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Past Approaches for Spent Nuclear Fuel, Transuranic, and High-Level Waste Disposal in the United States—Part 2: Siting Process, Staged Development, and Public Preferences

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Past Approaches for Spent Nuclear Fuel, High-Level, and Transuranic Waste Disposal in the United States— Part 2: Site Selection, Staged Development, and Public Preferences

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ABSTRACT

This report presents pertinent aspects of the ~50-year United States experience in siting a mined geologic disposal repository for spent nuclear fuel (SNF), transuranic (TRU) waste, and high-level radioactive waste (HLW) as related to site selection and the staged process for site investigations as specified in the *Nuclear Waste Policy Act of 1982* and generic and site-specific regulations of the US Department of Energy (DOE), US Environmental Protection Agency (EPA), and US Nuclear Regulatory Commission (NRC). The roles of the Environmental Impact Statement and guidance in international consensus standards by the International Atomic Energy Agency are also mentioned. The focus is on siting and developing the Waste Isolation Pilot Plant, an operating repository for TRU waste from atomic energy defense activities, and the proposed Yucca Mountain repository for commercial SNF and HLW. In the social dimension, the role of institutional stakeholders is described. Past national surveys related to waste management options for storage and disposal provide insight on public preferences of other stakeholders. The descriptions are intended to help other countries more fully understand the stages adopted for siting and developing repositories in the United States.

Keywords: geologic repository site selection, high-level radioactive waste disposal; safety assessment; performance assessment; public surveys

PREFACE

This report collects the historical progression of siting activities at the operating Waste Isolation Pilot Plant (WIPP) and the proposed Yucca Mountain (YM) Repository. This report categorizes the activities by the general steps of siting to allow more direct comparisons between the YM and WIPP repository programs. Hence, information is occasionally presented out of chronological order. The YM Repository siting activities derive primarily from *Milestones for Selection, Characterization, and Analysis of the Performance of a Repository for Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain,*[1] which in turn summarizes activities described in ten journal articles in a special issue of *Reliability Engineering System Safety* on the performance assessment for the Yucca Mountain license application.[2-11] The WIPP siting activities derive from *Milestones for disposal of radioactive waste at the Waste Isolation Pilot Plant (WIPP) in the United States,*[12] which in turn summarizes activities in a journal article for a special issue of *Reliability Engineering and System Safety* on the performance assessment for WIPP.[13] These sources provide much more information than is compiled here.

The motivation for this report was the desire of International Atomic Energy Agency (IAEA) to document experiences of advanced disposal programs and provide insight on site selection for member states beginning siting activities for geologic disposal facilities. For its project, IAEA asked advanced disposal programs to provide a short description of its experience. A short description proved difficult since the United States has sited two deep geologic repositories for radioactive waste: WIPP, an operating repository in bedded salt for transuranic waste from defense atomic energy activities and the proposed YM repository in volcanic tuff. The proposed YM repository program is more widely recognized in the international community. Furthermore, the *Nuclear Waste Policy Act of 1982*[14] established a clear framework for siting a repository for disposal of commercial spent nuclear fuel and high level waste. Although WIPP did not have federal legislation that specifically listed siting steps, it followed the same siting stages as the YM repository program. This report explicitly describes these similarities to provide background for countries beginning siting efforts.

A companion report, *Past Approaches for Spent Nuclear Fuel, High-Level, and Transuranic Waste Disposal in the United States—Part 1: Safety Criteria and Treatment of Uncertainty,*[15] discusses the safety criteria that were adopted as the United States was selecting the WIPP site in bedded salt and YM repository in volcanic tuff.

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CONTENTS

FIGURES

TABLES

ACRONYMS AND INITIALISMS

ACNW	NRC Advisory Committee on Nuclear Waste
AEC	Atomic Energy Commission; formed by *Atomic Energy Act of 1946*[16] a forerunner of ERDA, DOE, and NRC
AMR	analysis model report; reports supporting the YM-PA-SR, YM-SSPA, YM-PA-04, or YM-PA-LA analysis
ASLB	Atomic Safety Licensing Board of NRC
BRC	Blue Ribbon Commission on America's Nuclear Future, formed by Presidential direction in 2010 to review current US waste management policy
BRWM	Board of Radioactive Waste Management, a permanent board formed in 1968 in the National Research Council of NAS
C&C	Consultation and Cooperation Agreement between DOE and State of New Mexico required in 1979 authorizing legislation for WIPP[17]
CCA	Compliance Certification Application to EPA in 1996 to evaluate compliance with 40 CFR 191
CFR	Code of Federal Regulations
CISF	concentrated interim storage facility
DOE	US Department of Energy, formed by *DOE Organization Act*,[18] replaced the Energy Research and Development Agency (ERDA).
DOE-EM	Office of Environmental Management in DOE
DOI	US Department of the Interior
DOT	US Department of Transportation
EA	Environmental Assessment for *Nuclear Waste Policy Act of 1982*.[14] This designation in NWPA can cause confusion since it was not related to an EA defined in 40 CFR 1501 regulations promulgated to implement NEPA.
ECRB	enhanced characterization of the repository block drift bored to Solitario Canyon Fault at Yucca Mountain between March and October 1988
EEG	Environmental Evaluation Group, formed in 1978 by State of New Mexico from funds provided by DOE to conduct independent technical evaluation of WIPP. *The National Defense Authorization Act, Fiscal Year 1989* assigned administrative oversight of EEG to the New Mexico Institute of Mining and Technology
EIS	Environmental Impact Statement for major federal projects required by *National Environmental Policy Act of 1969* [19]
EPA	US Environmental Protection Agency
EPRI	Electrical Power Research Institute
ERDA	Energy Research and Development Agency, a forerunner of the DOE, was formed as an agency of the executive branch by the 1974 *Energy Reorganization Act* and replaced portions of AEC.[20]
FEP	features, events (natural and anthropogenic phenomena of short duration), and processes (natural phenomena of long duration)
HLW	high-level (radioactive) waste is "…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…" [14, §2(12)] Although not used in this manner in this report, general articles regarding radioactive waste often use the term HLW to imply any combination of SNF and HLW that require disposal in a deep, geologic repository. NRC includes SNF in its definition of HLW.

IAEA	International Atomic Energy Agency, Vienna, Austria was established in 1957 as an autonomous agency by General Assembly of the United Nations to foster research and development of the peaceful uses of nuclear energy.
IRG	Interagency Review Group on Nuclear Waste Management, formed by President Carter in 1978 on the recommendation of Secretary of Energy Schlesinger. The group consisted of 14 agencies including DOE
LSN	Licensing Support Network for documents related to YMP and ASLB hearings
M&O	Management and Operating (contractor for DOE)
MRS	monitored retrievable storage proposed in NWPA (see also RSSF and CISF)
MTHM	metric tons of heavy metal initially placed in nuclear reactor (legal and regulatory mass unit)
NAS	National Academy of Sciences, nonprofit society of distinguished scholars engaged in scientific and engineering research. NAS was chartered by Congress in 1863 with the mandate to advise the federal government on scientific and technical matters. Currently, the National Academy also consists of the National Academy of Engineering and the National Institute of Health. The National Academy National Research Council (NA/NRC), which is composed of several standing committees and boards of National Academy members and nominated scientists, conducts the studies requested by Congress. Keeping with tradition, this report uses the NAS designation for studies conducted by NA/NRC.
NASA	National Aeronautical and Space Administration
NEPA	*National Environmental Protection Act of 1969*[19] set environmental policy by requiring an environmental impact statement on all major federal projects.
NNSS	Nevada National Security Site (formally Nevada Test Site—NTS)
NRC	US Nuclear Regulatory Commission was formed in the 1974 *Energy Reorganization Act*[20] from portions of AEC
NWMO	Nuclear Waste Management Organization of Canada
NWPA	*Nuclear Waste Policy Act of 1982*[14]
NWPAA	*Nuclear Waste Policy Amendments Act of 1987*[21]
NWTRB	Nuclear Waste Technical Review Board, established by NWPAA, to advise Congress and DOE on radioactive waste management
NWTS	Nuclear Waste Terminal Storage; in the 1979, a mined, geologic repository was categorized as a storage option, and a repository was called nuclear waste terminal storage facility in the US. Storage referred to waste isolation and the ability to readily retrieve in the near-term during a pilot phase (hence, the name for WIPP), but with retrievability still possible after closure. Disposal was referred to waste isolation with no initial provision or intention for retrieval, such as deep borehole disposal
OCRWM	Office of Civilian Radioactive Waste Management (established by NWPA in DOE)
ORNL	Oak Ridge National Laboratory
PA	performance assessment, the process of assessing whether a system or component meets a set of performance criteria; for the US, the process is a stochastic simulation; the system is a deep geologic repository disposal system; the performance criteria are the long-term measures in the EPA post-closure environmental protection standard.
PAVT	PA Verification Test for EPA using their own assumptions for the spallings model and changes in distributions for 26 parameters with more pessimistic bias
PMA	performance margin analysis to assess conservative bias and margin of safety in YM-PA-LA
PRA	probabilistic risk assessment

QA	quality assurance
RCRA	*Resource Conservation and Recovery Act of 1976*[22], as used herein it also includes the *Hazardous and Solid Waste Amendments of 1984,*[23] such as the "no-migration" petition requirements.
RSSF	Retrievable Surface Storage Facility for SNF and HLW storage proposed in 1972 by AEC
Sandia	Sandia National Laboratories
SAR/LA	Safety Analysis Report for the License Application (for the proposed YM repository)
SCP	Site Characterization Plan completed in 1988 for evaluating YM repository as required by NRC regulations prior to extensive characterization of a geologic repository.
SNF	spent nuclear fuel, "…fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated by reprocessing."[14]
SPDV	site and preliminary design validation program for WIPP that was conducted after reaching repository depth to validate that room and drift dimensions in the preliminary design are stable.
SPM	System Prioritization Methodology that attempted to linked PA with decision theory to help prioritize WIPP experimental work for WIPP-PA-CCA
SR	site recommendation
SSPA	supplemental science PA
TRU	transuranic; all elements of the periodic table having atomic numbers greater than uranium 92. TRU waste is waste with a long-lived alpha activity > 100 nCi/g [24]. TRU waste, an EPA waste category is similar to the intermediate-level waste (ILW) category of the IAEA, which is to be disposed in a geologic repository.
TRUPACT	Transuranic Package Transport container for transporting TRU waste to WIPP for use on flatbed trailer; Model I designed as standard cargo container; Model II designed as pressurized hemispherical container
TVA	Tennessee Valley Authority
URL	underground research laboratory; YM and WIPP projects used both offsite and onsite URLs
USGS	US Geological Survey (agency of DOI)
US	United States
UZ	unsaturated zone
VA	viability assessment of YM repository requested by Congress in 1987
WMO	waste management organization (generic)
WIPP	Waste Isolation Pilot Plant (repository in southeastern New Mexico for TRU waste from atomic energy defense activities)
WIPP LWA	*WIPP Land Withdrawal Act* of 1992[25]
YM	Yucca Mountain located at boundary between Nellis Air Force Range and NNSS

1 INTRODUCTION

This paper summarizes aspects of the 50-year United States (US) experience in developing geologic disposal for transuranic (TRU) waste, spent nuclear fuel (SNF), and high-level radioactive waste (HLW) related to site selection, the staged process for investigation, the role of performance assessment, and public preferences. The intent here is to help other countries more fully understand the stages adopted for siting a mined geologic repository in the US. As evident from the summary, siting a mined geologic repository for radioactive waste is difficult, as with any complex social-political issue.

This paper presents the technical dimension described in generic and site-specific siting regulations of the US Department of Energy (DOE), US Environmental Protection Agency (EPA), and US Nuclear Regulatory Commission (NRC) and its relationship to the past, incompletely defined, social dimension, as specified in *Nuclear Waste Policy Act of 1982* (NWPA).[14;26] and its amendments for disposing commercial SNF and HLW.[14;21] NWPA and regulations resulted in a proposed repository at Yucca Mountain (YM) in Nevada.

