPP as repository for commercial SNF and thus requiring NRC licensing. **Dec:** Congress defines mission of WIPP as a research and development for disposal of only defense TRU waste; exempts WIPP from NRC licensing; and requires DOE to sign a "Consultation & Cooperation (C&C) Agreement with NM

1980 NM and DOE begin negotiations on C&C Agreement to define procedures and process of cooperation. **Mar:** Carter rescinds 1980 funds for WIPP because it is unlicensed repository for defense TRU and announces interim strategy for other disposal projects at WIPP. **Jul:** House Armed Services Committee disagrees with Carter policy and returns rescinded funds to WIPP.

1981 Jan: DOE decides to proceed with Site and Preliminary Design Validation (SPDV). In response, **Mar:** Citizens for Alternatives to Radioactive Dumping (CARD) asks for preliminary injunction Developing generic disposal criteria is difficult; thus, EPA starts developing standards for each type of radioactive waste. **May:** NM sues DOE and Department of Interior (DOI) alleging violations of federal and state laws. **Jun:** WIPP Project Mgr. McGough rekindles disagreements between DOE and New Mexico by stating HLW could be emplaced by 1983 and remain during the operating phase of WIPP. **Jul:** Southwest Research & Information Center (SWRIC) sues and begins filing numerous interrogatories to which DOE must respond. In response to lawsuits, DOE Sec. Edwards visits NM to talk to Gov King and accedes to a Stipulated Agreement (SA) for (1) geotechnical experiments, (2) SNL reports on 17 technical issues, such as disruptive events (e.g., breccias pipe, salt dissolution, and salt deformation) that are to be dismissed through site characterization; (3) state & public review of WIPP changes, and (4) creation of a state/federal task force to oversee transportation issues (e.g., emergency response and highway upgrades). C&C Agreement attached as App A; a working agreement is App B. U.S. Dist. Judge Burciaga stays lawsuits

1982 Dec: 20th working draft becomes proposed disposal standard, 40 CFR 191, for HLW, SNF, and transuranic (TRU); draft defines Performance Assessment (PA), establishes a population-based release limit for radionuclides at a 10 km boundary, and requires displaying entire distribution of uncertain results. Supplemental SA signed committing DOE (1) to seek funds for upgrading highways in NM, (2) to more geotechnical studies, and (3) liability for WIPP-related accidents.

1983 In response to questions by EEG, DOE concludes draft 40 CFR 191 applies to disposal phase but not to test phase of WIPP. **Jan:** In *Nuclear Waste Policy Act* (NWPA), Congress directs promulgation of EPA and NRC disposal regulations. **Jan-Sep**: EPA Science Advisory Board (SAB) holds 9 public meetings on 40 CFR 191. **May:** Oak Ridge complex admits releasing 2×10^6 lb Hg between 1950 and 1977. Revelation prompts Natural Resources Defense Council (NRDC) tand Legal Environmental Assistance Foundation (LEAF) to sue DOE

1984 Jan: SAB endorses probabilistic, population-limit approach and 10^4 yr regulatory period of 40 CFR 191 but recommends (1) screening criteria for FEPs be increased by a factor of 10 to median probability of 10^{-3} in 10^4, (2) radionuclide limits be increased a factor of 10; and (3) probability for first level be increased from 0.01 in draft to 0.5. **Apr:** Court rules DOE is subject of RCRA requirements even though AEA exempted DOE from human health laws. **Nov:** Hazardous & Solid Waste Amendments (HSWA) to RCRA bans land disposal of hazardous waste without treatment unless disposal site and generator demonstrates "no migration" for as long as waste remains hazardous. 1st modification to C&C Agreement limits remote handled (RH) TRU waste to 5.1×10^6 Ci.

1985 Feb: NRDC sues EPA to issue 40 CFR 191 as mandated in NWPA. **Sep:** EPA promulgates 40 CFR 191 that sets 5 km boundary, clarifies inclusion of uncertainty to provide an unbiased estimate of "reasonable expectation," retains FEP screening criteria of 10^{-4} in 10^4, rounds limits and often increases a factor of 10, and increases probability for first level of limiting distribution from 0.01 in draft to 0.1 and second level from 10^{-4} to 10^{-3}. EPA defines TRU as waste with activity >100 nCi/g and half-life > 20 yr. **Nov:** DOE attempts to define "by-product material" to include mixed waste and thus exclude applicability of RCRA regulation to WIPP and other DOE facilities.

1986 EPA states that mixed waste is subject to RCRA regulations. **Mar:** NRDC and others sue EPA over groundwater and individual protection standards in 40 CFR 191.

1987 May: DOE defines "by-product material" to exclude everything except radionuclides; hence, TRU waste is subject to RCRA. **Jul**: In response to legal challenges to individual and groundwater protection requirements, Court of Appeals for 1st Circuit remands 40 CFR 191. **Aug:** 2nd amendment to C&C Agreement commits DOE to use 40 CFR 191 as 1st issued until reissued by EPA and to apply NRC and Dept of Transportation (DOT) regulations to TRU transport.

1988 Oct: ID Gov Andrus bans shipments of radioactive waste into state because WIPP not open. With continued technical problems (e.g., TRUPACT-II for transporting TRU to WIPP not yet NRC licensed) and policy differences (e.g., Congressman Richardson wants funding for roads and compliance with 40 CFR 191 before receipt of waste, i.e., no unregulated pilot phase), NM Congressional delegation cannot reach consensus and *WIPP Land Withdrawal Act* (LWA) dies **Dec:** ID Gov Andrus, CO Gov Romer, and NM Gov Carruthers meet in Salt Lake City to discuss WIPP and options to avert shutdown of Rocky Flats Plant from lack of storage imposed by CO and inability to ship to ID; DOE agrees to pursue both administrative and legislative land withdrawal for WIPP.

1989 WIPP Management and Operating (M&O) contractor, Westinghouse, completes RCRA no migration petition for RCRA variance for WIPP pilot phase. **Mar:** DOE completes 1st supplemental draft EIS.

1990 EPA issues no migration variance for pilot phase.

1991 Westinghouse completes Parts A & B of RCRA permit application to State of NM.

1992 Oct: Congress passes WIPP LWA that transfers land from DOI to DOE, establishes EPA as regulator for WIPP, requires recertifying WIPP every 5 yr, reinstates 40 CFR 191 except for disputed individual and groundwater requirements, requires DOE cooperation with EEG, gives NM $600 million over 30 yr.

1993 Feb: EPA announces intent to promulgate 40 CFR 194 to specify requirements for implementing 40 CFR 191 at WIPP. **Dec:** In response to court remand and WIPP LWA, EPA repromulgates 40 CFR 191, which sets the individual dose limit at 0.15 mSv/yr over 10^4 yr and makes groundwater requirements equivalent to those of *Safe Water Drinking Act.*

1995 Jan: EPA proposes implementing criteria for WIPP in 40 CFR 194. **Mar:** DOE submits draft Compliance Certification Application (CCA) to EPA to get comments on format and contents.

1996 Feb: EPA promulgates 40 CFR 194 that (1) requires peer review of (a) waste characterization, (b) engineered barriers, and (c) conceptual models; (2) requires a monitoring system, (3) specifies requirements on (a) quality assurance, (b) peer review, and (c) expert judgment; and (4) requires potash mining to be considered in PA. **Sep:** Congress amends WIPP LWA to relieve WIPP of filing a no migration petition, but other requirements of RCRA controlled by State of NM still apply such as characterization. **Oct:** DOE submits CCA to EPA. **Nov:** WIPP Panel of NAS reports that WIPP site "excellent choice" geologically. DOE completes 2nd Supplemental draft EIS. **Dec:** EPA begins detailed CCA review.

1997 May: EPA administrator Browner decrees DOE application complete, which starts the 1 yr clock for review of CCA. **Oct:** EPA issues draft rule to approve WIPP with conditions: (1) requires use of panel seals; (2) requires QA for waste generators, (3) lists requirements for using process knowledge to characterize waste, requires schedule for installing passive markers, denies any credit for passive controls on human intrusion rate.

1998 May: EPA certifies WIPP. **Jul:** NM Attorney General Udall sues alleging insufficient time to comment on CCA. CARD and SWRIC also file lawsuits.

1999 Mar: Without hearings, Judge Penn refuses to impose preliminary injunction and lifts previous injunction; 4 days later WIPP receives 1st shipment of non-RCRA waste from LANL. **Jul:** Appeals Court for DC Circuit upholds EPA Certification. **Oct:** NM grants WIPP RCRA permit.

A-2.3 WIPP Site Selection

1942: Manhattan Engineering District of Corps of Engineers selects site for Los Alamos National Labs (LANL) to develop a nuclear bomb. All type of waste initially dumped in canyons at LANL.

1943 Operations begin at Oak Ridge National Lab (ORNL) to extract Pu for Manhattan Project; waste disposed in trenches.

1944 Nuclear waste disposal begins at LANL using trenches and augered holes and at Hanford Reservation using tanks, underground cassions, trenches, ponds, and railroad cars. [Rechard 2000b]

1945 Atomic bomb exploded at Trinity Site near Alamogordo, NM.

1946 *Atomic Energy Act of 1946* establishes government monopoly on atomic weapon production and nuclear material and creates Atomic Energy Commission (AEC) with 7 commissioners to oversee monopoly.

1952 Idaho National Laboratory (INL) completes Radioactive Waste Management Complex (RWMC) for storage and disposal of nuclear waste.

1953 Savannah River Plant begins waste storage and disposal on site in trenches at Old Burial Ground.

1954 In *Atomic Energy Act of 1954*, Congress expands the mission of AEC to allow regulated, private atomic energy use; thus, the need to dispose larger quantities of nuclear waste becomes an issue. Rocky Flats Plant, weapon facility near Denver, begins shipping nuclear transuranic (TRU) waste to Idaho for disposal at RWMC.

1955 Sep: AEC asks National Academy of Sciences (NAS) to examine disposal of nuclear wastes; NAS holds workshop with 65 scientists at Princeton.

1957 May: Rock Flats Plant catches fire but kept secret. **Sep:** NAS recommends nuclear waste disposal in salt beds or salt domes. Oak Ridge begins disposal research in salt.

1961 US Geological Survey (USGS) evaluates stratigraphy and AEC mines into Salado Fm at Gnome site near Carlsbad, NM, as part of Plowshare program.

1962 USGS reports on salt deposits suitable for waste disposal throughout US. Permian basin in parts of NM, KS, TX, and OK is one of areas identified.

1963 Jul: ORNL begins Project Salt Vault, a simple underground research lab (URL) in which 14 spent nuclear fuel (SNF) placed in floor and heaters placed in pillars at an existing salt mine near Lyons, Kansas.

1965 Savannah River Plant (SRP) begins disposing TRU waste in trenches on site.

1966 NAS reaffirms use of salt beds for the disposal and strongly criticizes current disposal practices.

1968 At request of Congress, General Accounting Office (GAO) audits AEC waste management practices and finds faults with records and management. AEC forms task force to address criticisms. **Mar:** After much negotiation (because of NAS frustration in AEC ignoring past advice), NAS sets up Committee of Radioactive Waste Management with broad representation of disciplines; later permanent board of NAS. First task is to revisit the issue of radioactive waste disposal and the used of bedded salt.

1969 ORNL demonstrates retrievability of 14 SNF assemblies from salt in Lyons mine. **May:** Rocky Flats Plant catches fire. Shipment of debris to INL increases attention on nuclear waste disposal.

1970 Jun: AEC tells Sen. Church of Idaho that the waste from the fire stored at INL will be removed by 1980. AEC tentatively selects salt mine near Lyons as repository. **Nov:** NAS reports bedded salt satisfactory and safest choice available for nuclear waste disposal.

1971 After many drills holes and some solution mining discovered at Lyons, Congress directs AEC to stop project until safety is certified. USGS tests permeability of strata around Gnome site for closure studies by AEC.

1972 May: AEC abandons Lyons project and announces plans for Retrievable Surface Storage Facility (RSSF) at Hanford Reservation to allow more time to develop a repository.

1973 Nationwide search for suitable alt site resumed. Encouraged by local political leaders and potash mine operators, Gov. King invites AEC to southeastern NM. USGS and ORNL recommend southeastern NM; lack of boreholes 2 miles from site important selection criterion but relaxed to 1 mile in 1975.

1974 Mar: ORNL begins field investigations for the Bedded Salt Pilot Plant (BSPP) by drilling AEC-7 and AEC-8. **May:** ORNL work suspended because AEC wished to emphasize RSSF and AEC Chairperson Ray would not withdraw land from oil exploration because of Arab oil embargo. **Sep:** AEC issues draft environmental impact statement (EIS) emphasizing reprocessing RSSF. **Nov:** Environmental Protection Agency (EPA) and anti-nuclear groups claim RSSF de facto disposal in comments on EIS.

1975 Jan: Energy Research and Development Administration (ERDA), successor to AEC, asks Sandia National Labs (SNL) and located in NM, to oversee investigations. **Mar:** SNL receives funding and starts 4 tasks: selecting site and characterizing, drafting conceptual design, writing EIS, and initiating scientific studies. **May:** ERDA-6 drilled at NW corner of ORNL selected site; well encounters deformed salt beds, brine, and H_2S. After studying oil well logs in area, SNL and USGS recommend relocation 11 km toward center of Delaware Basin to avoid deformed salt beds.

1976 Jan: Project is officially named the Waste Isolation Pilot Plant (WIPP).

A-2.4 Summary of WIPP Characterization

Site characterization performs two functions: It provides information to demonstrate current understanding of the behavior of the natural barriers of the disposal system. It also provides information for the performance assessment, which interweaves scientific information to analyze the potential behavior of the waste in the engineered barriers and natural barriers to assess the compliance of a disposal system with regulatory requirements. Detailed scientific understanding of the unsaturated flow in fractures was initially lacking; thus, much work and site characterization expense was required to improve this scientific understanding. However, the needs of the regulatory analysis set boundaries on what is necessary to fully understand about the natural barriers (both figuratively and, most obviously, the specified boundaries of the natural barrier at either (set at 5 km from the repository in 40 CFR 191).

Site characterization at WIPP progressed through three study phases: (1) non-intrusive evaluation and literature search for site selection; (2) exploration from the surface for evaluating repository feasibility; and (3) exploration underground to evaluate viability, recommend the site, and support the compliance assessment.

A-2.4.1 Surface Characterization for Feasibility

Culebra Transmissivity at WIPP

> During site selection, interest in fluid flow in water-bearing units of the area had focused on its effects on dissolution; after selection, interest shifted to the role of these units as potential pathways for radionuclide release. Also 75 new line miles of seismic reflection data and 9000 resistivity measurements were collected across the site. In addition, 47 boreholes were completed under the direction of the USGS.
>
> USGS geohydrologists had suggested that the Magenta and Culebra Members of the Rustler Formation (hereafter shortened to Magenta, Culebra, and Rustler) and the Rustler/Salado contact zone were potential pathways for radionuclide release. At the time, the relative importance of these units was unknown, so the first tests targeted all three…
>
> Experimental activities included determining the mineralogy of the bedded salts and the overlying formations. Also, the sorptive properties of the clays in the salt and overlying dolomitic rocks in the Rustler were evaluated, and the geochemical composition of the waters in the Rustler was determined. The stability of the salt was also examined by determining whether Rb-Sr isotope ratios suggested any significant recystallization or brine flow through the formation since its deposition about 255 million years ago.

Salado Permeability at WIPP

> …the potential magnitude of the pressure from gas generated by waste from microbial degradation of organic material was not known; thus in 1979 Sandia tested the AEC-7 well to determine the permeability of the Salado in order to ascertain the ability of the repository to contain gas…The range of in situ permeability, in turn, suggested that if gas from microbial action (and anoxic corrosion from brine migration to hot canisters) were generated by TRU waste at less than 5 mole/drum/yr, the gas would dissipate into the rock without reaching lithostatic pressure; thus the TRU waste would be acceptable in the WIPP repository without incineration. Accordingly, a fledgling program to characterize gas generation, begun in 1978, was canceled after 1979.

Experiments and Model Development of Salt Behavior at WIPP

> Sandia began to build a salt creep laboratory in 1974. Testing on specimens from mines and salt domes was in progress by 1975, and creep in salt from ERDA-9 cores was studied in 1977. Sandia initiated a 3-year program in 1979 to evaluate, through in situ and laboratory experiments, salt deformations around mine openings and the effects of heat on acceleration of salt creep. The in situ experiments were conducted in a nearby potash mine and at the Avery Island salt dome in Louisiana.
>
> The first modeling efforts in 1975 reviewed empirical constitutive creep laws developed during Project Salt Vault and numerical modeling capabilities available in the mining industry. Some of the first calculations, completed in 1978, evaluated a potential concern that hot canisters would become buoyant in the plastic salt and move significant vertical distances. Sandia modeled the repository, with Sandia-developed codes and constitutive laws, and used the results in 1980 to examine the reasonableness of various proposed modifications to the room dimensions in the 1977

conceptual design, which had been based on experience with the area's potash mines. Predictions from other numerical codes were compared extensively to test data in 1980, and more calculations on predicted room deformation were conducted in 1982 and 1985.

A-2.4.2 Characterization for Viability at WIPP

Brine Reservoirs at WIPP

As part of the negotiated settlement with the State of New Mexico, the DOE deepened WIPP-12 into the Castile in November 1981. The WIPP Project encountered a brine reservoir at a pressure high enough that brine could flow to the surface. The discovery of the reservoir prompted the rotation of the waste panels from their planned location north of the experimental area to south of the shafts in 1982, thus moving the disposal region ~1800 m to the south, which is the current configuration. This well was extensively tested through 1983. Also, geophysical studies indicated that a brine reservoir could also extend to the south of WIPP-12. DOE-1 was drilled in 1982 to obtain geologic data and evaluate the brine reservoirs in the Castile. No brine was found, and the well was later used to test hydraulic conditions in the Culebra. Both the DOE and the EEG conducted consequence analyses of a drilling encounter with a brine reservoir similar to that found in WIPP-12, concluding that the health consequences were minor. In addition, several new geophysical techniques were used to determine whether such brine reservoirs might exist under the waste panels, but by 1987, these studies were inconclusive. A zone of lower resistivity in the Castile existed under a portion of the waste disposal area and could be interpreted as brine; however, the zone was beneath the Castile's upper anhydrite layer where brine had been encountered earlier.