This paper also presents the technical and social dimension for the Waste Isolation Pilot Plant (WIPP), a geologic repository in 600-m thick bedded salt in southern New Mexico for TRU waste produced from atomic energy defense activities.[17] WIPP was sited under administrative procedures in the 1970s. Yet, the procedural steps set up for commercial SNF and HLW under NWPA coincide with what was followed for WIPP. Furthermore, some siting activities at WIPP influenced NWPA and DOE siting guidance. Finally, the interaction with the State of New Mexico and the public at WIPP more closely follows stakeholder[a] interactions that have occurred internationally when siting repositories.

In 2012, the Blue Ribbon Commission on America's Nuclear Future (BRC) completed its review of the current US policy for storage, reprocessing, and disposal of SNF and HLW. BRC recommended a collaborative approach to siting radioactive waste management facilities, which had been followed somewhat for WIPP (i.e., developing a social dimension of identifying and supporting potentially willing host states and communities).[26, p. 118]

The suggested requirements of the International Atomic Energy Agency (IAEA) are also noted. These IAEA recommendations are an international consensus of member states that include the US. Although the US experience is reflected in the IAEA recommendations, IAEA recommendations provide a broader perspective since they include experience from other countries that have successfully sited repositories for SNF/HLW geologic disposal such as Finland, Sweden, France, Canada, and Switzerland.

Results from national public surveys pertinent to siting storage and disposal facilities are also presented to set the stage and provide additional insight (Fig. 1). For example, on average, the US public prefers that nuclear power continue to provide 20% of electrical power over the next 20 years in a 2017 national survey even though, on average, the public prefers to dramatically increase the share of electrical power coming from renewables (wind, solar, hydropower, geothermal) and to dramatically decrease the share coming from fossil fuels.[29]

To maintain nuclear power at 20%, new reactors must be built to replace those closing, which, in turn will increase the amount of commercial SNF that must ultimately be disposed. In another survey, ~56% of the public perceives nuclear power as a high benefit even though it also perceives it as high risk,[29] which highlights the importance the public places on siting approaches.

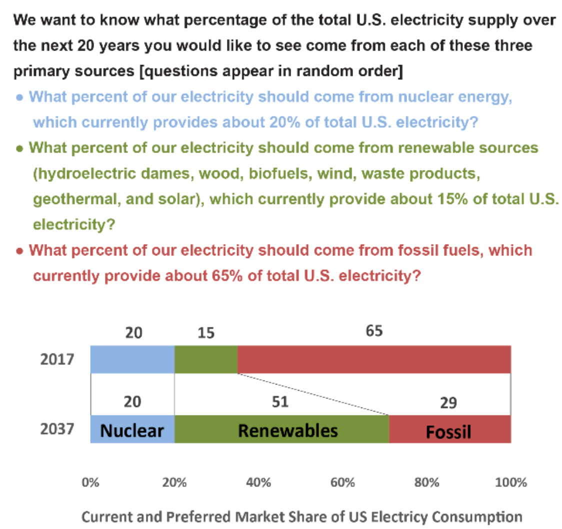

Fig. 1. Current market share of total US electricity consumption and average public preferred market share in next 20 years for nuclear power, renewables, and fossil fuel in 2017 national survey.[29, Figure 2]

The public has provided general preferences for management of radioactive waste from nuclear power. For example, in 2011 and again in 2016, the public was asked their preference (on a scale from 1 for strongly oppose to 7 for strongly support) for 3 storage/disposal choices for commercial SNF: (1) surface storage with ready recovery and retrieval; (2) mine-like repositories with recovery difficult but retrieval still possible; and (3)

[a] Herein we use the IAEA definition of a stakeholder as "anyone who feels impacted by an activity, whether physically or emotionally."[27] A more general and related term is "interested party."[28]

deep borehole disposal with very difficult recovery and retrieval (Fig. 2).

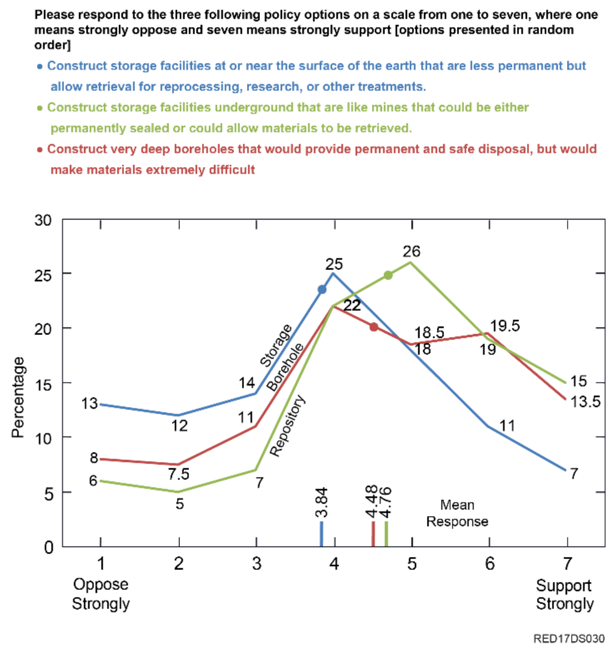

Fig. 2. When presented with three waste options for managing spent nuclear fuel, US public support is greatest for mine-like repositories and least for continued surface dry storage in 2016 survey.[30, Figure 2-10;31]

In these choices, depth at which the radioactive materials are stored/disposed is indirectly related to waste retrievability. Public preference is greatest for geologic mine-like repositories (Fig. 2): 60% of the respondents supported the mine-like repository design in 2016 (63% in 2011). This preference for mine-like repositories is greater than either the 50% support for the deep-borehole design in 2016 (40% in 2011) or the 36% support for surface dry-storage in 2016 (34% in 2011). [b]

2 US POLICY ON RADIOACTIVE WASTE DISPOSAL

In the 1970s and early 1980s, the primary aspects of the radioactive waste disposal policy related to the siting process were set and included (1) US commitment to mined, geologic disposal, and (2) establishing the framework by identifying the institutions to (a) implement this commitment, (b) set standards, and (c) regulate, which were respectively the DOE, EPA, and NRC (Tables 1 and 2).

2.1 Exploring Strategies for Nuclear Waste Management

In 1955, the Atomic Energy Commission (AEC), precursor to DOE, asked the National Academy of Science (NAS) to examine disposal options for HLW. In 1957, NAS recommended HLW disposal in salt as the best option to consider.[32] Shortly thereafter the US Geological Survey (USGS) began survey of salt formations in the continental US (Table 1).[33]

Nuclear waste management, particularly disposal, was placed on the "national agenda" in the 1970s. Attention to nuclear waste management was stoked in 1969, when the Rocky Flats plant for milling plutonium caught fire. The plan was to store the waste debris in Idaho but was opposed by the Senator Church of Idaho without a plan for disposal. AEC tentatively chose a salt mine in Lyons Kansas in 1970, where AEC had been conducting disposal experiments since the 1960s. By 1971, however, the mine site was deemed unsuitable because of a history of solution mining in the area and extensive state and local opposition (Table 1).

In 1972, AEC announced plans for a Retrievable Surface Storage Facility (RSSF) so that repository development could proceed more deliberatively, but EPA and anti-nuclear grouped claimed the RSSF was *de facto* permanent in comments on the Environmental Impact Statement (EIS). The criticisms prompted the newly formed Energy Research and Development Agency (ERDA and precursor to DOE) to abandon

[b] The survey provided background on the options prior to asking for a preference as follows:
Next, we want to consider the design of permanent storage and disposal facilities for the United States. Scientists and engineers are considering three general options: [3 options presented in random order]

- *Store spent nuclear fuel at or near the surface of the earth in concrete and steel structures. This allows monitoring and future retrieval of the spent fuel. It is considered to provide a safe means to manage the material for about a hundred years.*
- *Build mine-like storage facilities that are up to several thousand feet deep underground. These can be constructed to allow materials to be retrieved, or they can be designed to permanently block access in the future. They are suitable for storage over many thousands of years, and are expected to contain the material until it is no longer radioactive*
- *Drill multiple boreholes of about 1.5 feet in diameter and up to three miles deep. Spent nuclear fuel would be stored tin the deepest parts of the boreholes that are in bedrock. There is almost no chance that the material could migrate into the surface environment over many thousands of years and are expected to contain the material until it is no longer radioactive. The spent nuclear fuel would be extremely difficult to retrieve after the boreholes are sealed.*

consolidated surface storage, even as a near-term solution, and emphasize geologic disposal.

In 1976, California passed a moratorium on new nuclear reactors until the federal government demonstrated radioactive waste disposal. This moratorium provided an impetus for President Ford to order ERDA to expand the radioactive waste disposal program.[34] In response, ERDA setup the Nuclear Waste Terminal Storage (NWTS) Program to search for disposal sites in salt, shale, and granite media (Table 2).

In 1978, President Carter formed the Interagency Review Group (IRG) on Nuclear Waste Management, consisting of 14 agencies, to re-visit options for waste disposal (Table 2). In March 1979, IRG concluded that the recently formed DOE should[35] (1) implement mined geologic disposal, (2) use multiple barriers, (3) conduct site selection in a stepwise manner, (4) look for sites in variety of media in different regions of US, (5) not delay disposal even though storage was safe, and (6) demonstrate commercial SNF/HLW disposal at WIPP [c] The latter suggestion caused much consternation within the State of New Mexico, since WIPP had been administratively designated solely for defense waste from atomic energy activities since 1974.[13] In 1979, Congress defined the WIPP mission for geologic disposal of only TRU waste from defense activities (i.e., the State of New Mexico insisted on blocking the possibility of defense SNF disposal to prevent resurrection of commercial SNF demonstration/ disposal).[17]

In a scoping study, ERDA had identified eight disposal options in 1975: shallow burial, deep geologic repositories, deep boreholes, sub-seabed, cavities with rock melt, well injection, ice sheets, and space (Table 2).[37] DOE concluded in the October 1980 Programmatic Waste Management EIS that a mined geologic repository was the best option for disposal because [38, p. 1.9, p. 1.33 & Table 6.2.9] (1) status of geologic disposal science and technology was sufficient to begin implementation (i.e., state of knowledge sufficient to select appropriate sites, characterize, develop appropriate waste forms and, and monitor deviation from anticipated performance); (2) the concept conformed with existing national laws and international agreements (e.g., prohibition of Antarctica and ocean disposal and constraints on space disposal); (3) the concept was independent of future development and size of the nuclear industry (i.e., ability to dispose waste from current once-through and future advanced nuclear cycles incorporating reprocessing and transmutation of transuranic radioisotopes); (4) environmental effects were low during construction and operations; (5) radiological effects were low during operations; (6) radiological effects were low after repository closure (based on the ability to analyze reasonable expectation of 10^3-year containment and 10^4-year isolation through the use of multiple barriers); and (7) corrective or mitigating actions were possible (i.e., favorable characteristics of retrievability during placement, and continued recovery after disposal, though increasingly difficult). In addition, the 1980 Waste Management EIS suggested deep borehole disposal worthy of further consideration, provided drilling technology improved such that boreholes of sufficient diameter could be drilled to > 2-km depth.

2.2 Commitment to Geologic Disposal in Nuclear Waste Policy Act

After nearly four years of debate and hearings over the findings of IRG, the 1980 Waste Management EIS, and studies of the Congressional Office of Technological Assessment, Congress affirmed the concept of public ownership of HLW and SNF from defense and commercial activities, and the need for public stewardship of this waste, acting through the federal government, to safeguard future generations. In NWPA,[14] Congress chose geologic disposal for commercial and defense SNF and HLW as national policy (Table 2).

Committing to siting a geologic repository for radioactive waste has two important dimensions: a *technical* dimension of whether a potential site meets the criteria for safe storage or disposal (e.g., the evaluation of prospective sites for hydrological, demographic, seismic and other technical factors that may influence site selection), and a *social* dimension that describes the relationship between institutional stakeholders and how they interact with other stakeholders; particularly, the host community and state/tribe stakeholders hosting a disposal facility. The tables herein show the extensive activities in the technical dimension in parallel with the procedures for institutional stakeholders in the social dimension when siting WIPP and Yucca Mountain (YM) repositories.

2.3 Implementing Geologic Disposal

NWPA established the Office of Civilian Radioactive Waste Management (OCRWM) within the government cabinet DOE to implement this responsibility through the siting, construction, operation, and closure of a repository for commercial SNF/HLW.

When the safety analysis report for construction the license application (SAR/LA) for the proposed commercial YM repository was submitted in 2008 to NRC, the implementor consisted of the OCRWM who was responsible for (a) nominating and selecting sites

[c] IRG referred to the siting dimensions as technical suitability filters and social acceptability filters; these terms were adopted later by Nuclear Waste Technical Review Board (NWTRB), as discussed in §5.4.[36]

through its site selection regulations, (b) interactions with NRC, (c) SAR/LA and its legal defense, (d) selecting supporting institutions, and (e) budget. Contracted to the OCRWM were (1) a Management and Operating (M&O) contractor who was responsible for (a) facility design, (b) state permits, and (c) pre-closure compliance; and (2) Sandia National Laboratories (Sandia), which as lead national laboratory had oversight over site investigations, and responsibility for demonstrating post-closure compliance with NRC regulations. was supported by other DOE national laboratories and USGS. Although Sandia had been involved in all stages of site investigation, other organizational schemes were used prior to 2001. Specifically, the Management and Operating (M&O) contractor for DOE changed as new contracts were bid. Also, the relationship between the M&O, national laboratories, and DOE changed when the terms of the M&O contract changed; and the technical roles of the national laboratories and USGS evolved.

The *Department of Energy National Security and Military Applications of Nuclear Energy Authorization Act of 1980*,[17] directed DOE to implement the construction of the WIPP facility. When the certification application for WIPP was submitted in 1996, the implementor consisted of the DOE Office of Environmental Management (DOE-EM), Westinghouse as the M&O contractor, and Sandia as scientific advisor and lead national laboratory to characterize and demonstrate post-closure compliance with EPA regulations.

To ease the burden on the reader, especially those in the international community, we usually avoid identifying specific tasks for the various agencies and institutions supporting OCRWM or DOE-EM and simply refer to the implementor as DOE.

2.4 Regulatory Environment

NWPA set the regulatory framework for siting repositories (as more thoroughly discussed in a companion report[15]).

2.4.1 EPA Generic Standard Applied at WIPP

US regulatory agencies had been working to formulate a notion of safe disposal for SNF, HLW, and TRU waste since 1976, when President Ford directed EPA to develop radiation protection standards. In response to NWPA, EPA published its draft environmental standards in Title 40 Code of Federal Regulations Part 191 (40 CFR 191) for SNF, HLW, and TRU waste disposal in 1982[39] and promulgated its final standards in 1985 (Table 1).[24] EPA adopted quantitative, stochastic performance assessment (PA) to assess the cumulative release of radionuclides at 10^4 years 5 km from the repository,[24] The 5-km boundary curtailed some regional groundwater analysis at WIPP and focused site characterization for evaluating the suitability of WIPP closer to the site (as discussed in §6). The cumulative release measure was also used at the YM repository through 1995.

2.4.2 EPA Implementing Regulation for WIPP

In the 1992 *Waste Isolation Pilot Plant Land Withdrawal Act* (WIPP LWA),[25] Congress reiterated that WIPP was solely for TRU waste from defense atomic energy activities. The WIPP LWA also designated EPA as its implementing regulator (Table 1). EPA's implementing regulation, 40 CFR 194, promulgated in 1996,[15, Table 5;40] specified requirements for the monitoring/confirmation program, assessing frequency of human intrusion, and technical peer review of models/parameters of a PA.[d] The 40 CFR 191 Standard and 40 CFR 194 implementing regulation were successfully applied at the WIPP, which opened in 1999.

2.4.3 Regulation of Mixed Waste at WIPP

Because of the presence of hazardous chemical waste in the TRU waste for WIPP, EPA regulations implementing the *Resource Conservation Recovery Act of 1976*[22] (RCRA) and the *Hazardous and Solid Waste Amendment of 1984*[23] also apply to WIPP. EPA granted authority to the State of New Mexico to implement the regulations for WIPP in 1990;[41] thus ,WIPP has both a federal and state regulator.

2.4.4 NRC Generic Implementing Regulation

In 1981, NRC promulgated procedures in 10 CFR 60 for licensing a repository for SNF and HLW.[42] In accordance with the mandate in NWPA, NRC added technical criteria in 1983.[43;44] Although some procedural aspects of 10 CFR 60 have been applied (e.g., DOE produced and NRC reviewed the YM site characterization report/plan as required in 10 CFR §60.11),[45;46] the technical requirements in 10 CFR 60 have not (e.g., compliance with deterministic performance objectives for the waste package).

2.5 Nuclear Waste Policy Amendments

The selection process and aggressive schedule outlined in NWPA for identifying the first repository site

[d] Outside the US, a PA is referred to as a safety assessment. As described by IAEA, "Safety assessment has to include quantification of the overall level of performance, analysis of the associated uncertainties and comparison with the relevant design requirements and safety standards…" However, safety assessment does not necessarily imply a stochastic simulation that quantitatively includes aleatoric and epistemic uncertainty as implied in EPA and NRC regulations. Hence, we continue to use the term PA herein.

did not soothe fears of the states. Also, the search for a second repository site heightened anxiety in the eastern US and was indefinitely delayed by the executive branch in 1986.

In the *Nuclear Waste Policy Amendments Act of 1987* (NWPAA),[21] Congress greatly reduced the scope of the repository site evaluation program and chose the YM site, located at the boundary between the Nellis Air Force Range and the Nevada National Security Site (NNSS), from the three finalists as the only site to characterize for the first repository. This choice, in turn, fueled strong opposition in Nevada.[47]

2.5.1 YM-Specific EPA Standard

In the *Energy Policy Act of 1992*, Congress directed EPA to promulgate radiation protection standards specifically for the proposed YM repository.[48, §801;49 2, Fig. 2b;50;51] Congress mandated EPA seek advice from NAS and to use individual dose as the indicator of health impact,[52] consistent with the international community.

In 2008, EPA promulgated the site-specific environmental standards, 40 CFR 197, which again required a stochastic PA of various plausible futures of the disposal system. The standard specified the mean peak dose over 10^6 years at the controlled area boundary no further south than the southern edge of NTS, ~18 km from the repository, as the performance measure. This measure prompted changes in site investigation since more of the natural barrier had to be evaluated for a ~18-km compliance boundary.

2.5.2 YM-Specific NRC Implementing Regulation

In 2009, NRC completed promulgation of the implementing regulations for the YM repository in 10 CFR 63 (Table 2). The NRC 10 CFR 63 regulations embodied a risk-informed, performance-based approach that did not include design criteria, qualitative siting criteria, or barrier performance criteria.

Rather than stipulate barrier performance, DOE was to identify and determine barrier capability from a PA. Both the 40 CFR 197 standard and 10 CFR 63 implementing regulation proved workable for the YM disposal system. DOE submitted the final SAR/LA in January 2008.[53]

Table 1. Historical steps to establish national policy when siting geologic repository for TRU waste from defense atomic activities.

Steps in Setting National Policy	Activities on Social Dimension	Activities on Technical Dimension
1a. Commitment to mined, geologic disposal; radioactive waste disposal placed on national agenda in 1970s	**1954:** *Atomic Energy Act of 1954* seeks peaceful uses of atomic energy; allows regulated private atomic energy development.[54] **1955 Sep:** AEC—precursor to DOE, asks NAS to examine disposal of HLW.[32] **1970 Mar:** AEC directs TRU waste be stored retrievably at AEC facilities rather than disposed with low-level waste. **Jun:** AEC tells Senator Church of Idaho that TRU debris from 1969 Rocky Flats fire will be removed from Idaho by 1980 and sent to salt mine near Lyons KS.[34, p. 67;55] **1972 May:** Because of problems with disposal at Lyons, AEC announces plans for RSSF such that repository development can proceed more deliberatively, but anti-nuclear groups claim RSSF *de facto* permanent in EIS comments. **1979 Dec:** Congress defines WIPP mission: dispose defense TRU waste from atomic energy activities.[17]	**1957** NAS recommends HLW disposal in salt as most promising method.[32] **Sep:** USGS surveys of salt formations.[33] Oak Ridge National Laboratory (ORNL) begins disposal research in Salt (1957-61). **1961 Dec:** NAS reaffirms use of salt.[56] **1962:** USGS reports on salt deposits suitable for waste disposal in Permian Basin in NM, KS, TX, and OK.[33] **1963:** ORNL begins Project Salt Vault, a field test in which irradiated fuel and electrics heaters are placed in existing salt mine at Lyons KS.[57;58] **1970 Nov:** NAS concludes bedded salt safest choice now available for nuclear waste disposal.[59] **1971:** Many drill holes and some solution mining discovered at Lyons KS. Congress directs AEC to stop Lyons project until safety certified.[34]
1b. DOE Implementing agency for developing TRU waste repository; DOE retains self-regulation unless Congress or courts specify otherwise	**1974 Oct:** Congress splits AEC into[20] (1) independent NRC, to regulate civilian use of nuclear material, and (2) ERDA responsible for nuclear weapons, nuclear power research, radioactive waste, and expanded energy role. **1977 Jan:** Congress forms DOE (successor to ERDA).[18]	**1976:** ERDA funds conference on geologic disposal system modeling to bring engineers and geologist to explore geological features, events, and processes (FEPs).
1c. EPA environmental standards for SNF/HLW and TRU waste	**1977 Feb:** EPA conducts workshop to understand public concerns and technical issues of waste disposal.[24] **1976 Oct:** President Ford orders ERDA to demonstrate disposal and EPA to develop standards for spent nuclear fuel (SNF) and HLW. [60] **1983 Jan:** NWPA §121(a) requires EPA issue radiation protection standards **1987 Aug:** In 2nd amendment to court-enforced Consultation and Cooperation (C&C) Agreement between DOE and State of New Mexico, DOE agrees to apply EPA 40 CFR 191 to WIPP	**1978 Jan:** EPA announces public forum to develop protection criteria for radioactive waste.[61] EPA publishes "Criteria for Radioactive Waste" and seeks comments.[62] **1982:** EPA publishes working draft 20 as proposed 40 CFR 191.[39] **1985 Sep:** EPA promulgates 40 CFR 191 that requires PA to assess cumulative release of radionuclides at 10^4 years at 5-km boundary.[24] EPA requires DOE avoid sites with scarce or easily accessible resources unless favorable site characteristics compensate for greater likelihood of disturbance. **1993:** Individual Protection and Groundwater Protection requirements in 40 CFR 191 revised according to Court remand.[63]
1.d. EPA Hazardous waste regulations for mixed radioactive waste	**1976:** Congress passes RCRA to reduce or eliminate hazardous waste generation to minimize threat to human health.[22;64] **1984 Apr:** In LEAF v. Hodel, Court requires DOE to apply RCRA to DOE facilities.[65] **Nov:** Congress passes *Hazardous and Solid Waste Amendments of 1984*,[23] which bans land disposal of hazardous waste unless disposal site demonstrates "no migration" of waste.	**1986:** EPA promulgates ruling that mixed waste (radioactive waste mixed with hazardous waste) is subject to RCRA and associated EPA regulations.[66] **1990:** EPA grants NM authority to regulate RCRA mixed waste; thus, WIPP becomes subject to NM regulations[41] in addition to EPA 40 CFR 191.
1e. Implementing EPA certification	**1992 Oct:** *Waste Isolation Pilot Plant Land Withdrawal Act*[25] (LWA)designates EPA as regulator for WIPP.[25]	**1996:** EPA promulgates regulation, 40 CFR 194, to implement 40 CFR 191 at WIPP.[40]
1f. Implementing NRC container licensing and DOT regulations	**1987 Aug:** In 2nd amendment to C&C Agreement between DOE and State of New Mexico, jurisdiction given to (1) NRC over WIPP transportation containers, (2) Department of Transportation (DOT) for transportation rules and routes	**1989 Aug:** NRC licenses Transuranic Package Transport (TRUPACT-II) for shipping contact-handled TRU waste to WIPP with standard drum inner handling container (NRC approves amendments for other handling containers in subsequent years).