Culebra Transmissivity at WIPP

In the 1980s, hydrologic characterization focused on the Culebra. USGS had provided additional information on the transmissivities of the Culebra as part of the Stipulated Agreement. In 1984, pumping tests at DOE-1 suggested fracture flow in the Culebra. By 1987, Sandia had estimated the Culebra transmissivity at 15 new locations and re-estimated the transmissivity of 7 wells; by 1989, Sandia had estimated Culebra transmissivity at 41 locations in an 860-km^2 area around the WIPP site...

In the 1990s, tests were conducted to characterize the Culebra at two relatively high-permeability locations. These high-quality tests included the seven-well tracer test conducted at H-19, multiwell retesting at H-11, and single-well injection and withdrawal tests at both H-19 and H-11. The purpose of the tests was to evaluate the complex fracture flow.

Culebra Sorption at WIPP

Sandia conducted several laboratory studies of sorption in the 1980s. These empirical studies used a variety of sorbents (dolomitic, anhydritic, and clay-rich rocks) and solutions (Salado, Castile, and Culebra brines), and in some cases included the effects of dissolved organics on sorption.

Because the State of New Mexico felt the early sorption studies were deficient, the DOE and the State of New Mexico modified the Consultation and Cooperation Agreement in 1988 to require New Mexico concurrence on any sorption distribution coefficients (K_ds) recommended for use in the final PA of the WIPP. While experimental data were being obtained, Sandia convened a panel of staff members to estimate ranges and probability distributions of K_ds in support of two preliminary PAs. In addition, retardation of radionuclides in the Culebra was more thoroughly studied in the laboratory. Early results from a batch experimental program using crushed dolomite were used in the CCA.

Salado Permeability at WIPP

Sandia did not originally intend to use the experimental region of the WIPP repository to study the permeability of the Salado. TRU waste generates relatively little heat, and so migration of brine because of a thermal gradient was of little concern after 1979 when high-level waste was excluded from the WIPP. Yet Sandia conducted some permeability tests around excavations because of continued interest in high-level waste disposal in salt beds elsewhere and as part of the sealing and waste canister programs.

Sandia first measured injected nitrogen flow around an underground drift in 1984 to determine the extent of the disturbed zone and corresponding permeability of the Salado. In 1986, Sandia conducted similar measurements using injected brine to evaluate the permeability of the intact salt. The predicted permeability ranged between 10^{-21} and 10^{-20} m^2, a factor of about 1000 less than the previously measured range in AEC-7 of 5×10^{-19} to 2×10^{-17} m^2.

In May 1987, Sandia reported that much more brine had migrated to the simulated high-level waste canisters than had been expected. Furthermore, a rough scoping calculation to evaluate repository performance identified inflow of intergranular Salado brine to the repository from a pressure gradient (rather than thermal gradient) as a concern for long-term performance if a human should inadvertently intrude into the repository with an exploratory well. By December, the national press was reporting on the issue of brine flow into the repository. In January 1988, New Mexico's congressional delegation asked the full Board of Radioactive Waste Management (BRWM) of the NAS to study the brine inflow controversy.

However also in 1987, Sandia made a concerted effort to theoretically study thermoelastic behavior of the salt and found that the seemingly contradictory in situ measurements of lower permeability but higher brine flow to simulated high-level waste canisters could be explained. The new theoretical model predicted less than 43 m^3 brine entering a disposal room over the first 100 yr. Given the resolution of measurements, the BRWM concluded that not enough brine would seep into the rooms to form a slurry of radioactive waste before the rooms had closed through salt creep.

Experiments and Model Development of Salt Behavior at WIPP

Laboratory creep tests were started on larger specimens from the underground workings of the WIPP in 1982; in situ salt creep experiments at the WIPP also began in 1982 as the main drift through the disposal area was excavated. Sandia began fielding more extensive in situ salt creep experiments in 1984 as experimental rooms were completed; heat was turned on in these rooms in 1985 to measure accelerated salt creep. However, when Congress decided in 1987 to characterize only the Yucca Mountain site as a commercial spent-fuel and high-level waste repository, the DOE canceled the simulated high-level waste experiments at the WIPP.

Although from a practical standpoint, the predicted and measured values of salt creep were close, the manually measured salt creep in the south drift in 1982 and the automated measurements of the SPDV rooms and various other experimental rooms in 1982–83 were nevertheless about three times greater than predicted values. Thus between 1985 and 1989 an alternate conceptual model and mathematical expression were incorporated into codes and tested. Thereafter, agreement of predictions with in situ measurements was excellent.

A-2.4.3 Summary of WIPP Site Characterization

1976 Jan: Project is officially named the "Waste Isolation Pilot Plant. **Apr:** ERDA-9 drilled to Castile Fm near center of new site.

1978 Aug: SNL completes geologic characterization report supporting Draft EIS on WIPP.

1979 1st in-situ permeability test of Salada Fm. salt from AEC-7 well. Laboratory tests made of permeability of ERDA-9 core.

1980 Tracer test conducted at H-2 in Culebra.

1981 Nov: Project strikes pressured brine reservoir while deepening WIPP-12 north of the repository as part of Stipulated Agreement (SA). Draw down test and other analysis continue on WIPP-12 until 1983.

1982 Jul: Drilling of DOE-1 started and completed to top of Anhydrite I in Castile Fm. **Dec:** SNL completes interim report on dissolution of evaporates in and around the Delaware Basin (part of SA). USGS completes breccias pip report (part of SA) and dismisses concerns. Small brine weeps observed on walls of excavations.

1983 Mar: SNL, USGS, and contractor complete most of 17 reports required by SA (e.g., USGS reports Culebra transmissivity at 20 locations; SNL reports on groundwater flow in Rustler Fm and deformation of evaporates near WIPP; Westinghouse contractor reports on brine reservoirs in the Castile Fm.). **May:** After reviewing results from SPDV program, NM Environmental Evaluation Group (EEG) concludes that "…the Los Medanos site has been characterized in sufficient detail to warrant confidence in the validation of the site for permanent emplacement of approximately 6 million ft^3 of defense TRU waste," but also recommends additional studies to resolve outstanding geotechnical issues such as evaluation of potential for brine reservoirs. **Aug:** Drilling of Cabin Baby started and completed to Bell Canyon Fm; geophysical logs run and deep sandstones of Bell Canyon Fm hydrologically tested.

1984 Pumping tests at DOE-1 suggest fracture flow in Culebra. 1st in-situ gas flow tests conducted around underground drifts.

1985 Sep: With the definition of a 5-km limit for the disposal system in 40 CFR 191, project begins to focus on near-field hydrologic modeling rather than regional modeling.

1986 SNL reports on pump tests at DOE-2. SNL conducts 1st in-situ brine injection tests to determine salt permeability around drifts.

1987 SNL finds possibility of pressurized brine reservoir below the TRU disposal area cannot be ruled out. **Dec:** Environmental groups raise concern of brine seepage into repository.

1988 Jan: EEG issues report on potential brine reservoirs under WIPP. NM Congressional delegation asks full NAS (not WIPP Panel) to study brine seepage controversy. Sep: SNL reports on in-situ permeability; 1000 times lower than 1979. SNL reports only minimal brine seepage possible. NAS conclude brine seepage no problem, but suggest more brine seepage tests. SNL completes pumping tests at H-11.

1989 SNL reports on reevaluation of Culebra permeability at AEC-7 and D-268 wells. **Jan-Aug:** Q-tunnel mined and instrumented for brine seepage experiment.

1993 Brine inflow to Q-tunnel can be explained as either dewatering of disturbed rock zone or Darcy flow through salt.

1994 Aug: SNL files permits to drill 7 new wells at hydropad H-19 for tracer test in Culebra.

1995 Feb: Drilling of wells for tracer tests begin.

1996 Apr: ANL completes tracer test in Culebra at H-19 and H-11; results suggest dual porosity transport reasonable conceptual model; single porosity transport can be ruled out. Jul: SNL reports on early results of retardation batch experiments to set linear sorption coefficients.

A-2.5 WIPP Repository Design

A-2.5.1 Early WIPP Conceptual Design

Quoting from the Historical Background on Performance Assessment for the Waste Isolation Pilot Plant[Rechard 2000]

> Concurrent with site selection and writing the EIS, Sandia prepared the conceptual design of the WIPP surface and underground facilities. The basic design drew on information gained from experience with nearby potash mines in the Delaware Basin. However, the extraction ratio was dramatically reduced to ~33% overall (~40% in any one disposal panel) to increase room stability and mine safety. The design for the transport containers and other hardware was based on Sandia's experience with equipment design at the Nevada Test Site. The conceptual design was completed in 1977 (and consisted of two levels). The upper disposal area for the CH-TRU waste consisted of eight closely spaced panels with eight rooms in each panel. The experimental area and disposal area for the RH-TRU waste, high-level waste, and spent nuclear fuel was set deeper near the base of the Salado Formation. The repository (originally) had five shafts.
>
> Although expansion was contemplated, space for CH- and RH-TRU waste buried prior to 1970 and TRU waste produced from future decontamination and decommission of facilities was not included in the initial design. Because Congress limited the WIPP to the disposal of defense TRU waste only in 1979, the second level was abandoned and the repository was reconfigured for the Final EIS as a single-level facility with four shafts (and RH-TRU placed in the walls of the CH-TRU disposal rooms).
>
> In 1978, the DOE contracted with Bechtel National, Inc., to be the architect/engineer for the WIPP Project, and Westinghouse Electric Corporation, for technical support…The detailed design (started in February 1979) envisioned that waste would be emplaced in all drifts, including those that connected rooms…The extraction ratio for a panel was similar to the conceptual design (38%), but the overall extraction ratio of the disposal area was decreased further to 22%.
>
> In March (of 1979), Bechtel began final design ("Title III") of the repository, and a design report was published in 1986 (with one of the four shafts eliminated). In the design submitted for the CCA, the TRU waste is to be placed in 55-gallon drums, grouped as 7-packs, 3 drums high or in metal boxes.

A-2.5.2 Construction of WIPP Repository

After publication of the Final EIS in 1980 and a record of decision in January 1981, the DOE began the Site and Preliminary Design Validation (SPDV) program to further characterize stratigraphy near the repository and validate room dimensions in the preliminary design. As part of the SPDV program, Fenix & Scisson, Inc., Sandia's contractor for the conceptual design and DOE's SPDV contractor, drilled two shafts starting in May and June, 1981...

In June 1982, the Army Corps of Engineers assumed responsibility for managing the SPVD and subsequent construction. Once the second shaft was completed in March 1982 and the repository level selected, excavations were begun in October to connect the two shafts, which was completed by the end of November...Although Bechtel's initial repository design placed the waste disposal area north of the experimental area, the disposal area was moved south of the shafts at the end of 1982 after the discovery of a brine reservoir in WIPP-12. Shortly thereafter, a drift to the south end of the disposal area was excavated and instrumented to confirm the stratigraphy and evaluate deformations around the repository.

In March 1983, the results from in situ experiments in the SPDV rooms were reported…Also that month, excavation began on rooms for Sandia's geotechnical experiments.

The WIPP Panel of NAS toured the underground excavation for the first time in April 1983 to examine the SPVD rooms. Four months later, the DOE announced its decision to proceed with full construction of surface facilities and continued excavation of the underground facility. The pilot hole for the third shaft, the exhaust shaft, was drilled in September 1983…In preparation for operations, the Management and Operations (M&O) contract was awarded to Westinghouse, which conducted the remaining construction activities after October 1986. In 1988, a fourth shaft was added for increased air circulation…By the end of 1988 the surface and underground facilities were essentially complete; they were declared officially complete in January 1990.

A-2.5.3 Repository Backfill at WIPP

The DOE had considered the use of backfill in the disposal area from the time of the initial conceptual design. In 1976, some thought was given to placing sorptive minerals such as apatite or bentonite around the drums to sorb radionuclides. More importantly, it was assumed that backfill would be emplaced in the repository to help fill the void space and reduce the magnitude of subsidence in overlying units, in addition to mitigating the potential for any underground fire. Although backfill in the disposal area was considered part of the baseline design for the repository, as reported in the supporting documents for the Supplemental EIS and the four preliminary PAs through 1992, the need for the backfill to mitigate subsidence and fire propagation diminished during the 1980s. These findings were formally reported in 1990 in the Safety Analysis Report, which concluded that fire propagation in the waste disposal region was unlikely even without backfill, and in a 1994 Westinghouse study, which indicated that the addition of backfill would have a negligible impact on the subsidence of overlying units.

For the 1996 PA in support of the CCA, however, backfill was reconsidered and again included in the design. A chemical backfill of MgO was proposed that would combine with any microbially produced CO_2 so that brine present in the repository would not become acidic, thereby increasing the solubility of the actinide radionuclides.

A-2.5.4 WIPP Shaft Backfill and Sealing Methods

Because of the difficulty presented by the presence of boreholes in the vicinity of the abandoned Lyons, Kansas, site, experiments on borehole plugs were immediately pursued by the WIPP Project in 1975. By 1977, three grouts had been selected and tested by plugging ERDA-10 drilled south of the WIPP site (near the Gnome site). In 1979, an experiment in AEC-7 tested the ability of a plug to withstand the 12.7-MPa pressure of the Ramsey Sands aquifer in the Bell Canyon Formation.

Initial concepts for backfilling shafts were described and the first laboratory tests on compacting crushed salt conducted in 1982. Sandia presented the first conceptual design for shaft backfill in 1984, which continued to evolve during the late 1980s. Crushed salt, the primary backfill for the shafts through the

Salado (usually referred to as "seals" in the WIPP Project), was expected to limit the creation of a preferred pathway for contaminant migration. Sandia developed a machine to build salt bricks from crushed salt in 1986 such that portions of the salt backfill in the drifts and shafts would be compacted to ensure adequate densities…

Stopping brine flow to the salt backfill from aquifers in the Rustler and upper units was also thought necessary because significant volumes of brine might delay or even prevent consolidation of the crushed salt. The first shaft sealing concepts envisioned large plugs of concrete, concrete-grout, or possibly other mixtures directly below the Rustler and halfway down the salt column to protect the lower crushed salt component prior to consolidation. However in 1990, bentonite clay, a swelling clay shown to be stable and with low permeability in brines in 1979 and 1984 studies, was added as a separate long-term component to the seals in the Rustler and at other seal locations in the Salado. Details of the various options were developed in 1993. In the 1990s, a more complete testing program was begun to demonstrate and develop confidence in the sealing concepts of the backfill and asphalt was added as a long-term component.

A-2.5.5 WIPP Panel Sealing Sealing Methods

Initially, the repository design did not include constructed barriers to separate the waste into modules. But when the WIPP Panel of the NAS expressed concern that fire in combustible portions of the waste could pose a hazard to mine workers, barriers throughout the disposal area were proposed to enhance mine safety. Shortly thereafter, plans called for isolating individual panels over the long term, with 30- to 40-m-long seals composed of preconsolidated salt and large concrete plugs at each end. During the early 1990s, the value of panel seals was questioned because of their limited ability to contain gas given the presence of anhydrite layers above and below the drifts. However, because they afforded some protection, the EPA stipulated that panel seals be used at the WIPP in its ruling on the compliance of the WIPP in 1998.

A-2.5.6 Summary of WIPP Repository Development

1974 Jun: AEC states all Pu must be solidified before shipment.

1975 Mar: SNL receives funding Energy Research and Development Administration (ERDA) and starts 4 tasks: selecting site and characterizing, drafting conceptual design, writing EIS, and initiating scientific studies. ERDA suggest opening date of 1982.

1976 Laboratory tests on TRU waste behavior and HLW packages initiated. Various natural backfills such as apatite or salt and bentonite considered for use in repository. Parsons, Brinkerhoff, Quade and Douglas, Inc., propose hypothetical HLW repository in salt for ERDA.

1977 Jun: SNL issues conceptual design report of WIPP repository with two levels. SNL plugs ERDA-10 well to test plugging boreholes in salt.

1978 Sandia National Labs (SNL) contracts with Los Alamos National Lab (LANL) to examine gas generated from TRU waste. **Jan:** Bechtel National starts as WIPP Architect/Engineer. **Jun:** Westinghouse starts as Technical Support Contractor. ERDA suggests 1985 opening date.

1979 Based on salt permeability tests in AEC-7 well, DOE cancels al gas generations and some backfill experiments. SNL begins 3-yr tests on thermal/structural effects in nearby potash mine, and Avery Island Louisiana dome salt. Consolidation of crushed salt studied in lab. Bechtel identifies 7 layers in Salado Fm. for WIPP. **Jul:** Conceptual (Title I) design of WIPP completed. DOE buys oil and gas leases around the site for $19 million. **Dec:** Congress states Waste Isolation Pilot Plant (WIPP) is to dispose only defense transuranic (TRU) waste.

1980 Westinghouse completes 1st Safety Analysis Report (SAR).

1981 As URL, tests begun in potash mine owned by Mississippi Chemical Mine Co. to evaluate corrosion of defense HLW canisters and overpack alloys. **Jan:** DOE publishes Record of Decision to proceed with Site and Preliminary Design Validation (SPDV) phase. **Feb:** DOE okays detailed (Title II) design phase. **May:** Fenix and Scisson, SPDV contractor, begins augering 1st 3.6-m salt handling shaft. **Jun:** Drilling of 2nd 1.8-m shaft begins. **Oct:** 1st shaft completed.

1982 Mar: 2nd shaft completed. Westinghouse suggests eliminating 4th shaft along with other cost savings. **May:** repository level selected. **Jun:** Army Corps of Engineers assumes responsibility for all phases of construction management. **Oct:** Underground excavation started to connect 2 shafts. **Nov:** 2 shafts connected. Based on WIPP-12 hitting brine, disposal area moved ~1800 m south but experimental area left in original area. SNL reports on shaft sealing concepts and in-situ tests planned for next several yr.

1983 Mar: DOE gives SPDV reports to NM and allows 60-day for review. Excavation of experimental rooms begins. Bechtel begins final (Title III) design. **Apr:** NAS WIPP Panel tours WIPP underground to examine SPDV tests. **Jul:** DOE announces decision to proceed to construction.