Table 2. Historical steps to establish national policy when siting geologic repository for commercial SNF/HLW.

Steps in Setting National Policy	Activities on Social Dimension	Activities on Technical Dimension
1a. Commitment to mined, geologic disposal: Radioactive waste disposal for commercial SNF/HLW	**1971** Atomic Energy Commission (AEC—precursor to DOE) requires all commercially generated HLW be solidified within 5 y and delivered to federal repository within 10 y.[67] **1974** AEC starts Geologic Disposal Evaluation Program for salt disposal. AEC identifies 8 disposal options: shallow burial, deep geologic storage, deep boreholes, sub-seabed, cavities with rock melt, well injection, ice sheets, and space.[37] **1976 Feb:** ERDA (formed from AEC) sets up Nuclear Waste Terminal Storage (NWTS) Program to search for sites in various media for commercial HLW and SNF. **Nov:** NWTS proposes developing 6 repositories to spread burden, minimize state impact, and provide portfolio of sites to reduce program risk. ERDA notifies 36 governors that it will look for sites in their states.[34] **1978 Mar:** President Carter forms Interagency Review Group (IRG), to study nuclear waste disposal.[35] **1983 Jan:** NWPA[14] selects geologic disposal and defines steps and schedule for siting first and second repository (a) requires evaluating portfolio of sites for 2 repositories (1st limited to 70,000 metric ton heavy metal—MTHM—until 2nd built to spread burden); (b) sets screening steps (e.g., environmental assessment—EA).	**1977 Aug:** Governor discontent caused by 36 letters, prompts ERDA to add previous land use as criterion for identifying sites and explores Hanford Reservation and NNSS.[68, p 2-11] **1978 Aug:** NAS lists 7 characteristics of an ideal repository site and also recommends HLW disposal only (no SNF). [69] **Oct:** In draft recommendations on radioactive waste management, IRG suggested mined geologic disposal; use of multiple barriers; looking for sites in variety of media in different regions of US (i.e., a portfolio of sites to reduce program risk); conducting repository development in a cautious, stepwise manner; not delaying disposal even though storage safe; and demonstrating commercial disposal of SNF/HLW at WIPP.[35] **1980 Oct:** DOE issues Programmatic EIS on options for commercial SNF disposal and selects mined repositories; sub-seabed and deep boreholes suggested as backup.[38]
1b. DOE assigned to develop repository	**1983 Jan:** NWPA sets up of single purpose office within DOE: Office of Civilian Radioactive Waste Management.	
1c. Negotiator to find alternate site	**1987 Dec:** NWPAA §10242 sets up Office of the Nuclear Waste Negotiator (outside of cabinet-level DOE)[21]	Negotiator sets up process after consultation with scientific, industry, political leaders
1c. EPA site-specific environmental standards	**1992 Oct:** *Energy Policy Act of 1992* §801(a) requests NAS recommend health-based standards for YM repository and EPA to issue site-specific standards, based on NAS recommendation.[48]	**2001:** EPA completes YM site-specific standards 40 CFR 197.[70] **2008:** 40 CFR 197 revised according to Court remand.[71]
1d. Implementing licensing process	**1983 Jan:** NWPA requires NRC oversee licensing of nuclear waste storage and disposal and in §121(b) requires 3 repository licensing steps: licenses for construction, operation, and closure. §121(b) also requires NRC issue site technical requirements that include multiple barriers **1992 Oct:** *Energy Policy Act of 1992* §801(b) requires NRC revise its regulations to agree with EPA site-specific standards.[48]	**1981 Jun:** NRC defines repository licensing procedures in 10 CFR 60 such as trial-like hearings in front of Atomic Safety Licensing Board (ASLB). **1983 Jun:** NRC promulgates technical criteria in 10 CFR 60 on repository subsystems to promote multiple barriers.[72] NRC codifies the 3 licensing steps in 10 CFR §2.101. **1985 Jul:** NRC adds technical criteria for repository in unsaturated zone [73] **2001:** NRC completes implementing regulation 10 CFR 63;[74] DOE is to provide PA and technical basis of multiple barriers. **2009:** 10 CFR 63 revised according to EPA promulgated standard 40 CFR 197[75]

3 DEVELOPING SITING PROCESS

In the social dimension, the siting process must meet the desires of the nation, state (or tribe), and the local community, and document a compelling answer to the question of “why here and not there?” In the technical dimension, the siting process must find a site that can be demonstrated to be safe.

The siting process has two goals pertinent to safety of the disposal system in the technical dimension:[76;77] (1) provide general information to demonstrate scientific understanding of the features present, potential events that may occur, and natural process currently acting in the engineered and natural barriers in a safety case, and (2) provide data for PAs on the influence of possible feature, events, and process (FEPs) on the future geologic disposal system behavior. To meet these two goals, NAS and IAEA have encouraged a waste management organization such as DOE to establish a framework that fosters adaptive learning in stages.[78]

3.1 Iteration of the Siting Process

The consensus requirements of IAEA specifically call for a step-by-step approach for developing a disposal facility (SSR-5):[76]

> Requirement 11: Step by step development and evaluation of disposal facilities
>
> Disposal facilities for radioactive waste shall be developed, operated and closed in a series of steps. Each of these steps shall be supported, as necessary, by iterative evaluations of the site, of the options for design, construction, operation and management, and of the performance and safety of the disposal system.

Conceptually, a step-by-step approach and iterations within each step encourages a learning organizational culture that allows opportunities for independent technical review, regulatory review, and political and public involvement in the technical process.

In corresponding guidance for site characterization, Requirement 15, IAEA notes [79, ¶6.4]

> …four stages may be recognized (i) the conceptual and planning stage, (ii) the area survey stage, (iii) the site investigation stage and (iv) the stage of detailed site characterization leading to site confirmation for construction…Site investigations progress from generalized studies at the early area survey stage to a programme of progressively more detailed characterization as specific objectives are addressed and uncertain features are targeted…

Sweden adopted a staged approach to site investigation. Following investigation for site identification, the first stage was to bring all nominated sites up to a comparable state of knowledge to determine, using limited effort, whether the site should remain a candidate. The second stage was to complete site investigations to gather all the information necessary to apply for a permit for the repository.[80-82] The Finnish repository program also identified investigation stages: Stage 1 included surface-based investigations, Stage 2 included further investigations from the surface, and construction of a shaft and access tunnel to target depth of 400 m to improve characterization, and Stage 3 for *in-situ* experiments on long-term performance and repository technology.

3.2 Siting Guidelines in NWPA

To fulfill federal government stewardship, Congress set up procedural steps in the social dimension and several requirements in the technical dimension for siting two federal repositories and developing and operating one repository in §112 of NWPA (as briefly mentioned above in §1.1.1).

In the technical dimension, NWPA set maximum population density near a site, and required qualifying and disqualifying criteria for location of mineral resources, natural features (e.g., geology, geohydrology, geophysics, and seismic activity), proximity to designated national treasures (e.g., National Parks), proximity to water supplies, and effects on water rights (Table 4). However, NWPA did not establish a methodology that needed to be followed for siting.

In the social dimension, NWPA envisioned a screening process of four stages (as implemented in §960.3-1-4—Table 4): (1) identifying potentially acceptable sites, (2) nominating sites as suitable for characterization, based on draft environmental assessments (EAs) (specifically, requiring that at least five sites be nominated), (3) recommending candidate sites for site characterization, based on final EAs, (specifically, requiring three candidate sites with at least two in different media). The implied fourth stage was recommending a candidate site for repository development after completion of site characterization. NWPA adopted an aggressive schedule for conducting these four stages for siting the first repository.

The premise of NWPA was that media diversity was necessary to reduce program risk (as suggest by ERDA in 1976 and IRG in 1979); yet, the diversity of sites being considered in the international community suggests that many different geologic media can safely host a repository. Thus, media diversity is not necessary to reduce program risk in future international siting programs.

Site investigations for both WIPP and YM repository projects progressed through four stages that corresponded to analysis of disposal system performance and are used in the report: (1) site identification stage (i.e., identifying potential acceptable sites in NWPA); (2) feasibility stage based on rough measures of performance using surface exploration, waste process knowledge, and general laboratory experiments (to nominate sites and recommend for characterization in NWPA); (3) suitability stage demonstrating viability of the disposal system based on site characterization; and (4) compliance/licensing stage based on completed site characterization with validated models. WIPP is currently in a fifth stage to monitor the natural environment and confirm performance of the disposal system behavior during operations to support eventual closure of WIPP.

3.3 Regulatory Siting Criteria

As regards siting criteria, NRC listed 8 favorable conditions and 24 potentially adverse conditions to consider (22 and 25, respectively if sub-conditions are counted) at §60.122, promulgated in 1983. DOE included these mostly qualitatively favorable and potentially adverse conditions in its siting guidelines, 10 CFR 960, as discussed below in §3.3 In the preamble to 10 CFR 60, NRC explained the intention of the siting criteria:[72, p. 28201]

> First, a site should exhibit an appropriate combination of favorable conditions, so as to encourage the selection of a site that is among the best that reasonably can be found. By referring to a "combination" of conditions, it implies that the analysis must reflect the interactive nature of geologic systems. Second, any potentially adverse conditions should be assessed in order to assure that they will not compromise the ability of the geologic repository to meet the performance objectives. It is important to recognize that a site is not disqualified as a result of the absence of a favorable condition or the presence of a potentially adverse condition

Hence, the purpose of identifying potentially adverse conditions at a site was to flag conditions to be analyzed before judging the acceptability of a site. This analysis might be a simple calculation to bound the probability or consequences of an adverse condition, or an adverse condition might be incorporated into a complete PA (incorporating both probability and consequences) to evaluate to what extent it affects the disposal system behavior.

With the Congressional selection of Yucca Mountain for characterization in 1987, NRC removed siting criteria in 10 CFR 63. Although not the NRC intent (as noted in the preamble), siting criteria could be construed to be subsystem requirements on the disposal system, which NAS had recommended omitting. Instead, DOE relied on a PA to (a) identify adverse conditions through identification of FEPs, (b) evaluate the influence of FEPs on the YM disposal system performance, and (c) provide the technical basis of multiple barriers important to isolation.

3.4 DOE Siting Guidelines

NWPA required that DOE promulgate siting guidelines (§112(a)) (Table 3). Like EPA and NRC, DOE promulgated two sets of siting guidelines for evaluating and selecting a repository site: generic guidelines in 10 CFR 960, and YM-specific guidelines in 10 CFR 963 (Table 3).

DOE completed draft 10 CFR 960 siting guidelines in February 1983 (within the 180-day window since NWPA enactment) and began consultation with EPA, Council of Environmental Quality, US Geological Survey, and interested Governors (Table 3). The guidelines were based on criteria used in the NWTS program, suggest criteria by the IAEA, and siting criteria in 10 CFR 60.

The guidelines were dividing into system guidelines and technical guidelines for both the preclosure and postclosure periods. System guidelines of 10 CFR 960 refer to isolation requirements of the EPA Standard 40 CFR 191 and waste containment requirements of the NRC regulation, 10 CFR 60.

Technical guidelines refer to the qualifying, favorable, potentially adverse, and disqualifying conditions. In the final 10 CFR 960 siting guidelines, promulgated in December 1984,[83] DOE included 17 disqualifying features, 10 of which were to be used for the first stage of identifying potentially acceptable sites. Postclosure disqualifying conditions included (1) previous mining, (2) <200 m of overburden, (3) active dissolution, and (4) active fault movement. Preclosure disqualifying conditions included (1) population criterion in NWPA, (2) land use criteria in NWPA (e.g., not located in boundaries of federal National Park System or State Protected Lands). Nomination and selection of candidate sites for a feasibility stage was to use all 17 disqualifying features (e.g., ≤1000-year groundwater travel time to the accessible environment).

DOE siting guidelines at §960.3-1-5 specifically state, "Comparisons between and among sites shall be based on the system guidelines, to the extent practicable…". However, "if the evidence for the sites is not adequate to substantiate such comparisons, then the comparison shall be based on the technical guidelines."

The Nuclear Waste Management Organization (NWMO) of Canada had two sets of criteria (roughly similar to the US) that they used to successfully find a final site in 2024 from the 21 communities that expressed interest in hosting a repository in 2012: (1) 5 initial screening criteria, and (2) 19 comprehensive criteria that a site must satisfy. NWMO iterated many times and progressively added more of the 19 comprehensive criteria each time more information became available rather than conduct three distinct iterations as for NWPA.

3.5 Site-Specific Siting Guidelines

DOE issued its YM-specific siting guidelines (10 CFR 963) in 2001, which were consistent with the risk-informed NRC site-specific regulation 10 CFR 63.[84] Under 10 CFR 963, recommendation of the YM site depended upon a PA that included consideration of all relevant regulatory factors (Table 3).

3.6 Stakeholder Role Under NWPA

The stakeholder role under NWPA was primarily limited to statutory/institutional stakeholders: EPA, NRC, and DOE. In addition, Congress established a procedure for a state Governor or a Native American Tribe leader to notify Congress of their disapproval of a site recommendation (NWPA §116(a)(2) and §118(a)) and the necessary procedure for Congress to override this disapproval (NWPA §115).

NWPA included a provision to encourage consultation and cooperation agreements with a host state, which followed the requirement for a consultation and cooperation agreement with the State of New Mexico in the 1979 WIPP authorization[17] and reiterated in the 1992 WIPP LWA.[25]

Though not explicitly mentioned in NWPA, states require permits for drilling investigative wells, water use from the State Engineer and inspections of operations such as boring of exploratory tunnel (i.e., underground research laboratory), as noted later in §5 on feasibility stage and §6 on suitability stage. Thus, permitting involves the State as a stakeholder.

NWPA required public hearings on (1) issues to address in an environmental assessment (NWPA §112(b)(2)),[68] (2) site characterization plans (SCP) (NWPA §112(b)(2)) (see §6.5), and (3) site recommendation (NWPA[35] §114(a)). Hence, the participation of the public (i.e., non-statutory/non-institutional stakeholders) for the WIPP and YM repository programs was through comments at these hearings, at the promulgation of draft EPA and NRC regulations, at the promulgation of draft DOE siting guidelines, and EIS issued when transitioning between siting phases such as site recommendation, construction authorization and selecting transportation routes for radioactive waste.

3.7 Alternative Stakeholder Role in NWPAA

The 1987 NWPAA[21] expanded the social dimension by establishing the Office of the Nuclear Waste Negotiator in the Office of the President, outside of DOE, to seek a willing community and corresponding state/tribe for a repository or an interim monitored retrieval storage (MRS) facility and negotiate terms (Table 3). If there was more than one willing community/site, then the Negotiator/DOE would need to pick one community/site.

The proposed agreement for one site was then to be submitted to Congress for enactment into law prior to committing significant resources to site characterization for the suitability stage.

After Congressional authorization, DOE was to conduct site characterization and then prepare a SAR/LA for submission to NRC for approving a construction license.

Table 3. Historical steps in developing siting process for commercial SNF/HLW.

Steps in Developing Siting Process	Activities on Social Dimension	Activities on Technical Dimension
2a. General consultation about principles and necessary features and steps involving individuals, communities, and other entities that may have a future stake in implementing repository siting; technical siting guidelines based on NWPA and NRC implementing regulations	**1983 Jan:** NWPA Subtitle A §112(a) requires disposal siting guidelines to include (1) qualitative qualifying factors and disqualifying factors/exclusionary criteria pertaining to location of valuable natural resources, hydrology, geophysics, seismic activity, proximity to atomic energy defense activities, proximity to water supplies, proximity to populations, effects on water rights, and proximity to designated national treasures (i.e., National Park System, National Wildlife Refuge System, National Wild and Scenic Rivers System, National Wilderness Preservation System, or National Forest Lands); (2) transportation factors related to proximity of site to currently storing HLW/SNF (3) population density > 1000/mi^2 as exclusionary criterion; and (4) various geologic media in portfolio of site considered. NWPA §112(a): requires DOE to issue siting guidelines requires. Siting guidelines shall include 3 siting decision stages (specified in 10 CFR 960.3-1-4): (1) identify potentially acceptable sites, (2) nominate ≥5 sites as suitable for characterization, accompanied by environmental assessments (10 CFR 960.3-2-2)), and (3) recommend 3 candidate sites for site characterization	**1983 Feb:** DOE completes draft of generic technical siting guidelines in 10 CFR 960 **1983 Jun:** NRC promulgates technical criteria which identify 8 favorable conditions and 24 potentially adverse conditions to consider in siting repository (10 CFR §60.122). • Site shall exhibit an appropriate combination of favorable conditions so that, together with the engineered barriers system, the favorable conditions present are sufficient to provide reasonable assurance that the performance objectives relating to isolation of the waste will be met (10 CFR §60.122(a)(1)). • Presence of potentially adverse conditions may be acceptable, if conditions do not compromise the performance of the geologic repository (10 CFR 60.122(a)(2)).
2b. *Consultation on proposed draft Final generic process*	**1983 Jan:** NWPA §112 (a) DOE must consult with EPA, Council of Environmental Quality, US Geological Survey, and interested Governors and obtain NRC concurrence.	**1983:** DOE conducts lengthy consultation. **1984 Dec:** Final 10 CFR 960 siting guidelines (10 CFR Part 960, Subpart C) included qualifying, favorable, potentially adverse, and disqualifying conditions. Of 17 disqualifying features, 10 are for the first stage of identifying potentially acceptable sites (e.g., no previous mining, >200 m of overburden)
2c. Site specific process for Yucca Mt compliance stage	**1987 Jan:** In Senate hearings, DOE reports that site characterization now estimated at ~$1 billion per site. [85] **Dec**: In NWPAA,[21, §5001] Congress selects YM to characterize first, (b) delays 2nd repository. **1992 Oct:** *Energy Policy Act of 1992* §801 requires EPA and NRC revise regulations to agree with NAS recommendations on YM site-specific standards.[48]	**1999 Nov**: DOE drafts guidelines (10 CFR 963) for evaluating YM suitability by using PA, following precedent set by NRC in draft 10 CFR 63.[84] **2001 Nov:** Final site-specific siting guidelines for YM completed (10 CFR 963) [86]
2d. Willingness process setup under NWPAA	**1987 Dec:** NWPAA §5041 sets up voluntary siting program for MRS or repository: The Negotiator was to (1) dialog with states and tribes; (2) negotiate proposed terms on hosting MRS or repository; (3) submit proposed agreement to Congress for enactment into law; (4) consult with affected nearby communities, states, and tribes. DOE role includes (1) making grants to state, tribe or affect nearby communities to assess site feasibility and suitability; (2) commenting on feasibility and suitability of site; (3) preparing EA of site; (4) conducting characterization and preparing SAR/LA for site authorized by Congress; (5) preparing EIS after site characterization; and (6) summiting SAR/LA to NRC	Nuclear Waste Negotiator siting office focuses on MRS rather than repository; (1) for 1st step,1st Negotiator solicits responses from communities and states or tribes, 2nd Negotiator seeks cooperative agreements; (2)(a) apply for DOE Phase I $\$10^5$ grant, (b) community gathers data with DOE support; (3)(a) governor permission, (b) apply for Phase IIA $\$2\times10^5$ grant, (c) negotiate, (d) DOE conducts feasibility analysis and prepares EA; (4)(a) present negotiation terms and EA to Congress, (b) Congress approves site characterization; (5)(a) governor permission, (b) apply for Phase IIB $\$2.8\times10^6$ grant, (c) negotiate, (d) DOE site characterization and prepares SAR/LA; (6)(a) review negotiation terms, site characterization; (b) prepare EIS; (6) submit SAR/LA to NRC for construction approval.
2e. DOE restarts willingness process	**2012** BRC recommends a collaborative approach to site future radioactive waste management facilities (i.e., developing a social dimension of identifying and supporting potentially willing host states and communities).[26, p. 118]	**2013** University of Oklahoma/Sandia report on national survey results on Consent-based siting.[87] **2015 Dec:** DOE solicits public comment on design of a willingness process.[88] **2017 Jan:** Draft Consent-Based Siting Process for Consolidated Storage and Disposal Facilities for SNF/HLW released for public comment **2023 Apr:** Consent-Based Siting Process for Federal Consolidated Interim Storage of Spent Nuclear Fuel published.

3.8 Siting criteria for developing institutional trust

The nonprofit Electric Power Research Institute (EPRI) has hypothesized that siting criteria are viewed by the US public as an important prerequisite for an open sitting process characterized by transparency, fairness, and trust in reaching a decision on siting.[89]

> Well-crafted siting guidelines can provide an open and transparent basis by which site characterization and site selection will be conducted and evaluated by all impacted stakeholders. However, overly restrictive siting criteria may result in premature disqualification of otherwise suitable candidate sites.[36, p. 41]

In support of this viewpoint, Nuclear Waste Technical Review Board (NWTRB—created in NWPAA to "evaluate the technical and scientific validity of activities undertaken" by DOE) encouraged adopting siting criteria that could be applied objectively:

> Therefore the Board recommends that, to the greatest extent possible, the development of any new site-suitability criteria minimize the ambiguity that facilitates the DOE implementer's discretion in applying them, helping ensure the objectivity of the process and public confidence in its outcome. If, at any point during the siting process, the criteria need to be changed, the DOE implementer should use a transparent and meaningfully participatory process to do so.

Indeed, these sentiments are the motivation for discussing the development of siting criteria prior to identifying potential acceptable sites. In the case of WIPP, however, fairly simple siting criteria were used to recommend southern New Mexico (Table 5)[93-96] and these criteria were not widely explained and vetted with the public.

Rather, broad measures of transparency and fairness were also used by the public in establishing institutional trust (see §5.4), not the application of detailed siting criteria. For WIPP, the local community invited the AEC to the Carlsbad area and as trust developed Carlsbad leaders became advocates for the repository during later siting feasibility, suitability, and compliance/licensing stages (§4, Table 5). If the role of the public is pre-defined in the social dimension, perhaps arguments about meeting technical siting criteria may not have to act as a surrogate for approval in the social dimension.

4 IMPLEMENTING SITE IDENTIFICATION

4.1 Order of Technical and Social Consideration in Siting

The process in NWPA placed emphasis on determining the technical suitability of the site. Cooperation and consultation were encouraged, like what occurred at WIPP, but the technical evaluation could proceed without this cooperation as occurred at the potential repository at Yucca Mountain. Only after the site was deemed to be scientifically suitable was the host state given the right to accept or veto going forward with implementing the facility; and the host state decision could be overridden by Congress in the social dimension.