Sep: DOE sets Oct 1988 as opening date. **Oct:** Drilling of pilot hole for 3rd shaft begins and is completed in Dec.

1984 Feb: Raised bore reaming completed for 3rd shaft. **Apr:** As experimental room excavated, SNL begins thermal/structural defense HLW tests in 1982. **Jun:** 2nd shaft enlarged from 1.8 m to 6 m.

1985 Jan: Blasting of 3rd shaft to final 4.6 m diameter completed. Excavation begins on circular Room H. SNL reports on continued discrepancy between measured and predicted salt creep first observed in south drift in 1982. **Apr-Oct**: SNL turns on heat for simulated defense HLW canister experiments.

1986: Feb: Pillar creep test begins in circular Room H. Heated (accelerated) tests of CH-TRU and RH-TRU container behavior start. **Oct:** In preparation for operations, Westinghouse awarded Management & Operation (M&O) contract. Army Corps of Engineers relieved of construction management duties.

1987 Wet salt compaction tests concluded, constitutive equation for consolidation developed, and shaft seal consolidation modeled; consolidation practically complete in <100 yr. **Dec:** In *Nuclear Waste Policy Amendment Act* (NWPAA), Congress selects Yucca Mt for SNF and HLW disposal.

1988 May: Westinghouse begins drilling pilot hole for 4th shaft after reevaluating 1982 decision to eliminate it. Sep: DOE announces that WIPP will not open as scheduled in Oct. **Dec**: DOE abruptly cancels SNF and HLW experiments at WIPP because of NWPAA; no funds available to removed and test simulated disposal containers

1989 Jan: DOE files request for administrative land withdrawal of 16 mi^2 with Dept of Interior. **Feb:** SNL resolves discrepancies between measured and predicted salt creep. **Mar:** Sec. Watkins creates Blue Ribbon Panel to examine WIPP readiness. In report supporting Supplemental EIS, SNL identifies generation of gases from waste and containers as issue because in-situ salt permeability factor of 1000 lower than measured from surface in wells in 1979 (packers leaked). **Jul:** Sec. Watkins announces an indefinite delay in opening WIPP. **Nov:** Berlin Wall falls signally the end of the Cold War and changing future demands for nuclear weapon material and amount and composition of TRU waste going to WIPP

1990 SNL and Westinghouse complete report on pilot phase of WIPP suggesting 0.5% of waste capacity be brought to WIPP for gas generation tests. **Jan:** Construction officially complete. **May:** Westinghouse completes final SAR. **Jun:** NAS WIPP Panel questions scientific need for in-situ waste tests at WIPP.

1991 Apr & Aug: To extend life of Room 1 in Panel 1 for gas generation tests, internal and external panels meet to recommend roof support. **Sep:** Westinghouse completes construction of roof support.

1993 Oct: DOE concurs with NAS and decides not to emplace actual or simulated waste in a pilot phase; lab tests started instead.

1995 Sep: Gas generation studies completed. **Oct:** IT Corp. completes cost/benefit study for Westinghouse and DOE of engineered barrier alternatives required by 40 CFR 194. **Dec:** DOE publishes revision of WIPP inventory.

1996 Tests on radionuclide solubility in WIPP brines completed.

A-3. Yucca Mountain Project

After the disposal site in bedded salt near Lyons, KS was rejected in 1972, Energy Research and Development Administration (ERDA) searched again for permanent disposal sites with the help of the US Geological Survey (USGS). In 1976, the USGS Director McKelvey suggested that ERDA emplace nuclear waste at the NTS.[Carter 1978, p 131] By 1978, the USGS has suggested that the DOE focus on Yucca Mountain.[Walker 2009, Vandenbosch and Vandenbosch 2007]

In 1982, the USGS had identified several advantages for using the unsaturated zone at Yucca Mountain. Advantages cited included[Roseboom 1983] (1) a highly porous, low permeability layer above the host layer and thus high capillarity to diminish percolation; (2) mineable but fractured tuff host rock layer to rapidly pass percolation; (3) zeolitics in nonwelded Calico Hills layer below the host layer to adsorb radionuclides; (4) passive ventilation of the repository to keep waste cool; (5) backfilling of drifts unnecessary; (6) sealing of shafts unnecessary; (7) long retrieval period because repository does not flood; (8) most waste would not contact water in the unsaturated zone since openings typically block flow; and (9) many exploratory holes could be drilled without compromising repository. Other advantages included (10) good thermal characteristics to conduct heat from the waste and (11) absence of significant economic resource deposition concurrent with tuff deposition.[DOE 1986]

Under the authority granted in the *Nuclear Waste Policy Act of 1982* (NWPA)[Pub. L. 97-425] (as discussed in §2.0), the DOE identified nine potential sites, including Yucca Mountain, in February 1983. By December 1984, DOE had issued draft Environmental Assessments (EAs) of all nine sites and nominated five sites for further evaluation.[DOE 1986a] After the method used to rank the five sites nominated for characterization in the draft EAs were strongly criticized by the NAS, the DOE completed a multi-attribute utility analysis comparing the sites and issued final EAs for the five nominated sites by May 1986. The Secretary of Energy recommended and President Reagan concurred in characterizing three of the sites, Deaf Smith in Texas, Hanford in Washington, and Yucca Mountain, all in different media (salt, basalt, and tuff), for a repository.

In the 1987 amendment to the NWPA, Congress selected Yucca Mountain to characterize first for disposal of SNF and HLW, nine years after being identified. Over the next 21 years, the DOE investigated the site, evaluated its feasibility, confirmed its viability (1998), made a site recommendation (2001), and prepared a license application for construction authorization. The license application was submitted to the Nuclear Regulatory Commission (NRC) in June 2008 and docketed for review that September.

During the NRC review in 2009, the new Administration recommended and Congress provided funding only for answering questions as the NRC prepared their Safety Evaluation Report. Most other work had to cease. In 2010, DOE formed *The Blue Ribbon Commission on America's Nuclear Future*. The DOE also proposed no funding for Yucca Mountain in FY11 and filed a motion to withdraw the license application with the Atomic Safety Licensing Board presiding over the hearings on the application, with no possibility of re-submittal. In June, the Board denied the motion but appeals are pending.

A-3.1 Legal Framework for Yucca Mountain Repository

A-3.1.1 Nuclear Waste Policy Act of 1982

During the deliberations of Congress on setting national policy on commercial radioactive waste, the Congressional Office of Technology Assessment (OTA) concluded:[OTA 1982]

> The greatest single obstacle that a successful 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 of administration; 2) whether it has the institutional capacity 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.

After nearly four years of work, the Congress passed the *Nuclear Waste Policy Act of 1982* (NWPA).[Pub L 97-425] The NWPA endorsed the policy, voiced earlier in studies such as the Interagency Review Group's report that the current generation should bear the costs of developing a permanent disposal option, selected the mined geologic disposal option, and defined the steps to achieve this goal. The NWPA also addressed each of the three issues of a credible waste management program by replacing the administrative process that was attempted in the 1970s with a Congressionally mandated process.

Concerning the first issue, NWPA required the federal government to identify two repository sites for commercial UNF and operate one of them. The first repository was statutorily limited to a size that would accommodate a maximum of 70,000 MTHM (metric tons heavy metal initially placed in reactor) until a second repository was in operation, thereby requiring a second repository (the definition of repository capacity based on MTHM and its implications for alternative fuel cycles are discussed in §8.0). NWPA required the federal government to enter into contracts with the utilities for acceptance of waste in exchange for payment of a fee on utilities with nuclear reactors (discussed below). NWPA required the DOE to provide storage for utilities with a demonstrated need and to advise Congress on the need, design, and site for a Monitored Retrievable Storage facility, and the NRC to issue regulations for storage at reactors (storage and integration with disposal are discussed further in §6.0 and §7.0). The NWPA also placed defense radioactive waste in the commercial repository (subject to Presidential approval) (as discussed in §7.0).

Also concerning the first issue, the NWPA established mandatory steps to meet the goals of NWPA and a timetable for opening the first repository (site characterization and screening is discussed further in Section 3). Although OTA and others suggested a conservative timetable, Congress insisted on an aggressive schedule that was agreed to by DOE in congressional testimony. The aggressive schedule provided an impetus to design large surface and underground facilities to achieve high waste disposal throughput rapidly, rather than staged development (as discussed in §5.0). The NWPA also allowed DOE to construct a Test and Evaluation Facility (TEF), which included both an underground research laboratory and surface test facility for handling waste (as discussed further in §4.0).

Concerning the second issue (institutional capacity to implement a program), the NWPA established a Nuclear Waste Fund financed by a fee of 0.1 ¢/kW-hr on utilities owning nuclear reactors, to pay for repository selection, construction, and operation (the impact of the form of the fee on advanced fuel cycles is discussed in §8.0).[Pub. L 97-425, §302] However, in 1985, Congress did not exempt the Waste Fund from the *Gramm-Rudman-Hollings Act* even though the funds were derived from a fee for contracted disposal services rather than a tax.[Pub. L. 99-177] Hence, annual appropriations became limited by the budget balancing process so that program funding became a constraint on the ability of the program to meet its mandated objectives despite the original intent to insulate the program from such constraints (as discussed further in §5.0).

Also related to the second issue, the NWPA assigned responsibility for the waste management functions to the single-purpose Office of Civilian Radioactive Waste Management (OCRWM), a new office within the U.S. Department of Energy (DOE) that absorbed the functions of the National Waste Terminal Storage Program within the DOE.[Pub. L 97-425, §304] The NWPA also required a study to more thoroughly evaluate alternative means of financing and managing the waste program.

Concerning the third issue, the NWPA addressed the difficulty of waste management in a federal system of government (as discussed further in §9.0). As noted earlier, Governor King and Secretary of Energy Edwards had negotiated a Stipulated Agreement and Consultation and Cooperation Agreement that had defined the relationship between the DOE and the State of New Mexico and the NWPA drew upon this WIPP experience by providing for negotiation of similar Consultation and Cooperation agreements with potential hosts for repositories. The NWPA directed the OCRWM to develop assessments of potential repository sites with opportunity for public involvement,[31] and required an EIS for the repository, but limited options that had to be considered since Congress had already selected the mined geologic disposal option. The NWPA established the procedure for a State or Indian Tribe to notify Congress of its disapproval of the selection of a site and the necessary procedure for Congress to decide whether to override this disapproval within 90 days. The law provided for expedited parliamentary procedures that would ensure a timely vote on a motion to override the disapproval of a site.

Related to the third issue, the NWPA established a regulatory environment, which is discussed below in §2.5.[Pub L 97-425, §121] NWPA directed the EPA to set public health standards for disposal and directed the NRC to implement these standards by requiring licensing in three steps: approval to construct; approval to receive and possess waste, and approval to close and decommission. The NWPA required a repository to be designed to permit the retrieval of UNF for any reason pertaining to public health or for the recovery of economically valuable contents of the UNF (as discussed in §2.6).[32] The

[31] The studies were called an Environmental Assessments (EA) in the NWPA, which initially caused confusion at the time since they were not related to an EA defined in 40 CFR 1501 regulations promulgated in 1979 to implement NEPA.

[32] The NWPA did not discuss the issue of mixed waste (i.e., hazardous components as defined under the Resource, Conservation, and Recovery Act—RCRA).[Pub L. 94-580] The YMP chose to ban mixed waste to avoid dual regulation by the NRC for SNF and

NWPA also identified site selection criteria that DOE was to promulgate as guidelines (as discussed in §2.8).

A-3.1.2 Nuclear Waste Policy Amendments Act of 1987

The DOE selection of the three site finalists for the first repository and the decision to indefinitely defer the search for a site for a second repository in 1986 were followed by considerable turmoil. Lawsuits were filed and over 40 bills were introduced in 1987 related to various aspects of SNF and HLW disposal, such as efforts to suspend the site selection process.[Vandenbosch and Vandenbosch 2007, Ch 5] In hearings on the bills, technical concerns raised about the Hanford and Deaf Smith sites included proximity to valuable water resources (i.e., shafts to bedded salt at Deaf Smith would pass through the agriculturally important Ogallala aquifer and the fractured basalt at Hanford, adjacent to the Columbia river, might provide connection to several prolific aquifers). Technical concerns at Yucca Mountain were the possibility of volcanic and seismic activity. The high cost of characterizing three sites (~$1 billion per site by 1986) caused Congressional concern.

To expedite the process, Congress decided to characterize solely Yucca Mountain in the *Nuclear Waste Policy Act Amendments of 1987* (NWPAA) with the DOE to come to Congress for further instructions should Yucca Mountain prove unsuitable (implicitly specifying a sequential characterization process that had been discussed in the Senate hearings).[Pub L 100-203, §5001] In an attempt to provide more technical credibility, the NWPAA of 1987 established direct outside technical oversight through the Nuclear Waste Technical Review Board (NWTRB), with a slate of candidates nominated by NAS and 11 appointed by the President, to advise DOE and Congress (technical credibility is discussed further in §9.0). Furthermore, the NWPAA, affirmed the DOE decision to delay consideration of a second repository, and stopped experimental work in crystalline rock, which at the time consisted principally of participation in international underground research laboratories. In addition, the NWPAA identified additional potentially disqualifying factors for any sites in crystalline rock subsequently evaluated for characterization or selection as a repository.[33] Based on the anticipated savings of only characterizing one site, the NWPAA also set up a compensation schedule for hosting a repository or a Monitored Retrievable Storage (MRS) facility.

The NWPAA of 1987 also rescinded DOE's selection of Tennessee for the site of the MRS facility, and created a volunteer siting mechanism, and established the Nuclear Waste Negotiator to implement the program. The 1987 amendment to the NWPA limited the storage capacity of the MRS, and required that it not be constructed prior to receipt of a construction authorization for a geologic repository, limiting its usefulness in managing spent nuclear fuel prior to having geologic disposal capability. Although some local communities participated in the first phase of the MRS siting process, no State Governor allowed a community to proceed to the second phase. Also, no Indian Tribe proceeded to the second phase. Fortunately, the NWPAA also required DOE to cooperate with the private sector in a program of licensed demonstrations.[Pub. L. 100-203, §218(a)] This and similar studies eventually provided a foundation for utilities to build dry cask storage to alleviate the limited wet storage space available and is currently the default nuclear waste management policy in the US (as discussed further in §6.0 and §7.0).

A-3.1.3 Energy Policy Act of 1992

In part because of concerns (voiced clearly in Senate debates) about the potential impacts of the derived limits in 40 CFR 191 when applied to gaseous release of ^{14}C, from a repository in the unsaturated zone (Yucca Mountain), the *Energy Policy Act of 1992* (EnPA)[Pub. L. 102-486] directed the EPA to

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HLW and a contentious State of Nevada for hazardous components. The WIPP, however, does have dual regulation (as discussed in §2.7).

[33] Seasonal increases in population, proximity to public drinking water supplies, including those of metropolitan areas, and the impact that characterization or siting decisions would have on lands owned or placed in trust by the United States for Indian tribes.

“promulgate, by rule, public health and safety standards for protection of the public from releases from radioactive materials stored or disposed of in the repository at the Yucca Mountain site.” The EnPA specified that “such standards shall prescribe the maximum annual effective dose equivalent to individual members of the public from releases to the accessible environment from radioactive materials stored or disposed of in the repository” and must be “based upon and consistent with the findings and recommendations of the National Academy of Sciences” in a study required by the Act.

A-3.1.4 YMP Legal and Regulatory Timeline

1978 Nov: NRC publishes general policy on licensing steps for a repository and seeks comments.

1979 EPA defines TRU as waste with activity >100 nCi/g. **May:** Appeals Court for DC Circuit rules NRC must assess whether there is reasonable assurance (or degree of confidence) that wastes from nuclear reactors can be safely stored until properly disposed. **Oct:** NRC begins deliberations on waste confidence rule. **Dec:** NRC proposes licensing steps.

1980 Dec: *Low-Level Waste Policy Act* (LLWPA), defines low-level waste (LLW) by what it is not.

1981 Feb: NRC promulgates licensing requirements (e.g., formal, on-the-record, trial-like hearings for construction and receipt licensing) and steps (e.g., Site Characterization Plan or SCP) in its implementing HLW regulation, 10 CFR 60.

1982 Apr: Congressional Office of Technological Assessment (OTA) finds that national policy issues overshadow technological problems of radioactive waste disposal. **Dec:** EPA proposes disposal standard, 40 CFR 191, for HLW, SNF, and transuranic (TRU)

1983 Jan: In *Nuclear Waste Policy Act* (NWPA), Congress (a) selects geologic disposal option and exempts DOE from considering other alternatives in an EIS; (b) directs promulgation of EPA and NRC disposal regulations; (c) requires NRC to comment on suitability of site prior to site recommendation; (d) defines State disapproval and override procedure. **Apr:** In 10 CFR 961, DOE publishes contract between DOE, 68 utilities, and 7 other commercial waste owners for disposal of commercial SNF and HLW and payment of fees into the Nuclear Waste Fund; contract gives utility with oldest fuel priority in queue but does not require utility to ship its oldest fuel. **Jun:** NRC promulgates technical criteria in 10 CFR 60 that sets 3 deterministic criteria on subsystems: 300-1000 yr package life, release rate limits on engineered barrier, and 1000 yr travel time in geologic barrier.

1984 Aug: NRC promulgates waste confidence rule with review in 5 yr.

1985 Jul: NRC adds criteria to 10 CFR 60 for repository in the unsaturated zone. **Sep:** EPA promulgates 40 CFR 191

1986 Jan: Congress transfers responsibility for greater-than class-C (GTCC) LLW from states to federal government in LLWPA amendment.[Pub. L. 99-240] **Jul:** NRC revises licensing procedures in 10 CFR 60 to agree with steps in NWPA.

1987 Jul: Court of Appeals for 1st Circuit remands 40 CFR 191.

1989 In response to LLWPAA, NRC amends 10 CFR 61, regulation for LLW, to require disposal of GTCC LLW in geologic repository unless NRC approves other method. **Apr:** Based on deliberations in July 1988 by representatives from NRC, DOE, Nevada governments, industry, Native Americans, and environmentalists, NRC promulgates in 10 CFR 2 (a) procedures for licensing hearings, and (b) process of submitting documents related to LA electronically in a Licensing Support System (later called Licensing Support Network or LSN) “to permit early submission of better focused contentions.” **Jul:** NRC clarifies need in 10 CFR 60 to update EIS when applying for construction, operating, and closure authorization.