Although equally important, either the social or technical dimension can occur first when seeking willing communities. In a 2013 national survey, the public was asked whether the *technical* screening and potential feasibility of a site for a consolidated interim storage facility (CISF) should be established prior to, or after, engaging in the *social* process of determining whether inviting potential host communities to express interest in nominating the site for characterization.[87;90] About 58% of the respondents prefer technical assessment of site prior to determining the willingness of states and communities to host an ISF (Table 4).

This preference for technically evaluating potential regions first occurs irrespective of support or opposition to interim storage. Furthermore, 63% of respondents prefer a technical evaluation first among those who currently live within 25 miles of current temporary on-site SNF storage facilities (Table 4). One may hypothesize that the majority of the US public wants some initial indication of site suitability through a technical screening before a community considers whether a controversial project is worthy of their time and energy to garner broad support.

Table 4. In 2013, US public generally preferred technical screening first to find feasible sites followed by a social decision on site nomination.[87, Table 7.1]

	First determine technical suitability of site (%)	**First have State and local community determine if they would like to host ISF (%)**
All responses	58	42
Opposed to ISF	55	45
Support ISF	61	39
Reside <25 miles from current SNF storage	63	37

The Department of Energy and Climate Change in the United Kingdom received similar public comments on the need for upfront information on geology, socio-economic impacts, and community investments. Hence, one aspect of the December 2018 revised United Kingdom siting process, entailed Nuclear Waste Services, subsidiary of the Nuclear Decommissioning Authority, to conduct a national screening, with the help of the British Geological Society, to identify suitable areas for siting a repository such that communities could assess whether they would like to participate.[91;92] Japan has adopted a similar approach in 2025, since communities were not willing to volunteer/participate in the 2002 nationwide call without technical information.[36, p. 34]

Hence, the approach ERDA took in asking the USGS to identify potential regions and areas for commercial repository sites was reasonable from the public viewpoint. But its sudden implementation without transparent engagement caused great consternation with state governors in 1977 (Table 2).

In the case of WIPP, the technical and social dimensions were considered simultaneously (Table 5). Elaborating upon the discussion in the previous section, the local leaders and Potash Mine operators (with tacet approval of the New Mexico governor) volunteered the salt deposits of the Los Medaños area around Carlsbad in 1973.[34] In the same year, a national search for suitable salt sites resumed using fairly simple selection criteria and the USGS, AEC, and Oak Ridge National Laboratory (ORNL) recommended southern New Mexico (Table 5).[93-96]

4.2 Three Phases of Identifying Acceptable Sites

Under the administrative procedure for the first stage of identifying potential sites, three phases were roughly followed: identification of potentially acceptable (1) regions, (2) areas, and (3) site/location. For example, USGS began survey of salt formations regions in 1957.[33] In 1962, USGS reported on salt deposits areas suitable for waste disposal in Permian Basin in New Mexico, Kansas, Texas, and Oklahoma (Table 5).[33]

The concept of using multiple barriers to build a robust disposal system permitted ERDA, the successor of AEC, to evaluate other geologic formations on land owned by the federal government in the 1970s. In 1976, USGS noted that the region around NNSS had several advantages because of its remoteness, desert conditions, past nuclear testing, closed groundwater basin, and many suitable host rocks not associated with economic resources (Table 6). By 1982, USGS noted additional advantages for using the thick, unsaturated zone (UZ) of the volcanic tuff at Yucca Mountain such as a mineable but fractured tuff host layer to rapidly pass percolation, the potential for passive ventilation because backfilling drifts would be unnecessary, and a long period with easy retrieval because the repository did not flood. The ability to use large waste packages, which facilitated direct linkage of the repository to waste management practices at the nuclear reactor, would eventually be appreciated as an additional advantage.[4;8]

For the first commercial repository, DOE identified the nine sites that had previously been selected for consideration using administrative procedures (Fig. 3), because the first stage was to be completed within 90 days of enactment of NWPA (Table 6). That is, siting did not start with Phase 1—Regional selection, and Phase 2—Area selection, but instead moved directly to Phase 3—potentially acceptable sites.[97] The alternative of starting with a new national site screening process had been explicitly considered and rejected by Congress during debates on NWPA.

Fig. 3. DOE issued draft EAs on 9 potentially acceptable sites and nominated 5 in 1984 for first repository feasibility and recommended 3 including Yucca Mountain for characterization/suitability in 1986; also, in 1986, DOE suggested 12 promising granitic areas for second repository in the southeast (SE), northeast (NE), and northcentral (NC) parts of the US.

4.3 Site Identification for Second Commercial SNF/HLW Repository

Under NWPA a second repository site was to be identified by July 1989 and DOE more methodically conducted the search. The first stage of identifying potentially acceptable sites considered general regional information to identify numerous potential regions.[98] In the second phase, pertinent literature information within favorable regions was used to identify 12 promising areas (Fig. 3).[99] If the siting process had continued, DOE would have considered local information within favorable areas to identify potentially acceptable sites in the third phase.

The search for the second repository had not been nationwide. The social bargain included in NWPA was that a second repository would be built such that more than one state would bear what at the time was considered the social stigma of a national repository.[47] Although not explicitly specified in NWPA, Congress and DOE generally understood that the second repository would reside in the eastern US to balance the selection of the first repository in the west (Fig. 3).

Thus, DOE conducted its search in the southeast (SE), northeast (NE), and northcentral (NC) regions of the US in the most prominent geologic media: crystalline, quartz-bearing, plutonic rocks (succinctly described as granite). Even though the siting process was more methodical, it still generated much controversy and was indefinitely delayed in NWPAA.[21] The indefinite delay in searching for second repository in NWPAA (along with the selection of Yucca Mountain as the first site for characterization) negated these explicit and implicit social bargains.[47]

4.4 Investigations for WIPP Site Identification

The search for regions, areas, and site location relied extensively upon USGS judgement, followed by DOE review. For WIPP, once the Permian Basin region was identified in 1962[33] and Delaware Basin area in southern New Mexico were identified by USGS in 1973, first ORNL[100] and then Sandia drilled site/location boreholes (Table 5). Specifically, Sandia's borehole at the northwest corner of the ORNL site encountered deformed salt beds, brine, and H_2S.[101] In response, Sandia relocated the WIPP site toward the center of the Delaware Basin. Horizontal bedding was encountered by borehole ERDA-9 in April 1976, as had been indicated by oil well logs. Consequently, ~3.5 years were spent on the WIPP site identification stage between 1973 and April 1976.

4.5 Investigations for YM Site Identification

USGS drilled the first borehole, UE25a-1, in 1978 to verify the presence of thick tuff layers. Eight more boreholes were drilled between 1980 and 1982 around the perimeter of the proposed repository area to develop a stratigraphic map of Yucca Mountain, prior to passage of NWPA.[2;3] Sandia conducted an extensive site/location screening at NNSS for the proposed YM repository in 1982 (Table 6).[102;103]

NWPA (in §112(b)(3)) favors the use of available information during the first two stages—site identification and feasibility—to identify potentially acceptable sites and nominate sites for detailed site characterization (third suitability stage). But NWPA and 10 CFR 60 allowed preliminary investigations if DOE determined that available information did not provide an adequate basis.

Many of the wells drilled near the repository (G-geologic, H-hydrologic, WT-water table, and UZ-unsaturated zone wells and several of the N series neutron probe boreholes) were completed for the site selection phase and accompanying 1984 PA (i.e., YM-PA-EA in Table 6).

Upon promulgation of 10 CFR 960,[83] DOE issued draft EAs on the 9 potentially acceptable sites and nominated 5 sites to complete final EAs in December 1984 (Fig. 3).[2;2;68;104-106] Along with information from a multi-attribute analysis,[107;108] DOE selected volcanic tuff at Yucca Mountain, Nevada; bedded salt at Deaf Smith, Texas; and basalt at Hanford in Washington for the feasibility stage in May 1986 (Fig. 3).[2;105;106] Thus, the site identification stage for the YM repository continued for 11 years, between February 1976 and May 1986 when the final EA was published (Table 6). The period is longer if one includes when the State of Nevada first indicated interest in 1972 or includes the long transition between May 1986 and December 1987 when Congress nominated Yucca Mountain in NWPAA for site investigation.

4.6 Interaction Between State and Local Community in Social Dimension

In the US, the siting of a potentially controversial facility, such as an HLW/SNF repository, in a local community can generate tension between the state and local community. Although the US is based on a federal-state system with shared authority to govern and collect revenue, the interaction between a local community and the state is based on a unitary system. The authority of county and city divisions of the state and the power afforded those entities to collect revenue are entirely or mostly dependent upon the state (i.e., a state constitution usually does not identify authority of local communities that cannot be usurped by the state). The state can often grant or remove the power to collect revenue at will, though some types of revenue have been granted by state constitutional amendments in recent years. Certainly, the local community must usually be in favor of a radioactive waste repository, but its agreement is not sufficient, as can occur with direct representation of a local community in a national parliament. In the US, the state is the primary party to any agreement with the federal government. While a local community may express interest in hosting a repository, as was the case for WIPP, the local community must garner support from the state's governor, influential state representatives/senators, and federal congressional representatives/ senators, at crucial decision points to move forward in the site selection process. This support was indeed present at WIPP, and after a protracted period of negotiation the local Carlsbad community prevailed (Table 5).

Absent this support, a local community is subject to the whims of other interest groups in the state. Hence, remoteness of a repository site that lacks modest population nearby and thus cannot develop public advocacy is not necessarily a desirable social-political virtue in the US.

Tension between a local community and the state and congressional representatives/senators may arise because the entities do not necessarily have the same interests. A local community may wish to expand opportunities, be they through improved tax base or guarantees of federal support, but the state and federal representatives/senators have varied interests and constituents that may not perceive a direct benefit from the facility and may actively thwart an interested local community.

The NWPAA addressed this dynamic by placing significant power with the State or Tribal Governor in initially allowing or denying a local community to express interest and move forward with siting for a facility (Tables 3 and 6). Thus, opposition to a facility was focused on the governor, while the local community had to gauge interest and develop local and then state support. None of the four state counties that showed initial interest in 1991 under NWPAA were able to develop local and state support before the state governor vetoed siting efforts (Table 6). Nine Indian Tribes were successful in completing the Phase I studies by 1992 and four tribes wished to continue to Phase IIA. However, opposition by residents outside the reservations resulted in Congress defunding the NWPAA volunteer program in 1994 (Table 6).

Table 5. Historical steps for site identification over 3.5 years for TRU waste from defense atomic activities.

Site Identification	Activities on Social Dimension	Activities on Technical Dimension
3a. Implement national site identification process for repository	**1973:** AEC resumes nationwide search for suitable salt site resumed.[93;94;96] **1974 May:** AEC suspends WIPP work to emphasize Retrievable Surface Storage Facility (RSSF); also, AEC does not want to withdraw land from oil exploration because of Arab oil embargo. **1975 Jan:** ERDA (formed in 1974 from AEC) asks Sandia National Laboratories (Sandia), local national lab, to oversee WIPP site investigations rather than ORNL. ERDA removes WIPP from commercial repository program. **1976 Jan:** Project is officially named the Waste Isolation Pilot Plant.[100]	**1973:** AEC, USGS, and ORNL recommend southeastern NM; several areas without boreholes within 2 miles.[109] **1974 Mar:** ORNL begins field investigations by drilling AEC-7 and AEC-8 in Delaware Basin.[100]; ORNL identifies FEPs not eliminated by site selection and conducts scenario development and deterministic analysis of WIPP.[56] **1975 Mar:** Sandia receives initial funding for 4 tasks: (1) selecting site; (2) producing conceptual design; (3) drafting site-selection EIS, (4) initiating scientific studies (which is part of site feasibility stage). **May:** ERDA-6 drilled at NW corner of original ORNL site encounters deformed salt beds, brine, and H_2S;[101] Sandia relocates WIPP toward center of Delaware Basin to avoid deformed bedding. **1976 Apr:** ERDA-9, drilled down to Castile Fm., finds mostly horizontal salt beds in Salado Fm.
3c. Implement willingness site identification;	**1973:** With tacit approval of Gov. King, local political leaders and potash mine operators invite AEC to southeastern NM to search for site.[34] **1974:** NM Gov. King establishes Technical Excellence Committee with WIPP oversight subcommittee.	