1990 Sep: NRC reaffirms confidence in mined geologic waste disposal with review in 10 yr. **Nov:** International Commission of Radiation Protection (ICRP) sets a limit of 1 mSv/yr for the public (average from natural sources at sea level excluding radon exposure).

1992 NRC and DOE reach agreement on procedures for interactions during the pre-licensing period **Oct:** Congress, in the *Energy Policy Act of 1992*, requires (a) the EPA to seek advice from the NAS, (b) the EPA to promulgate a site-specific standard using a dose criterion for a repository at Yucca Mt, and (c) the NRC to revise 10 CFR 60, to agree with the new EPA standard.

1995 Mar: For a site-specific regulation, NAS recommends (a) risk calculation to whenever dose is largest (likely within 10^6-yr period) and (b) suggests reporting risk from human intrusion separately. **May:** DOE notifies utilities that it does not have obligation to accept SNF by Jan 1998. **Jun:** NRC policy statement calls for detailed modeling with unbiased parameters in analysis under their purview, including PAs.

1996 Jul: Court of Appeals for DC Circuit vacates DOE interpretation and states that DOE will be liable for missing 1998 contract deadline. **Dec:** NRC clarifies terms in 10 CFR 60.

1997 Jan: To meet NWPA requirement to comment on site suitability (later called sufficiency review), NRC staff identifies 9 key technical issues (KTI) (plus a 10th issue related to promulgating 10 CFR 63) important to repository performance and decides to annually write 9 reports on the KTI topics to facilitate issue resolution. In addition, NRC and DOE plan technical exchanges to facilitate issue resolution. **May:** ICRP recommends an individual dose limit of 1 mSv/yr (from a single source such as radioactive waste disposal) and suggests a target of 0.3 mSv/yr for radioactive waste disposal. ICRP makes no recommendations for limits or use of a collective, population dose. **Nov:** Court of Appeals for DC Circuit reaffirms that DOE will be liable for the missed deadline. Court does not require DOE to physically move waste to an interim storage site, nor allow utilities to suspend payments into the Nuclear Waste Fund. Court states remedy is to sue for damages.

1998 Feb: Utilities petition Court of Appeals for DC Circuit to force DOE to accept waste. NRC completes 1st version and 1st revision of 9 reports on KTIs: **Sep 97 & Aug:** Evolution of the Near-Field Environment (ENFE) technical exchange; **Mar & Nov:** Container Life and Source Term (CLST); **Apr & Nov:** Total System Performance Assessment and Integration (TSPAI). **Jul:** In revision of program plan required by NWPA, DOE outlines steps for completing VA, preparing site recommendation (SR) in 2001, and submitting license in 2002.

1999 Feb: In draft 10 CFR 63 for Yucca Mt, NRC proposes (a) 10^4 yr regulatory period, (b) total effective dose equivalent (TEDE) limit of 0.25 mSv/yr, (c) critical group 20 km from the site of 100 families on 15 to 20 farms using current farming practices under arid and semi-arid conditions; and (d) climate change from arid to semi-arid. Proposed 10 CFR 63 omits design and siting criteria present in 10 CFR 60 and calls for more conservative "reasonable assurance" compliance concept. Energy Sec Richardson proposes to take title of commercial SNF and assume management of onsite storage; rough estimates of cost for storage until 2010 are between $2 and $3 billion to be paid for out Nuclear Waste Fund. Nuclear opponents reject idea because they want to punish utilities by keeping them liable for waste problems; utilities reject idea because it removes pressure to open repository. **Aug:** In draft 40 CFR 197 for Yucca Mt, EPA proposes (a) 10^4 yr regulatory period but calculation out to peak dose for EIS, (b) 0.15 mSv/yr effective dose equivalent (EDE) limit (similar to 40 CFR 191), (c) 0.40 mSv/yr dose limit to protect groundwater, (d) compliance for a reasonably maximally exposed individual (RMEI) rather than critical group member, (e) 4 alternative locations for point of compliance, and (f) dictates a "reasonable expectation compliance concept (similar to 40 CFR 191) and states this concept cannot be changed by NRC implementation.

2000 NRC and YMP conduct public meetings to reach 293 agreements in 9 KTI areas as to what to resolve and include in LA for the NRC sufficiency review prior to site recommendation.

2001 Apr: While encouraging more informal hearings, NRC retains formal hearings for construction and receipt licensing at repositories. **May:** In amendment to 10 CFR 2, NRC adopts DOE suggestion to require electronic access to pertinent documents 6 months prior to submission of the license application (LA) to construct repository. **Jun:** EPA promulgates 40 CFR 197, which selects a compliance boundary at 18 km from repository (thereby increasing importance of characterizing SZ)." Nevada petitions Court of Appeals for DC Circuit to declare 40 CFR 197 invalid since it does not require geology to be primary barrier.[Te] **Nov:** NRC promulgates 10 CFR 63, which adopts EPA concept of "reasonable expectation" and 0.15 mSv/yr dose limit. NRC issues sufficiency review stating their confidence that DOE will have sufficient information in LA to resolve issues.

2002 Apr: Using arguments similar to June lawsuit, Nevada petitions Court of Appeals of DC Circuit to declare 10 CFR 63 void since regulations do not require geologic criteria. **Sep:** Court of Appeals, 11th Circuit, rules settlement between Peco Energy, operator of 3 Peach Bottom reactors, and DOE to allow Peco to offset Nuclear Fund Tax in lieu of charging a fee for storing waste is not proper. All taxpayers must pay, not a subset of taxpayers through utilities fees.

2003 Jul: NRC releases final version of LA review plan, developed to maintain consistency during the review.

2004 Jun: DOE makes ~1.2 million documents including ~700,000 e-mails (~5.6 million pages) publicly available in LSN. **Jul:** Court of Appeals for DC Circuit rejects Nevada lawsuits except Court vacates portion of 40 CFR 197; Court states EPA rejected, without sufficient basis, NAS recommendation for a regulatory period to when dose is largest.[373 F3d 1251] ASLB rejects initial certification of LSN. ASLB notes that ~4 million e-mails from personnel no longer affiliated with YMP had not been reviewed for their relevancy.

2005 Aug: In draft revision of 40 CFR 197, EPA extends period of compliance to 10^6 yr and proposes a peak dose limit of 0.15 mSv/yr for mean of simulations for 1st 10^4 yr and 3.5 mSv/yr for *median* of simulations between 10^4 and 10^6 yr. **Sep:** As requested by EPA, NRC defines model style for climate change after 10^4 yr in draft revision of 10 CFR 63: NRC proposes DOE model a constant average percolation rate reaching the repository that is sampled from a log-uniform distribution between 13–64 mm/yr.

2006 May: IAEA publishes its model standard for geologic disposal that adopt the ICRP recommendation of a maximum exposure dose of 1 mSv/yr and average dose of 0.3 mSv/yr (or health risk of 10^{-5}/yr) over a regulatory period not too large for meaningful evaluation.

2007 May: DOE announces the LSN contains 3.4 million documents related to YMP. **Oct:** Court of Federal Claims awards Xcel Energy, owner of 3 nuclear plants in Minnesota, $116.5 million for DOE failing to take SNF by 1998 contract date. **Dec:** ASLB rules that certification of LSN in October is valid and DOE may continue to add important documents to the LSN.

2008 Sept: NRC dockets the Safety Assessment Report (SAR) of the license application seeking construction authorization. EPA promulgates amendments to 40 CFR 197 with three changes from draft: dose limit after 10^4 yr lowered to 1 mSv/yr; mean selected as the measure of interest throughout regulatory period; and FEP screening criteria restated as annual probability of 10^{-8}.

2009 Mar: NRC promulgates amendments to 10 CFR 63 that expands range of repository percolation to between 10 and 100 mm/yr with mean of 41 mm/yr.

A-3.1.5 YMP Siting Process

After a potential disposal site in bedded salt in Kansas was abondoned in 1972, ERDA, the successor to AEC, searched again for permanent disposal sites with the help of the US Geological Survey (USGS). Winograd, a geologist at the USGS, had earlier suggested disposal in unsaturated thick alluvium for HLW and TRU. In 1972, Senator Cannon (NV) urged the AEC to consider the Nevada Test Site (NTS). In 1975, the Nevada legislature asked ERDA to consider NTS for management of radioactive waste. Also, AEC studies had mentioned possible waste disposal in the unsaturated zone in tuff and shale in arid and semi-arid regions.

Two events clearly placed nuclear waste disposal on the national agenda in the 1970s: a fire at the DOE's Rocky Flats facility near Denver that produced plutonium contaminated waste that was shipped to Idaho, prompting a commitment from AEC to remove it from the state within 10 years; and adoption of a law in California that placed a moratorium on approval of new nuclear power plants until the federal government had developed a waste disposal facility. In response, President Ford requested that the ERDA accelerate the demonstration of permanent disposal. The ERDA Office of Waste Isolation (OWI) set up National Waste Terminal Storage (NWTS) program to develop technology and facilities for storage and disposal of HLW and spent nuclear fuel (SNF) from commercial and possibly defense sources (i.e., during the 1970s, disposal concepts alternately considered combining and separating commercially generated waste and defense-related waste.). The goal was an operational repository between 1997 and 2006. That same year, the USGS Director McKelvey suggested that ERDA emplace nuclear waste at the NTS because of its (a) closed hydrologic groundwater basin, (b) long groundwater flow paths to potential outflow points, (c) many different types of rock at NTS suitable for waste isolation, (d) remoteness, (e) past nuclear testing, (f) desert (~150 mm/yr precipitation), and (g) thick, unsaturated zone. In 1977, ERDA added previous land use as a criterion for *identifying*[34] potential repository sites.

In 1978, the newly formed DOE decided that a repository could be built in the southwestern portion of NTS and not disrupt weapons tests. Site investigations began at the Calico Hills area to look at granite and argillite; Wahmonie to look at granite; and Yucca Mountain to look at volcanic tuff. The investigations found only small, highly fracture granite masses and structurally complex argillite; however, borehole UE-25a#1, cored to ~2,500 ft, confirmed the presence of thick volcanic tuff deposits.

In 1979, the USGS recommended that investigations focus on welded tuff at Yucca Mountain underlying Yucca Mountain.[DOE 1985] Investigations to find suitable argillite and granite sites in other parts of NTS were stopped; however, work at Climax granite continued to determine the general suitability of granite elsewhere.

Because tuff was not considered previously by NAS, DOE wrote to NAS in 1978 and asked for its perspective on the preliminary data, approach, and identified issues. Besides the obvious necessary thickness, depth, and hydrologic advantages of this NTS desert location, welded tuff included (1) good thermal characteristics to conduct heat from the waste, (2) good stability to allow waste to be retrieved during the operating phase, (3) the ability of zeolitic, nonwelded tuff below the repository to adsorb radionuclides, and (4) absence of significant economic resource deposition concurrent with tuff deposition. The letter also described potential concerns about volcanism and seismicity. The underlying study was published a year later.

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[34] However, neither the DOE 10 CFR 960 site guidelines nor the NRC 10 CFR 60 regulation suggested previous land use as a criterion for final site selection.

By 1982, the Site Evaluation Working Group, organized by Sandia in 1980, had formally screened 15 locations in the southwestern portion of NTS and reported that Yucca Mountain remained the preferred site for a repository. Also, the USGS had identified several advantages for using the unsaturated zone (UZ) at Yucca Mountain and on their recommendation, the DOE moved the repository to the UZ.

As the first step in the siting process for a first repository mandated by the NWPA, the DOE identified Yucca Mountain along with eight other potential sites in February 1983 (three salt dome sites—one in Louisiana and two in Mississippi, four bedded salt sites—two in Texas and two in Utah, one tuff site at Yucca Mountain in Nevada, and one basalt site at Hanford, Washington). In the identification process, the DOE included the concept of lowering overall program risk by using a "portfolio" of sites, as required by NWPA to recommend sites in different geologic media, and codified in the site guidelines, 10 CFR 960, promulgated in 1984, and originally recommended by the 1979 Interagency Review Group. The Yucca Mountain tuff site added diversity to the sites in dome salt, bedded salt, and one basalt site identified by DOE. The next month, DOE held hearings to solicit comments from State of Nevada and public regarding nomination of Yucca Mountain and solicit issues to discuss in the EA and the Site Characterization Plan (SCP) required by NRC. Governor Bryan declared that "It is unfair in my view for the rest of the nation to ask Nevada, in light of its past and present commitment in the nuclear field, to assume this new burden," which might discourage growth of Las Vegas as a tourist attraction.

Due to the extremely tight schedule constraints on the siting process for the first repository, the nine sites that were already under consideration using administrative procedures applicable at the time the Act was passed formed the basis for site screening for the first repository: two sites in Texas and two sites in Utah, all in bedded salt; two sites in Mississippi and one in Louisiana in dome salt; one site in Washington State in basalt; and the Yucca Mountain site in Nevada in tuff. (The alternative of starting with a national site screening process had been explicitly considered and rejected during the debates on the NWPA.) This led to some questions about whether the guidelines could be applied fairly and effectively if the sites for initial consideration were already selected before the guidelines were developed.[OTA 1985]

By December 1984, DOE had issued draft Environmental Assessments (EAs) of all nine sites as required by NWPA. The draft EAs suggested five candidate sites for nomination (three salt sites: Davis Canyon, Utah; Deaf Smith, Texas; Richton dome, Mississippi; one basalt site: Hanford, Washington; and one tuff site: Yucca Mountain). The DOE also presented a ranking analysis in the draft EAs that suggested Deaf Smith, Yucca Mountain, and Hanford were the top three of the five candidate sites. As part of the EA, DOE also completed a preliminary evaluation of Yucca Mountain against 10 CFR 960 site selection guidelines and found no disqualifying conditions.

DOE completed final EAs for the five sites by May 1986. Because of criticism of the ranking analysis used for identifying the list of five nominated sites, multi-attributive utility decision analysis was applied. The multi-attribute analysis ranked Deaf Smith 1st, Yucca Mountain 3rd, and Hanford 5th. However, when DOE included the concept of lowering overall program risk by using a "portfolio" of sites, as required by NWPA to recommend sites in different geologic media, and codified in the site guidelines, 10 CFR 960, the Secretary of Energy recommended and President Reagan concurred in characterizing three different media (salt, basalt, and tuff) for a repository.

Congress decided to continue characterization of only Yucca Mountain in the *Nuclear Waste Policy Amendments Act of 1987* (NWPAA). Site selection by Congress was perceived as unfair and led to unwavering opposition to Yucca Mountain by state officials thereafter. The Early Site Suitability Evaluation (ESSE), a second preliminary evaluation of Yucca Mountain against 10 CFR 960 guidelines, was published in January 1992. Again, DOE reported no disqualifying conditions.

A-3.1.6 YMP Siting Selection Timeline

1950 Dec: Nevada Proving Grounds (later Nevada Test Site or NTS) selected for nuclear weapons testing; first tests begin following year.

1957 Dec: First commercial nuclear reactor starts up in Pennsylvania**.**

1972 Winograd of USGS proposes use of unsaturated zone (UZ) alluvium for HLW and transuranic (TRU) waste disposal. **May:** Atomic Energy Commission (AEC) abandons Lyons project and announces plans for Retrievable Surface Storage Facility (RSSF) at Hanford Reservation to allow more time to develop a repository. Nevada Senator Cannon urges AEC to use NTS for reprocessing and waste disposal.

1973 Nationwide search for suitable disposal site resumed.

1975 Because of unemployment in southern Nevada, state legislature passes resolution urging Energy Research and Development Administration (ERDA), successor to AEC, to choose NTS for storage and processing of nuclear material. USGS develops conceptual model for regional groundwater flow at NTS.

1976 USGS proposes emplacing nuclear waste at NTS. USGS first looks at Eleana Argilllite Fm at Syncline Ridge. Lawrence Livermore National Lab (LLNL) begins search for repository sites in granite on NTS such as Twinridge Hill, and Timber Mountain. Climax granite, accessible from nuclear weapon test tunnels, set up as underground research lab (URL). **May:** In deviation from 1974 AEC draft EIS, ERDA issues 5-volume report on 3 options for waste disposal: space, transmutation, and mined, geologic disposal. **Jun:** California enacts moratorium on building nuclear reactors until US demonstrates disposal. **Oct:** President Ford orders demonstration of nuclear waste disposal; ERDA Office of Waste Isolation (OWI) sets up National Waste Terminal Storage (NWTS) program to develop technology and facilities for storage and disposal of HLW and SNF from both commercial and defense sources. The goal is a repository between 1997 and 2006. **Nov:** ERDA notifies 36 governors that they would look for repository sites in their state.

1977 Aug: ERDA adds previous land use as criterion for identifying sites **Oct:** Newly formed Department of Energy (DOE), successor of ERDA, establishes Nevada Nuclear Waste Storage Investigations (NNWSI) project to continue looking at NTS.[DOE 1986a] Major participants are Sandia National Labs (SNL), Los Alamos National Lab (LANL), LLNL, and USGS.

1978 USGS discusses issues related to site characterization repository perturbations, groundwater movement, containment period, and suggests using multiple barriers. **Feb:** LLNL identifies 30 granitic sites in southwestern portion of NTS. **Mar:** President Carter forms Interagency Review Group (IRG), to make recommendations on nuclear waste disposal. **Apr:** SNL reports on heater experiments in Eleana Argillite Fm. Borehole at Syncline Ridge finds argillite is structurally too complex. Borehole at Calico-Hills does not find granite within 900 m and finds argillite structurally too complex. Borehole at Wahmonie finds granite mass is too small, faulted, and hydrothermally altered. Study of thick alluvium deferred because of its low thermal conductivity. Borehole UE-25a#1, cored to ~750 m, confirms presence of thick tuff deposits at Yucca Mt. **May-July:** DOE decides that repository can be built in southwestern portion of the NTS and not disrupt weapon tests; investigations at granite locations of NTS are stopped; however, work at Climax granite continues as URL to determine suitability of granite. Because shale/clay formations are no longer under consideration within NTS or in eastern US, DOE stops study of Eleana Argillite Fm. **Aug:** At request of NRC, NAS lists 7 characteristics of an ideal repository site and also recommends HLW disposal only (no high value CSNF).

1979 Feb: Sandia and Los Alamos wrap-up adsorption/desorption experiments on argillite. **Mar:** *The China Syndrome* movie released March 16; on March 28,Three Mile Island reactor accident occurs. IRG recommends mined geologic disposal, use of multiple barriers, and consideration of sites in variety of media in different regions of US and notes that safe interim storage is not a reason to delay disposal.[IRG 1979; Carter 1987, p. 135] DOE identifies granite deposits in 17 states. Comptroller General recommends that federal ownership of lands already contaminated with nuclear waste be used to identify sites. **Sept:** Because tuff not considered previously, DOE asks SNL and LANL to make presentations to NAS on suitability of tuff for waste disposal. **Oct:** USGS recommends DOE focus on the thick layers of welded tuff at Yucca Mt.

1980 Feb: President Carter issues waste management policy proposing selecting 1-2 sites from 4-5 candidates with state participation on waste matters. **Oct:** DOE issues EIS on options for commercial SNF disposal and selects mined repositories with subseabed disposal and deep boreholes as potential backups.[DOE 1980c]

1981 Jun: Winograd of USGS again proposes use of thick unsaturated alluvium in desert for HLW disposal. His suggestion leads to use of unsaturated zone (UZ) at Yucca Mountain the next year and approval for disposal of TRU and low-level waste (LLW) in 36-m deep boreholes at Greater Confinement Disposal (GCD) facility at NTS.

1982 Jul: USGS recommends DOE focus on ~350-m thick Topopah Spring Fm in UZ. **Aug:** Site Evaluation Working Group, organized in 1980, reports that Yucca Mt remains preferred site out of 15 locations in southwest NTS.

1983 Jan: In *Nuclear Waste Policy Act* (NWPA), Congress (a) establishes Office of Civilian Radioactive Waste Management (OCRWM) within DOE with single purpose to design, build, and operate HLW repositories; (b) requires DOE to identify two sites and operate one of them; (c) requires promulgation of site selection guidelines, (d) sets timetable for nominating at least 5 sites, recommending 3 viable sites, and selecting and opening first repository by 1987; (d) limits 1st repository to 70,000 MTHM for regional equity; (e) requires Environmental

Assessment (EA) of viable sites; and (h) directs DOE to advise Congress on site for Monitored Retrievable Storage (MRS). **Feb:** Parts of OWI become OCRWM; DOE formally identifies 9 sites already under consideration (3 salt dome sites, 4 bedded salt sites, 1 tuff site at Yucca Mt, and 1 basalt site at Hanford). DOE publishes draft guidelines for selecting a site (10 CFR 960). **Mar:** DOE solicits comments from State of Nevada and public regarding nomination of Yucca Mt and issues to discuss in EA and Site Characterization Plan (SCP).[DOE 1985] Gov Bryan declares nomination an unfair burden since it might discourage growth of Las Vegas. **Dec:** ^{90}Sr, tritium, and other nuclear waste placed in GCD test borehole, 3 m in diameter and 36 m deep, on NTS.

1984 May: Disposal of 330 Ci of ^{239}Pu in 60 Mg of classified TRU waste from radioactive cleanup begins at GCD on NTS. **Dec:** DOE finalizes 10 CFR 960 site selection guidelines. DOE issues draft EA on all 9 potential sites and nominates 5 sites for characterization (Yucca Mt; Davis Canyon, UT; Deaf Smith, TX; Richton dome, MS; and Hanford, WA).

1986 Apr: Chernobyl reactor accident. **May**: DOE recommends 3 sites (Yucca Mt, Deaf Smith, and Hanford) for further characterization based on final EAs of 5 sites and multi-utility analysis. DOE applies concept of lowering program risk by using portfolio of sites. President Reagan approves the recommendations. From 1979 list of sites in 17 states, DOE recommends 12 sites in 7 states for 2nd repository but postpones characterization because new reactors not being built, and because administration wished to avoid losing Senate control because of uproar.

1987 DOE recommends 3 MRS sites, all in Tennessee. **Dec**: In NWP Amendment Act (NWPAA), Congress (a) selects Yucca Mt as 1st site to characterize; (b) affirms DOE decision to delay 2nd repository; (c) nullifies selection of Tennessee for MRS and institutes voluntary program (expired in Jan 1995 without success); (d) limits size of MRS and links construction to repository construction schedule, which limits MRS role in storing and aging SNF; and (e) grants $5 million annually during planning and construction and $10 million annually during operation to communities hosting a repository or MRS.

1989 Aug: Last of 2.3 MCi of LLW tritium disposed in boreholes at GCD on NTS.

1991 Mar: Supreme Court denies petition for review of Nevada's "effective notice of disapproval"; based on ruling, US District Court orders Nevada to take action on 3 permits for characterizing Yucca Mt. **Sep:** Court of Appeals for 9th Circuit rules ban on nuclear waste shipments imposed by Idaho Gov Andrus are illegal.

1992 Jan: DOE completes Early Site Suitability Evaluation (ESSE) (started in the spring of 1991) using 10 CFR 960 criteria. ESSE finds no disqualifying conditions.

1994 Dec: In periodic program plan required by NWPA, DOE sets three milestones: (1) publish findings on suitability of Yucca Mt in 1998; (2) assuming favorable findings in EIS, Secretary to recommend site to President in 2000; and (3) DOE to submit license application (LA) for construction to NRC in 2001.

1997 Congress calls for a viability assessment (VA) that includes a PA of probable behavior, a design of the repository and WP, cost estimates for completing the LA, and cost estimates for constructing, operating, and closing the repository.

1998 Nov: VA shows that Yucca Mt remains a viable and promising site.

1999 Jul: Based on VA, DOE publishes 1600-page draft EIS on either building Yucca Mt or leaving waste at 77 sites around US. **Nov:** DOE proposes revised guidelines (10 CFR 963) for evaluating suitability of Yucca Mt, consistent with NWPAA.

2000 Oct: DOE estimates ~4 tonnes of Pu released in the 1021 bomb experiments (100 atmospheric and 921 underground) at NTS over 40 yr.

2001 Based on workshop in 1999, NAS concludes that after 40 yr of study, "geologic disposal remains the only scientifically and technically credible long-term solution available to meet safety needs." **Aug:** DOE releases Preliminary Site Suitability Evaluation (PSSE) report, which discusses site recommendation (SR) based on (1) proposed criteria in 10 CFR 963 and (2) technical support in Science & Engineering Report (S&ER) describing PA. **Sep:** al Qaeda terrorists commandeer 4 commercial jets and fly 2 into World Trade Center and 1 into the Pentagon. **Nov:** DOE promulgates site selection guidelines in 10 CFR 963. **Dec:** DOE completes supplement to draft EIS on Yucca Mt.

2002 Feb: DOE completes 10^4-page Final EIS on Yucca Mt. EIS estimates $43 billion for construction and operation and $4 billion for transportation and storage; recommends rail transportation to site. Energy Sec Abraham recommends Yucca Mt site to President Bush. President Bush recommends site to Congress. **Apr:** Nevada Gov Guinn disapproves the recommendation under special rules in NWPA; Congress has 90 days to override disapproval. **May:** House overrides Nevada's disapproval 306 to 117. **Jul:** Senate overrides disapproval 60 to 39. President Bush signs *Yucca Mountain Development Act*, authorizing DOE to apply to NRC for construction authorization. **Aug:** District Judge Campbell strikes down Utah laws designed to keep nuclear waste out of state through excessive fees and numerous permits.

2004 Jul: Court of Appeals for DC Circuit rejects all Nevada lawsuits on site selection process (NWPA amendments rendered moot challenges on site selection process).

2005 May: NRC approves storage license for Private Fuel Storage (PFS) at Goshute Skull Valley Indian Reservation in Utah for 40 MTHM.

2006 Sept: Bureau of Indian Affairs (BIA), nullifies lease between Goshute tribe and PFS, claiming storage might be permanent and that federal, tribal, and local law enforcement were inadequate to protect from terrorists.

2008 Jun: DOE submits LA/SAR to NRC.

2010 Feb: Obama Administration proposes no FY11 budget for YMP **Mar:** DOE files motion with ASLB to withdraw LA/SAR with prejudice. **Jun:** ASLB denies motion

A-3.2 Yucca Mountain Characterization

Similar to WIPP, site characterization at Yucca Mountain progressed through three study phases: (1) non-intrusive evaluation and literature search for site selection; (2) exploration from the surface for evaluating repository feasibility; and (3) exploration underground to evaluate viability, recommend the site, and support the compliance assessment. During these phases,freatures, events, and processes important to repository performance were analyzed; for Yucca Mountain, in particular, the volcanic and seismic hazards were characterized. Also, site characterization at Yucca Mountain sought to determine properties of (1) transport of radionuclides through unsaturated zone below the repository and through the saturated zone in early analysis and thereafter using regional water level measurements, borehole potentiometric measurements, single and multi-well pump tests, sorption experiments on core, and tracer tests at the C-well complex; (2) movement of water near the drift as the tuff was heated by the waste was simulated in the early 1990s, and thereafter using single heater and drift-scale heater tests and modeling of transport in the biosphere was supported by population surveys; (3) net infiltration into the mountain, fracture and matrix component of percolation through the volcanic tuff above the repository, and seepage into open drifts for the viability assessment and thereafter using precipitation measurements, neutron probe measurements, laboratory hydraulic tests on core, pneumatic tests, fracture mapping in the Exploratory Studies Facility (ESF), ^{36}Cl concentrations, and temperature profiles; and (4) the chemical environment around the drifts and drift degradation using pore water measurements for the site recommendation and license application.

A-3.2.1 Site Characterization at Yucca Mountain in Early 1980s

A concerted effort to gather information on the geologic barrier characteristics of Yucca Mountain started from the surface in 1980 with the drilling of stratigraphic borehole G-1 and hydrologic borehole H-1. With the completion of six major geologic and hydrologic boreholes around the perimeter of the repository (G-2, G-3, GU-3, H-3, H-4, and H-5) and mapping of faults and fractures, the USGS was able to develop a three-dimensional stratigraphic map of the Yucca Mountain area in 1982. By 1984, G-4 (at the proposed ESF shaft), and H-6 were completed and geologic map constructed.

As a type of underground research lab (URL), Sandia began a small diameter heater to evaluate thermal mechanical response and see if, as observed in Salt Vault, water migrated to the heater in welded tuff. The test was conducted in G-tunnel under Rainer Mesa to the north of Yucca Mountain in the middle of NTS in 1980 and reported some results by 1983. Sandia had also completed a larger heated block experiment in G-tunnel by 1986.

By 1984 Lawrence Livermore and Los Alamos had reported on migration and sorption of radionuclides on tuff in the laboratory and solubility limits and corresponding thermodynamic data. Also, Lawrence Livermore had reported on geochemical tuff/water interaction experiments.

The oxidizing environment of Yucca Mountain, as represented by the range of Eh, was acknowledged as an unfavorable situation. However, corrosion of the steel plugs, borehole sleeves and canister were postulated to adequately compensate for this initially oxidizing condition by producing a reducing micro-environment even though this reducing micro-environment was not explicitly accounted for in the range of Eh values selected.

A-3.2.2 Site Characterization at Yucca Mountain in Early 1990s

Site characterization often felt the brunt of funding difficulties, but in the late 1980s and early 1990s controversies with the State of Nevada thwarted investigations. Since publishing the site characterization plan (SCP) in 1988, DOE had unsuccessfully sought permits from the State of Nevada for surface exploration. Then in September 1990, the Court of Appeals for Ninth Circuit ruled Nevada's "effective notice of disapproval" was premature and could not require DOE to cease investigations. By June 1991, the State issued an air quality permit for site investigations and by July state issued an underground injection control permit. The State Engineer granted a temporary ground water permit for site characterization in August 1992.

The Nuclear Regulatory Commission rule, 10 CFR 60, required the DOE to conduct site characterization activities at the depth of the repository. In its Site Characterization Plan (SCP), the DOE included the construction of exploratory shafts and a number of tests in drifts at the bottom of the shaft. In response to objections by the Nuclear Regulatory Commission to the Site Characterization Plan, the Department of Energy undertook a study to examine different ways to characterize the subsurface of the repository horizon at Yucca Mountain. The Exploratory Studies Facility Alternatives Study examined 34 different configurations for underground access and testing involving shafts, ramps, and characterization activities both in the Topopah Spring horizon and the Calico Hills horizon. The option selected for the Exploratory Studies Facility consisted of two ramps and the north-south tunnel connecting them which ran along the east side of the potential repository layout. Exploration was to include both the Topopah Spring horizon and the Calico Hills horizon. Excavation of Exploratory Studies Facility began in 1994, but reduced Congressional funding resulted in the Department of Energy using a single tunnel boring machine starting from the North portal and limiting excavation to the Topopah Spring horizon.

DOE conducted a Calico Hills Risk/Benefit Analysis (CHRBA) in 1989 to study usefulness of excavating the Calico Hills (CHn) when constructing the Exploratory Studies Facility (ESF) The CHRBA study concluded excavation of the CHn not necessary but it might reduce program risks and increase scientific confidence. In October 1991, the DOE conducted a Test Prioritization Task (TPT), a spreadsheet study to rank importance of site characterization experiments. In the TPT study about 100 potentially adverse conditions from DOE site guidance 10 CFR 960 and NRC 10 CFR 60 are screened and consolidated into 32 concerns and then ranked based on management judgment and some technical assessments (but not a PA). Three major concerns were ^{14}C gas flow; complex geology for gas flow; and complex geology for groundwater flow. Most other concerns and their corresponding tests were of little consequence to the issue of site feasibility and viability. Because of the time and high cost, the DOE decided to reduce surface-based characterization through wells and move to underground studies once the ESF was completed.

By the early 1990s, enough circumstantial evidence had accumulated to suggest that the water could flow down fractures for long distances before the water was carried away in air moving through the mountain, was absorbed into the matrix pores, or reached the deep aquifer. This circumstantial evidence consisted of (1) USGS observation of continuous seepage from several fractures in G-tunnel in 1984, (2) Los Alamos observation of calcite and opal on the walls of fractures and vugs in well cores in 1985. (3) USGS discovery of drilling fluids in dry-drilled UZ-1, presumably from well G-1 300 m away in 1990; and (4) Los Alamos discovery of elevated ^{36}Cl concentration in well UZ-6 in 1990 from testing of nuclear weapons above ground at NTS during the 1950s.

Using experimental results of actinide sorption on tuff conducted between 1977 and 1985, Los Alamos developed a traditional sorpotion model and a kinetic sorption model in 1987. In response to the initial review by the NWTRB, DOE held a sorption workshop at Los Alamos to explore techniques for testing and modeling sorption in 1990. In 1989, the behavior of artificial colloids in column experiments using tuff suggest that colloid transport would not be significant at Yucca Mt.

In 1984, the USGS developed a 2-D, finite-element, steady-state, regional groundwater model. The composite properties of the 1000 m thickness of stratigraphic layers (including the upper unconfined volcanic aquifer the lower confined carbonated aquifer and representing 1) were calibrated by hand to match hydraulic heads 26 wells around Yucca Mountain and 64 wells near Death Valley. The 1984 model extended 70 km to the southwest to Death Valley to include potential discharge areas at Franklin Lake playa and Furnace Creek. Flow patterns suggested that Yucca Mountain provided no noticeable percolation influx to the groundwater system. Additional USGS field site characterization of infiltration and regional SZ flow was stopped in 1986 by DOE until 1991 to improve the QA program. Also in 1988, NRC advised DOE that the entire YMP QA program was inadequate.

In 1993, the USGS reported on U-isotopic dating of ancient spring deposits 18 km to the southwest of Yucca Mountain at the southern end of Crater Flats and Sr-isotopic dating of calcites deposits in wellbores around Yucca Mountain. The U-isotopic dating suggested that the water table in the region had been between 80 and 115 m higher ~18 ka. Sr-isotopic dating found modern-day calcite deposits ~85 m above the current water table in core from G-2.

A-3.2.3 Site Characterization for the YMP Viability Assessment

In 1995 and 1996, USGS completed two major deliverables: moisture measurements in 99 shallow neutron boreholes and the infiltration model, INFIL, which was a distributed but discrete-cell, water balance, field capacity model of the soil and bedrock. The USGS results with INFIL showed current net infiltration roughly 10 times greater than the high estimate from an earlier analysis (i.e., a mean of 12 mm/yr and median of 7.7 mm/yr over the repository area for the Viability Assessment versus a mean/median of 1.2 mm/yr from preliminary 1994 USGS estimates.

A 3-D mountain-scale model was developed to evaluate percolation flow fields using of a dual-permeability model (DKM) formulation that represented fractures (high permeability, low porosity) and matrix (low permeability, high porosity) as distinct continua that could interact through mass transfer terms at every point within the model domain.. The stratigraphy included dipping faults and additional rocks units than included previously. USGS laboratory measurements on well core were used to set the matrix properties. Fracture density measurements and air-injection experiments along the ESF and boreholes were used to set the fracture properties. The Detailed Line Survey (DLS) performed by the USGS/Bureau of Reclamation provided a set of fracture density measurements in the ESF. Saturation data from core and in-situ water potential data were used to initially calibrate matrix properties. In situ pneumatic data from SD-7 and SD-12 were used to initially calibrate fracture permeability. The fracture and matrix properties to form perched water at the location of perched water in six wells (G-2, UZ-14, SD-7, SD-9, SD-12, NRG-7a).

In May 1996, Lawrence Berkeley began a year-long Single Heater Test (SHT). A 5-m long heater with 3.86 kW output was placed in Alcove 5 of the ESF. The observations showed that conduction (rather than convection) was the dominant heat transfer mechanism. Observations also showed that Equivalent Continuum Model (ECM_ predictions of thermal driven water movement under predicted temperatures because of artificial refluxing. The Dual Permeability Model (DKM) conceptualization matched experiment temperatures better.