Table 6. Historical steps for site identification over 11 years for commercial SNF/HLW.

Site Identification	Activities on Social Dimension	Activities on Technical Dimension
3a. Implement national site identification /candidacy process for 1st repository based on regional geologic investigation via literature, analogous data, and a few boreholes to confirm stratigraphy; also develop repository and waste package design to assist in siting selection; finally, prepare preliminary PA using readily available information to support environmental assessment	• **1972 May:** Nevada Senator Cannon urges AEC to use NNSS for reprocessing and waste disposal [110, p. 92]. • **1975:** Because of unemployment in Nevada, state legislature urges ERDA to choose NNSS for storage and processing of nuclear material.[111] NWPA §116(a): DOE to identify "potentially acceptable sites" and notify state governors; §112(b)(2): DOE to hold public hearing on issues to be addressed in EA and SCP; §112(b)(1)(A): DOE shall nominate ≥5 sites suitable to characterize and include EAs per §112(b)(1)(E) • **1983 Feb:** DOE identifies 9 potentially acceptable sites for first repository already under consideration using administrative procedures (4 bedded salt, 3 salt dome, 1 tuff site at YM, and 1 basalt site at Hanford—where the latter 2 sites were based on prior land use:) [34, p. 229]. • **1983 Mar:** DOE solicits comments from State of Nevada and public regarding nomination of YM as required in §112(b)(2).[112] **Apr:** Governor Bryan declares YM identification an unfair burden, Nevada already has NNSS and waste might discourage growth of Las Vegas.[113] • **1984 Dec:** DOE selects 5 sites for final EAs (Yucca Mt, Nevada; Davis Canyon, Utah; Deaf Smith, Texas; Richton Dome, Mississippi; and Hanford, Washington). Criticism of ranking prompts DOE to try multi-attribute utility analysis to rank the 5 sites.[107;108] NWPA §112(b)(1)(B): DOE to recommend ≥3 sites to characterize in at least 2 different media • **1986 May**: DOE nominates 3 sites (YM [68], Deaf Smith, and Hanford with ranking of 1, 3 and 5 by multi-attribute study) to investigate for 1st repository (feasibility stage).[105] DOE uses portfolio of sites and media to lower program risk as suggested by NWPA. President Reagan approves portfolio.	**1976 Feb:** USGS suggests emplacing HLW at NNSS.[114] **1977 Oct:** DOE establishes Nevada Nuclear Waste Storage Investigations (NNWSI) Project to continue looking at NNSS [68]. **1978 Apr:** DOE decides repository can be built in 100-km^2 area in southwestern portion of NNSS and not disrupt weapon tests.[68, p. 2-14] USGS identifies 5 sites in 100 km^2 area. USGS finds thick tuff deposits at YM in borehole UE25#a-1.[115] **Oct:** USGS recommends thick layers of tuff at YM.[112] **1982** Sandia conducts extensive site/location screening.[102;103] **Jul:** Repository moved to unsaturated zone.[116] **Dec:** Initial design of YM repository,[117] and initial design of YM package completed.[118] **1981-1984:** G, H, WT, UZ boreholes drilled at YM site **1980-1987:** Heater tests in G-tunnel underground research laboratory (i.e., offsite underground research laboratory—URL—on NNSS). **1984 Sep**: SNL designs stair-step repository to keep horizontal disposal drifts for EA.[119] **Dec:** SNL completes YM-PA-EA that shows comparison with 1982 draft 40 CFR 191.[120] Draft EAs and underlying PA published for all 9 sites.[104] **May 1986:** Final YM-PA-EA assumes a 5 km^2 repository 170 m above the water table with heat load of 14 W/m^2. Both floor and pillar emplacement are considered.[68]
3b. Implement national site identification /candidacy process for 2nd repository based on regional geologic investigation via literature to identify regions and then potential areas.	NWPA §112(b)(1)(C) DOE shall nominate 5 sites for 2nd repository, which shall include at least 3 additional sites not nominated for first repository and recommend 3 candidate sites for characterization for 2nd repository	**1979 Mar:** The first phase considered general regional information to identify >200 granitic sites in 17 eastern states.[98] In the second phase, pertinent information within favorable regions was used to identify 12 promising areas.[121] For Phase 3, DOE proposed evaluating 12 crystalline (granitic) rock areas in 7 states (5 in the eastern US, 2 in the Midwest) for the 2nd repository, but postponed their evaluation in 1986 because of high characterization costs, great concern in the east, and because new reactors not being built.[122]
3c. Implement willingness site identification; exploration of interest by potential communities either self-identified or contacted by Negotiator.	**1991 Jun:** Negotiator announces it is seeking communities willing to participate in hosting storage site with 3 study phases. DOE to provide grants of $\$10^5$ to explore interest for communities who apply:[123;124] **1993 Oct:** Congress, with help of NM Senator Domenici, defunds DOE grants **1994:** Congress lets voluntary repository/MRS siting office expire without participates moving to second phase.	**1991 Jul:** Counties in 4 states and 16 tribes seek Phase I grants. **1992 Aug:** Counties in AZ, ND, UT, WY withdraw e.g., WY Gov declines to allow Fremont County community to seek MRS, citing *de facto* disposal and difficulty in negotiating with feds (i.e., like "dancing with 900 lb gorilla"). 9 tribes complete Phase I. **1993:** 4 tribes advance to phase IIA grants ($\$2\times10^5$) which requires permission of State or Tribal Governor; Mescalero Apache NM ready for Phase IIB ($\$2.8\times10^6$). **1995 Jan:** Because Negotiator office closed, Goshute Skull Valley Indian tribe in Utah starts negotiating directly with utilities to build private MRS facility.

5 IMPLEMENTING FEASIBILITY STAGE

5.1 Technical Investigations for WIPP Feasibility Stage

The WIPP feasibility stage began in 1976 when Sandia began significant technical site investigations (Table 7). During site selection, interest in water bearing units above the repository focused on potential for salt dissolution. In the feasibility stage after selection, interest shifted to role of water bearing units as potential pathways for radionuclide release. In 1978, Sandia completed a major geologic investigation report,[125] which estimated hydraulic conductivity in several regions of Culebra from 4 wells of the 47 boreholes completed by USGS. Also in 1979, Sandia fielded several experiments in nearby Potash Mine and Avery Island salt dome salt in Louisiana on crushed salt consolidation[126] and thermal/structure effects (i.e., off site underground research laboratory—URL).[127;128] During 1979, the Architect/Engineer, Bechtel National, identified 7 potential horizons for the repository and a preliminary design of the repository. By October 1980, the final site-selection EIS was completed.[129] Hence, the feasibility stage for WIPP lasted ~4.5 years between 1976 and October 1980.

5.2 Social Dimension during WIPP Feasibility Stage

During the feasibility stage for WIPP, several institutions important to the review of WIPP in the social dimension were formed. First, DOE requested that NAS form a panel to review the scientific aspects of WIPP.[100] This WIPP review group was set up as a panel under the Board of Radioactive Waste Management (BRWM) of National Academies, with funding from DOE, and held quarterly meetings throughout the feasibility, suitability, and compliance stages. Second, DOE contracted with the State of New Mexico in 1978 to establish the Environmental Evaluation Group (EEG) to provide full-time, independent technical assessment of WIPP EEG commented on environment and public health/safety though the feasibility, suitability, and compliance stages. At first, EEG was funded through DOE but after 1986 it was funded directly by Congress. EEG was initially an entity within the New Mexico Environment Department but conflicts that emerged as administrations changed lead to eventually administratively associating EEG with the New Mexico Institute of Mining and Technology in Socorro.

The NM legislature also established[130] (1) Governor’s Radioactive Waste Consultation Task Force to negotiate with DOE, and (2) Legislative Radioactive and Hazardous Materials Committee to keep the legislature appraised of WIPP activities.

Two advisory groups to President Carter recommended changing the administratively defined mission of WIPP to include demonstrating commercial SNF/HLW disposal (Deutsch Report—Table 7 and IRG—Table 8), but Congress disagreed and at the end of 1979[17] (1) established WIPP as a research and development facility for only TRU waste from defense atomic energy activities, (2) exempted WIPP from NRC licensing since it was exclusively for defense TRU waste, and (3) required DOE negotiate a Consultation & Cooperation (C&C) Agreement with the State of New Mexico. Eventually, the C&C Agreement was an important mechanism for the State of New Mexico to express its wishes for site characterization during the suitability stage, as noted in §6.2.

5.3 Social Dimension during YM Feasibility Stage

Following the example of the NAS Review Panel for WIPP, NWPAA established NWTRB, to advise Congress and DOE and radioactive waste management, in general, and ensure scientific credibility of YM Project, in particular, through formal outside technical review. The NWTRB consisted of 11 members appointed by the President from a slate of candidates nominated by NAS. Many of the changes made in site characterization and engineered barrier design, were made in response or supported by NWTRB comments after their first report in 1990, which (1) criticized using drilling/blasting to excavate an URL in the proposed repository region, (2) criticized a lack of progress in applying the PA methodology since PA-EA was completed in 1984-86; and (3) suggested replacing shafts with ramps to the underground facility. In 1992, NWTRB urged system study of storage, transportation, disposal such as using large packages placed horizontally to avoid handling SNF at the YM repository.[131;132] In 1998, DOE implemented the NWTRB suggestion for a second test drift as part of URL at the site: the enhanced characterization of the repository block (ECRB) bored to Solitario Canyon Fault.[133]

5.4 Institutional Trust

When rating their trust in the information provided by different agencies involved with managing radioactive waste in a 2016 national survey, the members of the public place the most trust in university scientists that study nuclear energy and related technologies (mean of 6.6 when rated between 1 for no trust and 10 for complete trust) or those from the NAS (mean of 6.5). Emergency managers (EMs) from state and local police and fire departments, were also highly trusted (mean of 6.1) (Fig. 4). Hence, review of WIPP by NAS WIPP Review Panel and review of YM Project by NWTRB (comprised of university scientists and NAS members), can be helpful in maintaining trust in the project.

Experts from government organizations like the US national laboratories for energy and security, EPA, NRC, and DOE were close behind the top trusted actors, followed closely by technical experts from environmental groups. State regulatory agencies were perceived as moderately trustworthy sources of information, with a mean slightly above midscale (5.3).

Actors not seen as highly trusted sources of information (in red) range from groups whose purpose is to oppose or support nuclear energy, both national and state/local news media, and utility companies (Fig. 4). But clearly, as is evident from the low trust rank of public utilities, the siting organization must not have a strong profit motive as public utilities if it is to retain public trust.