In 1997, Lawrence Livermore completed a Large-Block Test (LBT), located at Fran Ridge near Yucca Mt. The purpose of the test was to evaluate movement of water and mineral deposition in fractures as water evaporates at bottom of block (maintained at 140 ^{o}C) and condenses at top of block (maintained at 60 ^{o}C).

In 1997, Los Alamos and Lawrence Livermore scientists reported on the migration of 0.8 pCi of Pu via colloids (10^{-14} M colloidal Pu) 1.3 km from 1968 1.15 million ton Benham bomb test detonated below the water table at NTS. The Viability Assessment used the information to make a crude approximation of colloidal transport of Pu.

A telephone survey of dietary habits and lifestyle of residents within an 80-km radius of Yucca Mountain was completed in June 1997 to obtain data for the biological transport model used in PA-VA. About 6725 households (~13000 adults) exist within the survey area.

A-3.2.4 Site Characterization for the YMP Site Recommendation

For the Site Recommendation, the basic approach to estimating the percolation at the repository level remained the same as for the Viability Assessment. However, the calibration process was more elaborate. For the Site Recommendation, 1-D columns were built for 11 boreholes with matrix saturation, matrix water potential, or fracture pneumatic pressure measurements (NRG-5, NRG-6, NRG-7a, SD-6, SD-7, SD-9, SD-12, UZ-4, UZ-14, UZ-16, and WT-24). Matrix saturation from core measurements were available from 7 of the 11 wells. Matrix water potential in-situ measurements were available at multiple depths from 4 of the 11 wells from October 1994 to December 2001 Thirty days of record from pneumatic data (collected between 1994 and 1999) at multiple depths from gas pressure transducers was used from 5 wells (NRG-5, NRG-6, NRG-7a, SD-7, and SD-12). The hydrologic parameters of all models faults were calibrated using UZ-7a, which intersects the Ghost Dance Fault. Perched water at the PTn/TSw interfaced observed in 7 wells (the 6 wells available for Viability Assessment plus WT-24).

In December 1997, DOE began an 8-year Drift-Scale heater Test (DST) in a 47.5-m long section of Alcove 5 of ESF. The test consisted of 9 container-sized heaters to simulate the heat from the disposal container in drift (~5 kW/m) and 50 heaters in walls to simulate the heat from adjacent drifts. The purpose of DST was to compare observations for the next 8 yr from 3500 temperature, chemical, mechanical, and neutron sensors with modeling predictions of thermal, mechanical, hydrologic, and chemical responses such as initial dry-out and later rewetting, thermally driven buoyant flow of air and water vapor, and “refluxing” as water vapor condenses and flow back toward the drift.

The evaluation of the seepage in PA-SR was much more elaborate than in the Viability Assessment. For the Site Recommendation, the model fracture properties were calibrated using data from water release tests conducted since 1997. In the tests, water was released from a horizontal borehole located less than a meter above the ceiling of niche along the ESF.

For PA-SR, Los Alamos developed a calibrated site-scale SZ flow model by varying permeability in the various stratigraphy to match water levels in 115 well head measurements available over the 1350 km^2 domain. In 1999, the first 8 wells of the Nye County Early Warning Drilling Program were completed and included among the 115 wells.

For transport calculations, the flowing interval spacing (i.e., the spacing between fracture zones with measurable flow) was determined from flow meter survey data available from 8 wells (H-1, H-3, H-4, G-4, UE25c#1, c#2, c#3, UE25p#1) with a total of 32 measurements in 5 hydrogeologic layers.

A-3.2.5 Site Characterization for YMP License Application

In October 2005, DOE directed Sandia to repeat implementation of the infiltration model and directed INL to review the technical merit of INFIL v2.0 model and compliance with QA procedures. This reevaluation occurred because in November 2004, while reviewing old e-mail for submission to the License Support Network (LSN), the YMP discovered correspondence between 3 USGS geohydrologists between 1998 and 2004 that raised questions about fabrication of QA records such as when computer programs were installed and when information on infiltration data were collected. By February 2006, the INL review had found that the net infiltration rates were corroborated by independent studies of infiltration in the southwest. By April 2006, the DOE Inspector General had found that although misconduct was suggested in the 26 e-mails, misconduct was not substantiated. However, the Inspector General concluded there was inadequate compliance with some QA procedures (obvious backdating of a software QA step) and software input files were not controlled. Hence, while the work was technically sound it was not suitable for the formal LA and Sandia was directed to continue to develop a new implementation of the infiltration model (MASSIF).

The Sandia implementation in MASSIF added (a) uncertainty in soil depth, (b) added uncertainty in bedrock conductivity, (c) developed soil hydraulic characteristics from an analogous site at Hanford for 4 soil types, and (d) greatly improved modeling of evapotranspiration to use site specific vegetation data based on LANDSAT images from three representative precipitation years (dry, moderate, and wet). With only a subset of USGS data qualified, MASSIF predicted 3 times more infiltration and with more variance. The NWTRB commented that MASSIF provided a more complete representation of parameter uncertainties but did not consider all data used by the USGS, was not calibrated with rock properties from USGS infiltration measurements, and did not sufficiently account for evapotranspiration from bedrock fractures, and, thus, was less consistent with temperature and ^{36}Cl concentration within mountain. Hence, Lawrence Berkeley had difficulty calibrating the UZ model with the new infiltration data. Because the models gave similar results with similar parameters,

For the License Application, the YMP sought to validate the presence of bomb-pulse ^{36}Cl within fractures within a few 100 mm of the walls of the ESF. Between March and October 1999, the USGS/LLNL took 50 core samples 4 m or 10 m into the walls where LANL had previous found bomb-pulse ^{36}Cl in two zones along the ESF: (1) at the Sundance fault (40 boreholes), and (2) at Drill Hole Wash fault (10 boreholes). Although ESF or laboratory contamination may have been a possible cause, the information collected did not point to this difficulty and the report did not come to any conclusions other than bomb-pulse ^{36}Cl was not corroborated by the USGS/LLNL validation study.

For the seepage analysis for the License Application, more data had been collected including air injections tests to estimate initial air permeability and seepage-rate from tests conducted at three niches along the ESF, one niche in the ECRB Cross-Drift, and in three boreholes drilled into the ceiling of the Cross-Drift. In total, 22 seepage tests in 10 different interval/test-locations were used for the final calibration for seepage calculations.

For the License Application, more well data were available for construction of the site-scale SZ flow model. Stratigraphic, potentiometric, and single and multi-well pumping data were available for calibration from 16 wells completed by 2004 in Phases II, III, and IV of the NC-EWDP and 5 wells from Phase V were available for validation. A total of 161 potentiometric data were used for calibration, which included the water table measurements from the 115 wells used for Site Recommendation and potentiometric data from other hydrologically isolated layers (e.g., 16 NC-EWDP wells provided 33 potentiometric measurements for different layers).

A-3.2.6 Summary of YMP Site Characterization

1976 Engine maintenance, assembly, and disassembly facility (built for nuclear rocket program cancelled in 1971) and onsite railroad are modified for SNF tests in Climax granite as underground research lab (URL) at Nevada Test Site (NTS).

1979 Feb: Facility constructed ~1,400 ft below surface in Climax granite and 20 floor boreholes drilled for SNF canisters.

1980 Apr: Fossil rat middens from middle Wisconsin through Holocene age collected and dated to determine climatic changes at Nevada Test Site (NTS). **Apr-May:** G-1 stratigraphic borehole cored to 1.9 km, logged, and hydrologically tested to examine tuff at Yucca Mt. 11 SNF canisters and 6 simulated canisters placed remotely in Climax facility. **Sep:** H-1 hydrologic test hole drilled 1.9 km into saturated zone at Yucca Mt. **Dec:** Sandia National Labs (SNL) with support from SAIC starts small heater/water-migration experiments in welded tuff in G-tunnel at NTS.

1981 Jan: Some water-level data collection begins. G-2 borehole completed and logged to 1.9 km. US Geological Survey (USGS) digs 5 trenches in the south and southeastern portions of Crater Flat, next to Yucca Mt: 2 trenches were dug at ancient springs and 3 trenches dug at 2 faults to determine their relative age with other geologic features in the area. The springs ~0.1 Ma; the 2 faults occurred with volcanic activity at Crater Flat (1.1 Ma).

1982 DOE estimates that ~4700 people have visited the Climax facility since constructed. Four major geologic and hydrologic drill holes completed (G-3, H-3, H-4, and H-5) and 2 more boreholes started (H-6, UE-25p#1). These 7 holes were bored along the perimeter of the potential repository block, except for UE-25p#1, which was located to reach the deep carbonate aquifer at its shallowest depth. USGS reports that the variation in temperature of groundwater around Yucca Mt is possibly from groundwater percolation and suggest downward movement of a 8 mm/yr. USGS develops 3-D model of stratigraphy of Yucca Mt. USGS develops 2-D, steady-state, model to simulate regional groundwater flow (175-km^2) in saturated zone (SZ) at NTS; **Jun:** Drilling of G-4 begins in at the proposed location of the ESF shaft, using air/foam. **Jul:** DOE moves repository to UZ in ~350-m thick Topopah

Spring Formation. **Nov:** Los Alamos National Lab (LANL) reports on laboratory radioisotope migration tests in tuff.

1983 Based on highly fractured outcrops in the field, USGS and SNL propose 3% of 150 mm/yr (4.5 mm/yr) precipitation percolates through fractures in Yucca Mt. USGS completes G-4, H-6, and UE-25p#1: G-4 drilled to depth of 950 m; H-6 drilled to depth of 1200 m; UE-25p#1 drilled to depth of 1300 m to the Paleozoic carbonate aquifer. USGS drills eleven 340-m deep boreholes to supplement other boreholes to set water table around Yucca Mt. USGS begins periodic water table measurements. High water table/perched water noted northwest of repository. **Jan:** At time of passage of *Nuclear Waste Policy Act* (NWPA), NRC estimates $100 million for characterization of 300 m of underground drift. **Jun:** Small-diameter heater test completed in G-tunnel to evaluate water migration and geomechanical response. LANL reports on sorption of radioisotopes on tuff.

1984 USGS reports on stratigraphy and geohydrology of G-3, G-4, UE-25p#1, H-1, and H-3 wells. USGS continues detailed mapping of faults, and fractures, and fracture orientations around Yucca Mt and proposed location of ESF and completes geological map of Yucca Mt. USGS notes continuous seepage from several fractures in G-tunnel under Rainer Mesa and postulates Rainer Mesa as analogue for Yucca Mountain during the glacial period. USGS modifies conceptual model of UZ flow and suggests that most of water infiltrating (4 mm/yr), is diverted laterally, with only 0.5 mm/yr moving downward through repository horizon as matrix flow. USGS creates new 2-D steady-state, regional model and matches hydraulic heads in 26 wells around Yucca Mountain and 64 wells near Death Valley. Model is ~1/3rd size of 1982 Waddell model. Infiltration study begins; boreholes drilled across washes and on crest to measure changes in water-content from precipitation. Also, 11 stations set up around Yucca Mt to measure chemical composition of precipitation. **May:** Lawrence Livermore National Labs (LLNL) reports on geochemical tuff/water interaction experiments; water from J-13 well used to simulate composition of groundwater. **Aug:** LANL reports on solubility limits for radioisotopes in tuff with EQ3/6 **Dec:** At end of 1983 and through 1984, three boreholes, UE-25c#1, #2, and #3 (C-wells), are drilled ~3 km east of repository and pumping tests conducted for estimating permeability.

1985 Also, USGS reports on stratigraphy and geohydrology of H-4 well. SNL defines stratigraphy for hydrologic modeling at Yucca Mt (i.e., PTn, TSw, CHn, PPw, BFw,TRw). LANL finds calcite and opal on deep fracture surfaces from well core that suggests deep fracture flow.

1987 Jan: In hearings before Senate Energy and Natural Resources Committee, DOE reports that site characterization now estimated at ~$1 billion per site. **Apr:** LANL measures ^{36}Cl/Cl ratios in water extracted from unsaturated tuff and proposes information be used to evaluate infiltration and percolation flux at Yucca Mt. **Jul, Aug, Dec:** LANL models kinetic sorption and traditional sorption on tuff using test results conducted between 1977 and 1985. **Dec:** Congress passes *Nuclear Waste Policy Amendment Act* (NWPAA) to 1st examine Yucca Mt partially to save characterization costs and establishes Nuclear Waste Technical Review Board (NWTRB) to advise DOE and Congress.

1989 Behavior of artificial colloids investigated in column experiments; results suggest that colloid transport not significant at Yucca Mt. DOE stops in-situ thermal testing in G-tunnel. **Jul:** In Calico Hills Risk/Benefit Analysis (CHRBA), DOE studies usefulness of excavating the Calico Hills unit; study suggests that the repository will meet requirements without testing; 2nd evaluation concludes, excavation could reduce program risks.

1990 Evidence found for deep fracture flow when LANL finds ^{36}Cl in well UZ-6 and USGS finds drilling fluids in dry-drilled UZ-1 from well G-1, 300 m to southeast. USGS examines hydrology around Franklin Lake playa using 1984 model. **Sep:** In response to NWTRB, DOE holds sorption workshop at LANL.

1991 Oct: DOE conducts Test Prioritization Task (TPT) to rank test importance. 3 major concerns were ^{14}C gas flow; complex geology for gas flow; and complex geology for groundwater flow.

1993 LANL continues to report on discovery of bomb pulse ^{36}Cl from boreholes within repository area. USGS develop regional-scale, steady-state, quasi 3-D model; other assumptions: steady-state, confined aquifer, 37.5-mi^2 grid blocks, two layers in carbonate aquifer only, large features (lakes, large rivers) modeled. **Mar:** After 10 months, UZ-16 borehole completed with new prototype continuous core and reaming air drill rig (LM-300) to avoid contaminating borehole with water. Annual operating cost ~$5.6 million. With only one rig working 5 days/week, it would take ~29 yr to complete planned 40 boreholes with total length of 30 km. DOE decides to reduce surface dry-drilling and move to underground studies once ESF is completed.

1994 May: PA-95 uses very low infiltration (0.02 and 1.2 m/yr) reported by USGS in preliminary observations in 99 shallow neutron boreholes. **Nov:** USGS begins in-situ tests of matrix water potential and gas pressure in numerous wells.

1995 LANL begins testing for ^{36}Cl at faults as boring progresses along ESF. **Mar:** USGS completes mapping of Ghost Dance Fault at surface; fault ~200 m wide; also find more recent northwest-trending fault, the Sundance fault, that traversed the Ghost Dance, and thus, Ghost Dance is inactive. **Apr:** Underground calcite and ^{36}Cl sampling, and moisture monitoring studies start at ESF North Ramp. LANL reports on Sr-isotopic dating of calcite deposits in wellbores and U-isotopic dating of spring deposits in Crater Flats suggesting water table rise of between 80 and 115 m during last glaciation 18 ka. **May-Jun:** USGS conducts interference test at C-wells.

1996 USGS reports on infiltration model, INFIL v1.0, which is a distributed but discrete-cell, water balance, field capacity model of the soil and bedrock. Moisture observations in 2 of the ~99 shallow neutron boreholes compare favorably with predictions. USGS publishes formal stratigraphy of Yucca Mt. USGS upgrades formation units defined in 1984 to groups, member units to formations, and divides the geologic stratigraphy of Paintbrush Group. **Feb**: USGS conducts pumping test in at C-wells at UE-25c#3; c#1, c#2, ONC-1, H-4, WT-3, and WT-14 are observation wells. **May-Nov:** After steady-state conditions reached, sorbing and nonsorbing tracers injected into borehole UE-25c#2 while pumping c#3 (1st nonsorbing tracer test). **May:** LBNL begins year long Single Heater Test (SHT), 5-m long heater with 3.86 kW output, in ESF at Alcove 5. **Nov:** In response to Congressionally mandated Viability Assessment, YMP forms 5 expert elicitation panels to examine: (1) UZ flow, (2) flow and transport in SZ, (3) waste package degradation, (4) waste form degradation, (5) near-field/altered-zone coupled effects. Unlike the 2 previously formed panels for (1) volcanic hazard, and (2) seismic hazard, these panels deal with immediate needs for the assessment and thus have a tight schedule and limited budget. YMP conducts UZ elicitation first; 7 experts (4 from outside DOE complex and USGS) provide uncertainties in parameters and processes.

1997 USGS develops a 3-layer, 3-D, steady-state regional flow model of SZ for the entire closed Death Valley basin (~2×10^4 km^2). For PA-VA, USGS develops a site-scale model with boundary conditions set by the regional model. **Jan:** Another conservative tracer test begins at C-wells. Test ends in Nov. While UE-25c#3 is pumped, benzoic acid is injected into c#2, and pyridone is injected into c#1. **Feb:** LLNL turns on heaters at Large-Block Test, located at Fran Ridge near Yucca Mt to evaluate water movement and mineral deposition in fractures. **May:** Heat turned off in SHT; test shows conduction (rather than convection) is dominant heat transfer mechanism; DKM conceptualization match temperatures better than ECM but still under predict slightly. UZ expert elicitation completed and agree (a) percolation equal to infiltration above repository; (b) percolation likely 10 times greater than PA-95; (c) flow in TSw mostly in fractures based on presence of bomb-pulse ^{36}Cl; and (d) capillary barrier would exist around drifts and likely divert water. **Jun:** YMP completes survey of dietary habits of residents within 80 km radius completed. **Aug:** DOE accepts NWTRB recommendation for a 2nd exploratory drift; drift named enhanced characterization of the repository block (ECRB). **Sep:** LANL and LLNL report on migration of 0.8 pCi of Pu via colloids 1 mile from 1.15-million ton Benham bomb test detonated in 1968 below water table at NTS (work published in1999). **Nov: L**BNL reports on seepage tests in niche at station 3650. **Dec:** LBNL begins $50 million, Drift-Scale Test (DST) in at 48-m long section of Alcove 5 in ESF, with 5 kW/m output. Test consists of 9 container-sized heaters, 50 heaters in walls to simulate adjacent drifts, and 3500 sensors.

1998 DOE funds USGS over 5 yr to update regional flow model. USGS updates geologic bedrock map first created in 1984; including fractures in ESF; Also, YMP completes tomographic seismic imaging between the ESF and the surface. YMP conducts regional demographic survey and analysis to establish drinking and eating habits of local population. Testing at C-wells shows aquifer permeability orders of magnitude greater than permeability found in core and ~2 orders of magnitude greater than single-well tests. Water levels in observations wells 3 km away are lowered. Expert elicitation of 5 experts (4 from outside DOE complex) on issues related to SZ groundwater flow and transport conducted for PA-VA. The experts examine the high water table northwest of the site; but conclude that identifying the cause is not important to PA. The experts conclude that water from Yucca Mt does not reach the deep carbonate aquifer below the repository but remains in the tuff aquifer. The experts consider the large dispersion used previously as unrealistic and provide an estimated range between a factor of 2 and 100. The SZ panel notes lack of data for key hydraulic parameters. **Mar-Aug:** LBNL conducts percolation test at North Portal of ESF: water uniformly distributed at surface; seepage observed 30 m below in Alcove 1; tests also conducted Jan to Jun 1999 and up to Jan 2000. **Jul:** LANL begins 3-yr experiment to test flow and transport in partially excavated 5 m block of CHnv 70 m below the surface at Busted Butte, a small butte 8 km southeast of Yucca Mt, since project would not bore to CHn with reduced funding. **Dec:** DOE estimates that license application (site characterization, repository design, and documentation) will cost $6 billion.

1999 Project stops drilling WT-24 in the high water-table zone because low permeability precludes well tests and because SZ expert panel thought resolving reason for zone not important. 1st 8 wells (Phase I) of Nye County Early Warning Drilling Program (NC-EWDP) completed. **Mar-Oct:** USGS drills 50 boreholes at Sundance and Drill Hole Wash faults to validate high ^{36}Cl found by LANL. **Jun:** 1 km of ECRB sealed to observe seepage.

2000 Mar: For PA-SR, USGS specifies future precipitation climate at Yucca Mt based on long-term precipitation at analog sites but improves selection criteria. LBNL summarizes knowledge of UZ and concludes (a) some percolation is diverted to the faults by nonwelded layers: 4% near surface, 15% at PTn, and 35% at CHn; and (b) 84% of percolation is through fractures. **Jul-Nov:** Pump test of NC-19D1 in alluvium completed. **Oct:** Transport test in CHnv layer ends at Busted Butted. Transport dominated by capillary-driven flow. Coupled thermal-hydrologic-chemistry simulations run for DST and SHT.

2001 Feb: Condensate found at bulkhead in closed-off end of ECRB at the Solitario Canyon fault; testing continues to confirm water is condensate and not seepage. **Dec:** NC-EWDP finds evidence of hot water in faults beneath site. Also, considerable vertical variation in water chemistry found in wells.

2002 Jan: After 4 yr, DOE turns off heaters in DST. During the test, 6 to 7 m of tuff dried out (drift diameter 5.5-m). **Oct:** Water levels in 43 wells primarily south of Yucca Mt have not changed much since 1960, except levels increased in a few wells in last 10-yr.

2003 Mar: DOE starts Science and Technology program with $1.7 million to improve understanding and develop technology that could reduce uncertainty and reduce project costs. **Nov:** LANL reports zeolites in CHnv below repository readily sorb short-lived Sr, Cs, and Ba.

2004 Nov: 16 new NC-EWDP wells almost completed (Phases II, III, IV). USGS/LLNL cannot validate LANL discovery of ^{36}Cl at Sundance fault. When reviewing old e-mails for LSN, YMP discovers correspondence between 3

USGS geohydrologists between 1998 and 2004 that raise questions about collection of infiltration data, when software installed, and fabrication of QA records.

2005 Feb: 1st evidence of natural seepage found near entrance to ESF (Alcove 1). **Mar:** DOE Inspector General opens criminal investigation into USGS e-mails since a few suggest opportunity to double bill DOE. **Oct:** DOE directs SNL to repeat infiltration model and directs INL to review technical merit of INFIL

2006 Feb: INL finds that infiltration corroborated by other studies of infiltration in southwest .YMP reports to NWTRB that Eh measurements at wells suggest a reducing zone exists down gradient from Yucca Mt that may retard ^{99}Tc, whose solubility is sensitive to oxidation. **Apr:** DOE Inspector General concludes that no criminal charges will be filed; i.e., although misconduct was suggested in 26 e-mails, it was not substantiated. **Aug:** No conclusions reached between LANL finding and USGS/LLNL not finding ^{36}Cl in ESF.

2007 Apr: SNL completes analysis using MASSIF. With new data, MASSIF predicts 3 times more infiltration with more uncertainty. SNL replacement cost ~ $12.9 million; and investigation cost another ~$12.7 million. **Dec:** NWTRB concludes MASSIF represents parameter uncertainties better but did not consider all data previously used by the USGS and did not sufficiently account for evapotranspiration from bedrock fractures; thus, MASSIF less consistent with evidence of temperature and ^{36}Cl concentration.

A-3.3 Yucca Mountain Repository and Package Design

A-3.3.1 YMP Repository Design in Early 1980s

The design of the repository has varied considerably over the life of the project. Initially, the favored horizon for the repository was in the SZ, but arguments in the late 1970s and early 1980s for disposal of HLW in unsaturated alluvium prompted consideration of the UZ in the Topopah Spring Formation by June 1982. That same year, Sandia reported on some preliminary designs.

By 1984, Sandia had reported on borehole sealing methods; construction methods for exploratory shafts; and the exploration area for the repository, which was >200 m below the surface and >100 m above the water table. These latter criterion would control the vertical location for the next 25 yr. The early repository design used a stair-step design to remain horizontal and in the middle nonlithophysal welded tuff unit of the Topapah Spring Formation.

The 70,000 MTHM repository was 6 km^2 when using a design criterion to keep the rock temperature < 200 ^{o}C and thereby avoid alteration of zeolic tuff minerals in layers under the repository and limit the temperature rise at the surface to < 6 ^{o}C. A power loading of 14 W/m^2 was sufficient to keep rock temperatures < 100 ^{o}C on the floor a few meters to tens of meters away from the small canisters.

Both vertical and horizontal emplacement were under consideration during the mid 1980s. Vertical emplacement was in the floor of an 6.1 m wide by 6.7 m tall disposal drift with one canister placed in 0.7-m diameter borehole spaced every 2 to 8 m. Horizontal emplacement was in the walls of a 6.1 m wide by 3.7 m tall disposal drift with ~35 canisters per borehole spaced every 3 to 36 m. Although pillar emplacement involved seven times less excavation (97 Gg versus 650 Gg), floor emplacement was the default option.

A-3.3.2 YMP Package Design in Early 1980s

At the same time Sandia was developing preliminary layout designs for the repository in 1982, Lawrence Livermore was developing preliminary designs for HLW and CSNF containers based on drafts of proposed technical criteria in 10 CFR 60. By 1983, candidate materials for a canister in the salt, basalt, and tuff repositories included stainless steel and high-nickel alloys. The hole liner was to be carbon steel. Copper alloys were also evaluated for waste containers but were not as effective in the oxidized, unsaturated zone for the tuff repository as in the anoxic, saturated zone proposed for the Swedish repository.

The pour canisters for defense HLW waste were assumed to be 0.61 m in diameter and 3 m long; the pour canisters for commercial HLW were assumed to be 0.32 m in diameter and 3 m long; and the canisters for commercial SNF were assumed to be 0.65 mm in diameter and between 4.0 and 4.75 m long. A total of ~33,000 canisters were anticipated if the commercial SNF was not consolidated or ~18,000 if commercial SNF was consolidated at the repository surface facility by removing assembly hardware surrounding the fuel rods.

A-3.3.3 YMP Repository Design in Site Characterization Plan

Rather than stair step the repository, the repository design in 1988 Site Characterization Plan (SCP) followed the ~6^o dip of the middle nonlithophysal tuff unit and remained >200 m below the surface and ~180 m above the water table. The repository consisted of an access drift around the perimeter and three main drifts down the center of the repository to move miners and service equipment, radioactive waste, and tuff. Miners were to enter the repository through a shaft, but radioactive waste entered and tuff was removed via respectively 7-m and 7.6-m excavated ramps to the surface. The general configuration of the disposal panels was the same as envisioned in earlier. Waste emplacement both vertically in boreholes in drift floor and horizontally in the drift pillars was still under consideration. For floor emplacement, the SCP envisioned disposal drifts 6.7 m high and 4.9 m wide and spaced 38 m apart. For pillar emplacement, the SCP envisioned disposal drifts 3.8 m high and 6.7 m wide, 430 m long, and spaced 230 m apart. The design now envisioned co-mingling CSNF and HLW in drifts to allow a more consistent spacing down the drift and still keep the thermal power loading below 14 W/m^2. For floor emplacement, the spacing was 4.6 m between 7.6 m deep CSNF drill holes with 2.3 m for an occasional HLW drill hole. For pillar emplacement, the spacing was 21 m and long enough for 14 CSNF canisters with 10.5 m for an occasional drill hole for 18 HLW canisters. With this configuration, temperatures were above boiling around the canisters for ~300 yr.

A-3.3.4 YMP Package Design in Site Characterization Plan

The SCP specified a short-lived waste package design. However, the YMP was considering longer-lived packages. As noted earlier, Lawrence Livermore had examined high-nickel alloys. Furthermore, Weinberg, former director of Oak Ridge, proposed in hearings on NWPAA in 1987 that US adopt Swedish approach of developing long-lived disposal containers (<300,000 yr). Also, the NRC had recently issued a staff position in response to a DOE request for clarification that the 300 to 1000 yr package requirement in 10 CFR 60 was a minimum range, not a minimum lifetime and maximum credit allowance. Finally in 1991, DOE sponsored a workshop to explore package designs that lasted longer than 1000 yr. Ideas adopted included (a) multi-barrier materials to reduce uncertainty; (b) multipurpose canister (MPC) for storage, transportation, and disposal to reduce handling; and (c) package simplification to ease fabrication.

The SCP package design specified a 9.5-mm thick, 304 stainless steel container either 0.61 or 0.66 m in diameter and either 3 or 4.8 m long. The SCP assumed that the handling facility at Yucca Mountain would consolidate most assemblies by removing hardware such that either 6 PWR assemblies or 18 BWR assemblies could fit into a canister along with the removed hardware. For those assemblies that could not be disassembled, the canisters could accommodate either 3 PWR or 6 BWR intact assemblies.

The SCP pour canister design for HLW had not changed from that used in early designs; however, the SCP did specify use of a stainless steel overpack 0.66 m in diameter (same diameter as CSNF) and 3.2 m long to encase the pour canister to ensure known behavior of the waste container and to make handling more consistent between HLW and CSNF.

A-3.3.5 YMP Repository Design in Early 1990s

Shortly after 1993, the construction technique for the repository was changed from drill-and-blast to a tunnel boring machine (TBM) to reduce costs and minimized disturbance based on the recommendation of the NWTRB in 1990 and a subsequent alternatives study in 1991. Consequently, the concept of modular panels was abandoned and long disposal drifts, spaced 25.4 m apart, were planned that branched out from the main access drifts. Also, a south ramp was added and the incline of the ramps reduced to facilitate using a TBM.

Two additional changes to the repository design were proposed to reduce costs and obtain high waste disposal throughput. The first proposed design change was to place radioactive waste in large disposal packages directly in the drifts. With in-drift emplacement, the size of the disposal drifts could be reduced to 5.5-m in diameter (rather than 6.7 m high and 4.9 m wide in the SCP design) since drifts did not have to accommodate equipment to drill into the drift floor or pillars.

The second proposed design change, championed by Lawrence Livermore, was to double the heat load (i.e., 28 W/m^2 rather than 14 W/m^2 proposed in the SCP) to dry out the region around the repository for several thousand years rather than just several hundred years. Although the spacing between drifts was 25.4 m for both heat loads (consistent with a maximum 30% extraction ratio), the spacing between disposal containers was decreased for the higher heat loading. The doubling of the heat loading halved the size such that the entire repository easily fit west of the Ghost Dance Fault. The drifts were assumed to be backfilled with tuff gravel 75 yr after waste emplacement.

In September of 1994, YMP began excavating the 8-km long, 7.6-m-diameter exploratory studies facility (ESF) tunnel, which was to be the main access drift of the repository if authorized. Progress was initially slow but greatly improved by September 1995 after YMP consulted with industry and had enough money to modify the TBM and add a conveyer to remove excavated rock. To avoid influencing future seepage experiments, little water was used to suppress silica dust in the tunnel; however, silica dust levels eventually exceeded dust limits set by Occupational Safety and Health Administration (OSHA) and in September 1996 DOE had to stop excavation while it implemented a dust suppression program that included workers wearing full-face masks.

A-3.3.6 YMP Package Design in Early 1990s

Two basic package designs were under consideration in the early 1990s that corresponded to the two emplacement schemes. The first waste package design, used for vertical floor emplacement, was similar to the canister proposed in the SCP except constructed of high-nickel Alloy 825, corrosion resistant material (CAM). By 1993, YMP had decided not to consolidate PWR and BWR assemblies and so the canister was envisioned to hold 4 PWR fuel assemblies, 10 BWR fuel assemblies, a hybrid combination of 3 PWR and 4 PWR assemblies, or a HLW stainless steel pour canister.

The second waste package design, used for in-drift horizontal emplacement, was much larger (1.75 m in diameter and 4.91 m long). The package used a multi-barrier design constructed of an layer of 9.5 mm Alloy 825 as a inner corrosion-resistant material (CRM), and an outer layer of 100 mm A516 mild steel for structural strength and as a corrosion allowance material (CAM). As proposed, the in-drift waste package held either 21 PWR assemblies, 40 BWR assemblies, or several HLW pour canisters.[Wilson et al. 1994, Figure 4-2] Hence, the volume of expensive alloy 825 was reduced somewhat by in-drift disposal.

For in-drift disposal, the DOE envisioned using a 25-mm thick, 304 stainless steel handling canister that would be loaded and sealed at the utility or DOE site. The handling canister would be overpacked for transportation (transportation cask), for storage (e.g., dry storage cask), and for disposal (disposal package); hence, the name multi-purpose canister (MPC). As championed by the NWTRB, [NWTRB 1991a; NWTRB 1992b] use of an MPC would eliminate the need to directly handle CSNF assemblies or HLW canisters anywhere other than at the utility or DOE storage site. The range in lengths of CSNF assemblies and DSNF assemblies and the limited crane capacity (75-ton vs. 125-ton) or rail access at some reactor sites implied that several MPC sizes would be needed.

A-3.3.7 YMP Repository Design in Viability Assessment

Construction of the ESF was completed in 1997. In 1998, construction of the enhanced characterization of repository block (ECRB) cross drift, championed by NWTRB, was started and completed 15 to 20 m above the elevation of the future disposal drifts.

As required by Congress, a more complete design was provided for Viability Assessment. For the Viability Assessment, the repository block was defined as that volume of tuff 100 m above the current water table, 200 m below the surface, 120 m west of Ghost Dance fault, and 60 m standoff distance from other major faults. The repository block included a small extension to the north of North Ramp for disposal drifts. The repository was designed horizontal primarily in the lower lithophysal unit but with a small fraction above in the middle nonlithophysal unit and even smaller fraction below in the lower nonlithophysal unit. A moderately temperature repository concept was used (i.e., 21 W/m^2 when considering only CSNF or 18.7 W/m^2 when also considering the 7000 MTHM of HLW. The drift spacing was 28 m (an extraction ratio <20%) to maintain the drift wall temperature < 200 ^oC.

Package spacing between hot CSNF packages was large and varied between 10.6 and 8.9 m. Every third or so CSNF package a cool co-disposal or DSNF package might be placed between two CSNF packages and in this case spacing between packages was reduced to ~2.3 m. To accommodate 10,213 packages for 70,000 MTHM at this thermal loading, ~107 km of disposal drift length was anticipated, which translated into a ~105 drifts. The area of the repository was ~3 km^2. No backfill was planned because of operational difficulties and concern that the backfill would increase temperatures inside the package to above 350 ^oC and, thereby, promote cladding damage.

A-3.3.8 YMP Package Design in Viability Assessment

Along with the repository design, a more complete design and description of the proposed manufacturing process for waste package was provided for the Viability Assessment. Congress in October of 1995, had stopped development of the 25-mm thick stainless steel MPC handling canister because of cost concerns for transportation, potential added handling costs to utilities including uncertainty in whether DOE or utility had responsibility for controlling acquisition/loading/testing/sealing the container, and perceived lack of fairness in bidding among potential vendors since one vendor had been involved in scoping calculations for DOE. The major change in package design was replacing the inner 20-mm Alloy 825 layer with Alloy 22 to increase life.

As alluded to in the previous section, DSNF was included in the Viability Assessment. DSNF and HLW were envisioned to be mostly co-disposed in 1663 packages with the remaining DSNF disposed in 883 packages. Co-disposal of usually one DSNF canister with 5 HLW canisters offered the advantage of greatly reducing the need for criticality control inside the package since the fissile mass of DSNF was limited. However, sufficient HLW and DSNF canister of the correct length needed to be available when packaged for disposal at the repository (i.e., the concept directly linked DSNF with HLW). Furthermore, the concept of co-mingling the cool DSNF/HLW packages with hot CSNF packages to maintain more uniform repository temperatures linked construction schedules for treatment and packaging at DOE sites and shipping schedules of all three waste types especially if insufficient storage space existed at the repository. Discrepancies existed between anticipated needs and availability of a sufficient number of HLW canisters and more of the operational details were completed for the license application.

A-3.3.9 YMP Repository Design in Site Recommendation

For the reference design for the site recommendation, the disposal area was ~4.6 km^2 and consisted of a combined disposal drift length of ~60 km. Because of concerns of pooling water above the repository during the first 1000 yr, the spacing between drifts was increased to 81 m to allow water drainage ("shedding") between the drifts. Also, the maximum initial heat load of the packages was set at 11.8 kW/pkg (achieved through blending of waste at the site).

Based on a License Application Design Study (LADS) conducted in the winter of 1999,[CRWMS M&O 1999] titanium drip shields were added to provide a second engineered barrier component while the packages were hot and more susceptible to localized corrosion. To create a capillary barrier, backfill was also considered as an option but its use was not seriously contemplated. Although not an issue with small vertically emplaced packages, backfill insulated the waste packages and promoted high internal temperatures for the large horizontal packages that could cause premature failure of CSNF cladding during the first 1000 yr after emplacement. Because of concerns that the concrete might adversely alter the pH of seeping water, the ground-control was changed from precast concrete liners to steel welded wire fabric with grouted rock bolts. In addition, the spacing between containers was reduced to 0.1 m to promote more uniform heating of the repository drift regardless of the individual differences in radioactive decay heat between containers. The LADS noted that a cooler repository could be produced by aging waste before emplacement, by a long period of ventilation after emplacement, or by increasing the space between packages.

A-3.3.10 YMP Package Design in Site Recommendation

Earlier analysis and LADS had shown the limited value of the carbon steel corrosion allowance layer of the package in a hot, humid environment. Hence, the design for the Site Recommendation switched the layers: the 20-mm thick Alloy 22 was now the outer layer and steel was the inner layer. Since the inner layer was now only for structural strength, the inner layer thickness was decreased to 50 mm. Also, the inner layer was changed to 316NG stainless steel to eliminate concerns with “oxide-wedging” associated with carbon steel. Shrink fitting of the outer barrier was abandoned to avoid tensile stresses that might increase likelihood of stress corrosion cracking. Also, an inner lid of Alloy 22, 10 mm thick, was added in addition to the outer 25 mm thick lid and the lid design modified to mitigate residual stresses. Adding a second 10 mm thick lid decreased the probability that a crack would penetrate through both lid welds and thereby reduced the probability of early waste package failure to such that it was screened out.

A-3.3.11 YMP Repository Design in License Application

For the license application, the repository layout shifted to the northwest to make use of more area north of the north ramp. The layout also divided the repository into 5 panels with reduced but more uniform disposal drift lengths. The use of panels, somewhat akin to early designs, allowed disposal without construction of the entire repository perimeter drift and ventilation system, which was more consistent with annual appropriations by Congress. The panel design also offered some flexibility in optimizing the layout with changes in waste forms. The disposal drifts were still surrounded by and connected to access drifts, which were, in turn, connected to ramps and air intake shafts that lead to the surface. For PA-LA, 11,629 waste packages emplaced horizontally end-to-end in the drifts, with a gap of <0.1 m, were model. No backfill was placed in the disposal drifts. The ground-control was steel welded wire fabric with friction rock bolts since grouted rock bolts might change the pH of seeping water.

Disposal of large packages inside the drift to save excavation costs and increase waste disposal throughput greatly increased modeling complexity necessary to evaluate the influence of events and processes on disposal system performance that took a number of years to fully resolve. For the nominal behavior modeled in the PA-93 and PA-95, both of which studied the performance implications in drift disposal, there was not much performance difference. The in-drift disposal method did increase the surface area available to intersect percolating water under nominal behavior, but this effect was generally small. While disruptive events such as seismic ground motion and volcanism, were equally possible for floor and in-drift emplacement, the complexity of modeling potential disruption was greater for in-drift disposal. For example, the influence of igneous intrusion for floor disposal was confined to heating the drift (in addition, to ejection of few canisters), while the influence of igneous intrusion on in-drift disposal extended to engulfing all the packages in PA-LA as magma could flow down all the drifts since backfill was omitted. For seismic ground motion, the effects on in-drift disposal included rockfall damage and packages hitting other packages and objects in the drifts. The most obvious change in modeling complexity was the presence of a large cavity such that some of flow percolating through fractures became drips, thermal convection occurred, and thermal gradients could cause airflow down the drifts. Even criticality control became more onerous in that seven times as many assemblies were in one container such that taking credit for the burn-up of fissile uranium and creation of fission products and actinides became an attractive concept to use to more easily dismiss the possibility of criticality as packages degraded.

A-3.3.12 YMP Package Design in License Application

Refinement of the manufacturing process, method of loading, and handling attachments occurred for the waste package after PA-SR. A major change for PA-LA, which influenced performance under seismic loads, was decision in January 2006 to use a 25-mm thick stainless steel Transportation, Aging, and Disposal (TAD) handling canister for CSNF. The motivation for the TAD was the complexity of the task of designing and subsequent high-cost of a surface facility for handling bare assemblies at the repository at the rate and total amount required.[35] Besides a stainless steel exterior, the TAD used stainless steel for internal support baskets. The canister had a massive 380-mm thick lid. Use of a canister that was loaded and welded close at the utility eliminated handling assemblies whenever transporting, storing, or disposing of CSNF; however, use of such a large canister reduced future operational flexibility and, thus, forced some decisions on disposal or storage, such as criticality control, to be made prior to the first shipment of CSNF. To keep the initial package heat load at 11.8 kW/pkg, storage pads for up to 21,000 MTHM were planned at the repository to cool the waste prior to disposal because (1) waste blending at the repository to provide more uniform heat loads was no longer possible when using a TAD, and (2) shipping hot waste might be in the best interest of a utility (a utility was allowed to ship any waste more than 5 yr old according to the Standard contract set in 1983).

[35] The use of handling containers (i.e, TADs) to reduce the handling of assemblies is not necessarily confined to in-drift disposal in that handling canisters could be used for floor disposal. Furthermore, the number of necessary trips might not increase substantially if the transportation cask could accommodate several smaller TADs.

A-3.3.13 Summary of YMP Repository Development

1963 Dec: Idaho National Lab (INL) begins oxidation of liquid high-level waste (HLW) to form solid calcine for storage.[Perge 1982]

1966 West Valley, NY reprocessing plant begins operation; continued operating until 1972; cleanup begun in 1980.

1970 Aug: Atomic Energy Commission (AEC) states all commercial HLW must be solidified within 5 yr and delivered to a repository within 10 yr.

1974 Sep: AEC issues draft EIS on managing HLW that emphasizes reprocessing of spent nuclear fuel (SNF) and surface storage.

1976 Oct: President Ford defers reprocessing in favor of once–through fuel cycle.

1977 Apr: President Carter indefinitely defers reprocessing of commercial SNF (CSNF) because of concerns about nuclear proliferation. He also opposes funding reprocessing at Barnwell, SC and Fast Breeder Reactor at Clinch River, TN. **Oct:** President and Department of Energy (DOE), successor to AEC, propose away-from-reactor (AFR) storage for SNF.

1981 President Reagan withdraws AFR proposal and lifts ban on reprocessing CSNF. **Oct:** DOE cancels all migration tests in Climax granite.

1982 Jan: Sandia National Labs (SNL) begins seal development seals for shafts and boreholes at Yucca Mt. **Apr:** DOE forms Ad Hoc Working Group to evaluate exploratory studies facility (ESF) shaft designs at Yucca Mt; group selects conventional drill/blast mining for construction. **Jun:** Drilling begins at G-4, proposed location of ESF shaft. **Jul:** US Geological Survey (USGS) recommends ~350-m thick welled Topopah Spring Formation (TSw) in unsaturated zone (UZ). **Aug:** Conceptual **(**Title I) design of ESF completed. **Oct:** Conceptual design of surface and subsurface facilities completed. **Dec:** SNL reports on preliminary designs for a tuff repository. Lawrence Livermore National Lab (LLNL) reports on preliminary design for SNF waste package. Based on drafts of 10 CFR 60, DOE requests more robust waste package for disposal.

1983 Jan: In *Nuclear Waste Policy Act* (NWPA), Congress states (a) DOE SNF (DSNF) and defense HLW (DHLW) will go to commercial repository unless President objects; (b) creates Nuclear Waste Trust fund via 0.1¢ *fee* on every kW-hr utilities produce, (c) requires DOE to contract with utilities to dispose waste to provide disincentive for administration policy changes. **Mar:** 3-yr storage of SNF at Climax completed; all 11 SNF canisters removed; one cut open and 2 rods removed for testing; rock temperature and displacements monitored for 6 months. **Aug:** Inclined access ramp for waste and tuff adopted for repository. Construction of ESF scheduled to begin in 1985 pending completion of requirements imposed by NWPA. Several studies completed on comparison of (a) vertical shaft and inclined access ramp, and (b) vertical floor and horizontal pillar emplacement. **Sep:** LLNL reports on package design using stainless steel and high-nickel alloys; same design proposed for salt, basalt, and tuff. Tests started to evaluate geochemical conditions around packages in UZ. In response to Swedish concept, DOE asks LLNL to evaluate copper alloys for packages. LLNL reports on degradation rates of CSNF and HLW glass. Los Alamos National Lab (LANL) reports on potential of colloidal Pu.

1984 SNL reports on area suitable for tuff repository. **Mar:** LLNL makes plans to evaluate CSNF cladding. **May:** LLNL reports on geochemical tuff/water interaction tests using J-13 well water. **Aug:** SNL reports on repository sealing concepts and ESF construction methods; also, seals in G-4 and UE-25p#1 are cored to determine permeability, porosity, and density. **Sep:** LLNL reports on corrosion mechanisms of CSNF cladding. SNL completes stair-step design to keep repository horizontal. **Nov:** LLNL and Argonne National Lab (ANL) report on leaching tests on HLW glass, which include gamma field to evaluate radiolysis influence. Hanford Engineering Development Laboratory completes plan for corrosion experiments of CSNF cladding for LLNL.

1985 SNL compares vertical floor, horizontal pillar, and horizontal in-drift emplacement. SNL studies 2-phase approach for excavating repository; modifications to 1984 design include use of two ramps at north end rather than one. President Reagan approves disposal of DOE SNF and defense HLW with CSNF. **Dec:** Gramm-Rudman-Hollings Act applies to nuclear waste trust fund even though from *fee* for service (not tax), which prevents large annual budget increases for characterization or construction at YMP.

1986 May: Environmental Assessment (EA) for Yucca Mt assumes a 5 km^2 repository mostly 300 m below the surface and between 170 m and 210 m above the water table with heat load of 14 W/m^2. Both floor and pillar emplacement are considered. Construction via drill/blast and tunnel boring machine (TBM) are considered.

1987 Apr: In hearings for NWPA amendments, former Director of Oak Ridge National Lab, Weinberg, proposes that US adopt Swedish approach of using long-lived packages (<300,000 yr).**Apr & Nov:** Pacific Northwest National Lab (PNNL) reports on radionuclide release from bare CSNF in open- and closed-vessel, batch tests. **Sep:** In 6 volumes, SNL describes repository design to be included in Site Characterization Plan (SCP). **Dec**: In *Nuclear Waste Policy Amendments Act* (NWPAA), Congress establishes Nuclear Waste Technical Review Board (NWTRB) to advise DOE and Congress.

1988 Feb: ANL reports on degradation of HLW glass during gamma irradiation. **Dec:** DOE publishes 9-volume SCP with ~300 activities for every conceivable surface-based, underground, and laboratory test, including modeling, but presents no ranking of studies. The 5.6 km^2 repository follows the ~6^o down dip, and remains >200 m below the surface and <183 m above water table. Both floor and pillar emplacement still considered. Design co-mingles CSNF and HLW to keep uniform heat load of 14

W/m^2. The SCP assumes CSNF is disassembled so that 6 PWR or 18 BWR assemblies fit into canister.

1989 Sep: ANL reports secondary U minerals formed in drip tests on CSNF.

1990 Mar: First NWTRB report (a) criticizes plan to use drilling/blasting to excavate 2 ESF shafts; (b) suggests replacing one shaft with an inclined ramp, which would cross several faults and tuff units; (c) suggests excavating an east-west drift across strata. **Apr:** In response to NWTRB and others, SNL explores alternatives to ESF shafts. **May:** In a staff position, NRC states DOE may take credit for a waste package lasting longer than 1000 yr (i.e., 300-1000 yr requirement in 10 CFR 60 minimum range). **Sep:** SNL concludes ESF alternative study and recommends 3 options out of 34: (a) inclined drifts to repository and lower Calico Hills (CHn) tuff; (b) inclined drift to repository and shaft to CHn; or (c) 1 inclined drift and 1 shaft to repository and 1 shaft to CHn.

1991 May: In 3rd report, NWTRB (a) praises ESF alternative study; (b) recommends DOE evaluate other alternatives including the influence of different power loads; (c) continues to request DOE minimize handling of waste during transportation, storage, and disposal. **Jun:** DOE sponsors workshop to explore package designs that last > 10^3 yr. Ideas adopted include (a) multi-barrier materials to reduce uncertainty; (b) multipurpose canister (MPC) to reduce handling; and (c) package simplification to ease fabrication. **Dec:** In response to $30 million funding cut for FY92, DOE curtails engineered barrier system (EBS) study, postpones EBS design until FY93, and postpones boring ESF until FY94.

1992 Congress ratifies *Strategic Arms Reduction Treaty* (START I), which reduces offensive arms by 30%. In response, DOE halts reprocessing and proposes direct disposal of DSNF. **May:** ANL reports that HLW glass forms colloids as it degrades. **Dec:** In 6th report, NWTRB urges DOE to conduct system study of storage, transportation, and disposal and consider MPCs with high capacity and self shielding.

1993 DOE changes construction method to TBM with mildly inclined access drifts. **Mar:** LLNL suggests using a high heat load to dry tuff around drifts to enhance repository performance.

1994 Apr: SNL completes guidelines for when, where, and how to seal boreholes. **Jun:** YMP specifies assumptions for package and repository design: (a) in-drift emplacement; (b) drift designed for 100 yr retrievability; (c) no backfill used; (d) repository designed for both a high 22-28 W/m^2 and low 7-10 W/m^2 heat load; (e) package lifetime >10^3 yr; (f) package for high-temperature repository has inner layer of Alloy 825 and outer layer of mild steel and for low-temperature repository has inner layer of Alloy 825, middle layer of mild steel, and outer layer of Monel 400; (g) package transported by rail underground; (h) no self-shielding package; (i) burn-up credit considered for package criticality control; and (j) period of concern for criticality is 10^4 yr. DOE plans EIS on disposal options for surplus weapons-grade Pu because of START I. Options include use in mixed-oxide fuels (MOX), disposal with HLW; deep borehole disposal; and accelerator destruction of Pu. **Sep:** YMP begins boring 8-km long, 7.6-m diameter ESF using TBM; progress is slow. To avoid influencing seepage tests, little water is used to suppress silica dust. DOE decides to use a moderately high heat-loading (21 W/m^2) to save costs of boring ~200 km of drifts, which allows repository to fit west of Ghost Dance Fault.

1995 Apr: Boring progress improves after YMP has money to make modifications to TBM and add conveyer to remove rock. Boring of ESF averages ~26 m/day in Sep, Oct, and Nov. **Oct:** Congress stops MPC development because of uncertain cost for transportation, added handling costs to utilities, and perceived lack of fairness in bidding. **Dec:** Boring of ESF sets a world record of 218 m in 5 days.

1996 Feb: Boring slows to 15 m/day as TBM encounters unstable rock. **Sep:** Package corrosion tests begin at LLNL after DOE finds funds to complete corrosion facility. DOE stops TBM to suppress dust and require full-face masks because silica dust exceeds limits set by Occupational Safety and Health Administration (OSHA).

1997 Apr: Boring of ESF is completed.

1998 Feb: To increase package lifetime, DOE replaces Alloy 825 with Alloy 22. **Mar:** Boring of 2.8-km long, 5-m diameter enhanced characterization of repository block (ECRB) cross drift is started with smaller TBM from Super Collider project; ECRB is 15 to 20 m above the ESF and penetrates layer where majority of repository will exist. **Jun:** YMP starts constructing ¼-scale drip shield and package at Atlas facility in North Las Vegas. **Oct:** ECRB completed to Solitario Canyon fault. **Dec:** YMP begins License Application Design Selection (LADS) study to select repository and package design for the site recommendation (SR) and license application (LA).

1999 Tests start on ¼-scale drip shield and package to evaluate condensation under drip shield and amount of water drawn under invert. **Apr:** YMP completes LADS. Ti drip shield added to protect package while hot and susceptible to localized corrosion. Alloy 22 switched to outer package layer; stainless steel used for inner support layer. Waste blended to 11.8 kW/pkg and packages spaced 0.1 m apart to keep temperatures similar. Drift support changed from concrete to steel mesh, ribs, and rock bolts. Drift spacing increased to 81 m to lower pillar temperatures and allow water to pass through repository. **Aug:** In draft EIS, various repository sizes are considered (70,000 to 105,000 MTHM).

2000 Aug: Nevada scientists present conditions under which Alloy 22 is susceptible to corrosion to NWTRB (traces of Pb, As, and Hg at high temperature).

2002 Feb: In deference to Russia and lack of budget, DOE rejects option to dispose 50 tonnes of surplus Pu at Yucca Mt and selects option to convert to MOX fuel.

2003 Repository moved farther north with 5 panels to increase flexibility in construction and waste forms; About 49 MTHM of CSNF has been generated; ~2500 MTHM of DSNF has been generated, which includes 65 MTHM of Naval SNF. The waste is stored in 39 states at 131 sites.

Nov: NWTRB comments that YMP has not convincingly screened out localized corrosion on drip shield or package because: (1) deliquescence could produce corrosive water high in Cl^- and lacking nitrate; (2) corrosive seepage water could be present; and (3) the thermal conditions in 1st 1000 yr are not well modeled since (a) thermal conductivity may be too high, (b) insulation of the package by rockfall is not modeled, and (c) the effects of natural ventilation not modeled. Scientists report that U may form studtite that could trap Pu and Np and prevent radionuclide migration.

2004 May: YMP present test results to NWTRB that show no localized corrosion induced by salt deliquescence for hot repository; the new experiments differ from previous work.

2005 Oct: Prompted by high cost of surface facility for handling high volume of assemblies, DOE resurrects Transport, Aging, and Disposal (TAD) canister that is loaded at a reactor. Design of surface facilities made modular with smaller, simpler facilities for receipt, wet handling, and closure to allow flexibility in use and enlargement. Also, concrete pads added with option to expand to 21,000 MTHM for aging hot CSNF and general buffer storage.

2006 Jan: Acting Director Golan announces a new path: implement TAD canister for CSNF; and designate SNL as lead laboratory to coordinate repository science and provide license defense during NRC hearings. In audit, NRC finds that LLNL never calibrated its measurements of humidity in corrosion experiments; DOE stops work at LLNL.

2007 Jun: DOE announces design requirements for TAD canisters; ~7800 TAD canisters, to be built by various vendors, are needed to dispose CSNF.

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