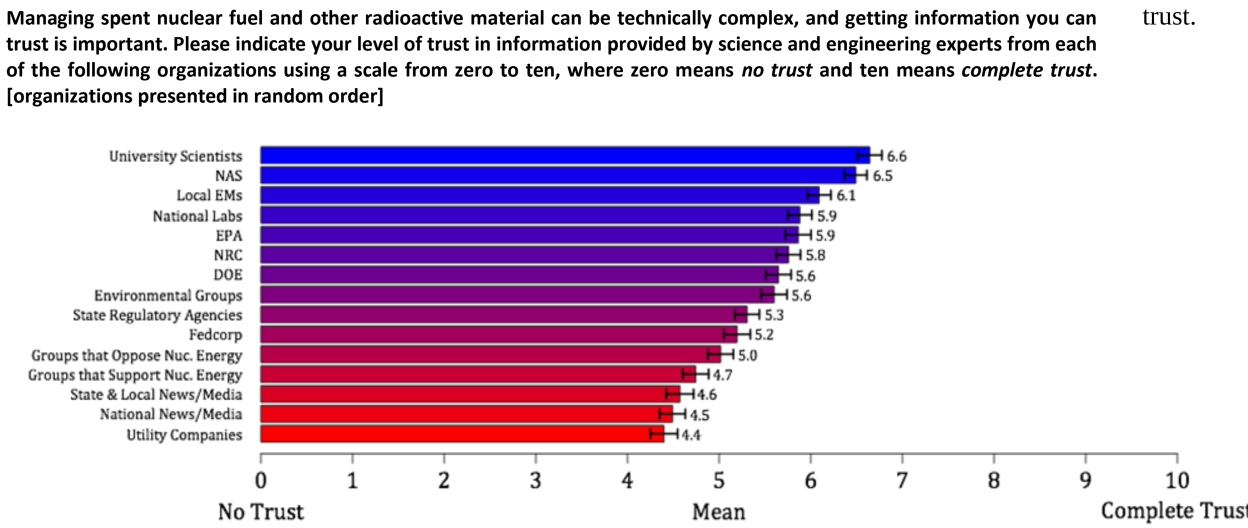

Fig. 4. Trust in information provided by organizations managing, providing oversight, or reporting on SNF and HLW in 2016 national survey, where EM is emergency managers/first responders and Fedcorp is a hypothetical independent waste management agency.[134, Figure E-10]

5.5 Projected Site Investigation Costs

NRC initially estimated the cost of *in-situ* characterization of a hard rock repository, such as at Yucca Mountain, at less than \$40 million in 1982,[3;43, p. 13973;135] under the assumption that much knowledge would be acquired during construction, similar to the situation that occurred at WIPP.[12;13] WIPP studied and resolved a wide variety of scientific topics of direct interest to the State of New Mexico during construction of surface facilities, shafts, and the URL under the Stipulated Agreement and C&C Agreement (Table 7).

The requirements for site characterization did not materially change but the controversy between the federal government and the State of Nevada changed expectations of DOE. Without state cooperation, agreements could not guide topics to study. Thus, the importance of the numerous studies suggested by scientists for research in draft SCPs were not as easily evaluated and ranked. Instead, all SCP activities were initially slated for funding. These factors had large cost implications. The cost of characterization of three candidate sites was estimated at ~\$1 billion per site in 1987 during hearings for NWPAA.[85] This cost increase curtailed Congressional support for multiple repository sites and NWPAA, passed as part of government deficit reduction, chose one site to characterize for YM repository (Tables 2 and 8).

5.6 YM Site Characterization Plan

As required by NWPA and 10 CFR 60, DOE issued a 9-volume SCP report listing ~300 activities for surface, underground, and laboratory tests that could be under taken for the YM disposal system in December 1988.[3;106;136] In 1991, DOE conducted a Test Prioritization Task to rank the importance of ~300 tests, in response to NRC critique.[137] By 1994, DOE had categorized SCP tests into those required to support (a) site suitability/viability analysis, (b) confirmation/licensing and develop an effective design, and (c) confirmation analysis of repository performance prior to closure.

5.7 Regulatory Review of Siting Reasoning

In §113(b) of NWPA, Congress called for NRC, State, and tribal review, and public hearings on the SCP prior to sinking shafts for *in-situ* experiments for the suitability stage. NRC provided extensive draft comments on DOE's draft SCP in July 1988 (Table 8) and final comments in August 1989.[3;72;106;136]

An alternative to the site characterization requirements of 10 CFR 60 is the approach adopted in 10 CFR 63, which provided maximum flexibility for characterization by simply requiring (1) site characterization be conducted prior to submittal of an application, and (2) investigations be conducted in a manner that limits adverse effects on repository performance. During site characterization, 10 CFR 63 (like 10 CFR 60) required semiannual reports to NRC that described (a) site characterization results, (b) new issues identified, (c) plans for additional studies, (d) previously planned studies no longer necessary, (e) future decisions points, and (f) changes to the site-characterization schedule.

In the initial promulgation of 10 CFR 60 in 1981 and 1983, NRC required DOE include the reasoning for a site candidacy in the SCP so that NRC could review and comment (§60.11). However, this provision was omitted in 1986 because NWPA had been silent as to whether NRC had a role beyond concurrence with the site selection criteria.[138, p. 27161]

5.8 Technical Investigations for YM Feasibility Stage

The YM feasibility stage began after the final EA in May 1986, Congress chose the YM site to characterize in December 1987, and the final SCP was published in December 1988 (Table 8). In March 1990, permeability testing began in the many surface boreholes. For example, bomb pulse ^{36}Cl was measured in boreholes, which suggests deep fracture flow. In 1993, USGS began drilling the SD well series. The SD well series were completed in 1999; however based on a NWTRB recommendation, DOE decided to curtail surface experiments and move to underground as the exploratory studies facility URL construction began with a tunnel boring machine.[132]

Sandia also explored alternatives to drilling shafts to the exploratory studies facility (located as tunnel along future disposal drifts) in response to the NWTRB critique.[139] The top options out of 34 combinations were ramps, as suggested by NWTRB. Based on the use of ramps, Sandia then developed a conceptual repository design for the feasibility stage in September 1990.

5.9 PA Role in Site Selection and Feasibility Stage

IAEA consensus guidance has recommended using PAs for early decisions about site selection; specifically,[140]

> **Requirement 12: Preparation, approval and use of the safety case and safety assessment for a disposal facility**
>
> A safety case and supporting safety assessment shall be prepared and updated by the operator, as necessary, at each step in the development of a disposal facility, in operation and after closure…

Because PAs provide valuable lessons during each iteration,[141] IAEA elaborated on Requirement 12:

> 4.12. A facility specific safety case has to be prepared *early* in the development of a disposal facility to provide a basis for licensing decisions and to guide activities in research and development, *site selection* and evaluation and design… [emphasis added].

Related to Requirement 12, the IAEA consensus guidance acknowledged that [140, ¶4.10]

> …the development of the safety case should be an iterative process that evolves with the development of the disposal facility…the formality and level of technical detail of the safety case will depend on the stage of development of the project…

Thus, the PA for site identification is not at the technical complexity necessary for evaluating compliance for licensing a facility and indeed the case at YM Project. The EAs conducted by DOE to identify nine potential sites for the commercial repository included a simple deterministic PA that estimated favorable and unfavorable results to compare behavior with the 1982 draft of EPA's 40 CFR 191[39] (Table 6).

Also, many US federal agencies and recommendations of various expert panels and leaders since the 1980s suggest use of general risk assessment at the beginning of a project.[64;142] The lessons from the 1984 Bhopal chemical accident,[143] 1986 Challenger shuttle accident,[144] and 1988 drilling accident in the North Sea,[145] point to using risk assessments early to recognize hazards.[64;142]

Risk assessment, of which PA is a subset, is a tool that was specifically developed to inform policy decisions, such as site selection. Importantly, NRC has been and remains a strong advocate of the use of PAs for all stages of repository investigation.[146] NRC in 1995 specifically established the policy of using probabilistic risk assessments, which are equivalent to PAs in the US, as an important aid to regulatory decisions related to nuclear activities.[147] The Advisory

Committee on Nuclear Waste (ACNW), established in 1988 by NRC, continued to encourage risk-informed approaches to waste management.[142;146]

PA has a role during site selection because PA is used at the end to demonstrate compliance. A PA may provide the only quantitative evaluation among primary qualitative siting criteria (and if any quantitative siting criteria have been established, they likely have been derived from a PA on a generic disposal system). Furthermore, using PA methodology from the beginning embeds its discipline into the project.

PAs, like general risk assessments, synthesize diverse facts from multiple scientific disciplines (and thus viewpoints) about waste disposal components to comprehend the system as a whole. Indeed, the assessment of the "combination" of favorable and potentially adverse conditions, required by 10 CFR 60, benefits from PA support. Not all components (and the underlying scientific disciplines) of the disposal system have equal weight within the disposal system. Although initial screening analysis can identify containment/isolation challenges and perceived uncertainties of a site,[146] it is the PA that provides a means to weigh the identified technical evidence for or against a site.

WIPP was sited prior to 40 CFR 191 and PA analysis. Rather, the supporting screening analysis for WIPP relied on the site-selection EIS (Table 5).[129;148] A simple source-term model based on a constant leach rate and a large regional model was developed. The latter regional model evaluated two-dimensional flow in the Culebra dolomite and one-dimensional radionuclide transport from the repository to the Pecos river over 250,000 years (10 half-lives of ^{239}Pu).[149, Fig. 3-25;150, Fig. 7-1]

Four early PA iterations evaluating selection and feasibility of placing SNF/HLW at YM repository occurred: (1) deterministic evaluations of a volcanic eruption [151], and undisturbed behavior [120;152] conducted to support the environmental assessment required by NWPA (YM-PA-EA—Table 6); (2) YM-PA-91,[153] the first stochastic simulation of both undisturbed behavior and disturbed behavior from igneous and human intrusion (Table 8); (3) YM-PA-93,[51] which provided guidance on characterizing site, selecting options for package placement (either vertical with small packages or horizontal with large packages), and demonstrated both dose and cumulative release measures (Table 8); and (4) YM-PA-95,[154] which improved modeling of the engineered barrier system to better evaluate dose measure (Table 8), as suggested by Congress in *Energy Policy Act of 1992*.[48, §801(a)]

Table 7. Historical steps in conducting investigations over 4.5 years for feasibility stage of TRU waste repository siting.

Steps	Activities on Social Dimension	Activities on Technical Dimension
4. Feasibility stage: investigation and evaluate rough measure of performance of nominated site	*4a. Develop implementing agency; develop institutions for scientific review and state/community cooperation*	*4b. Conduct site investigations using surface exploration methods, waste process knowledge, and general laboratory experiments; evaluate rough measures of performance*
	1978 Jan: Bechtel National starts as WIPP Architect/Engineer. **Jun:** Westinghouse Electric Corp starts as Technical Support Contractor. DOE conducts local hearings on proposed WIPP. DOE requests NAS form panel to review scientific aspects of WIPP.[100] DOE contracts with NM to establish EEG to provide full-time, independent assessment of WIPP and oversee environment, public health and safety. NM legislature establishes[130] (1) Governor's Radioactive Waste Consultation Task Force to negotiate with DOE, and (2) Legislative Radioactive and Hazardous Materials Committee to review activities at WIPP. **Oct:** MIT professor Deutsch recommends that WIPP demonstrate commercial SNF and HLW disposal; DOE presses on with recommendation until 1979 enabling law as a way to satisfy California law banning nuclear plants in California until SNF/HLW disposal demonstrated.[34] **1979 Dec:** Congress defines mission of WIPP:[17] • Sets up WIPP as research and development facility for only TRU waste from defense atomic energy activities • Exempts WIPP from NRC licensing • Requires DOE negotiate C&C Agreement with NM **Apr:** DOE publishes Draft EIS on WIPP site selection published. Draft EIS defines WIPP as combined defense/commercial repository.[129] **1980:** DOE and NM begin negotiations on procedures and process of cooperation for C&C Agreement. **Oct:** Final EIS eliminates commercial HLW/SNF disposal at WIPP.[129] **Nov:** DOE applies to Department of Interior (DOI) for administrative withdrawal of WIPP land for Site and Preliminary Design Validation (SPDV) program.[155]	**1976:** Sandia begins geologic site investigation and engineering design. **Apr:** Laboratory tests on TRU waste behavior and HLW/SNF packages initiated.[156;157] Sandia sends guidance to TRU waste generators and storage sites, that waste is to be incinerated to remove organic material. **1977:** Sandia issues conceptual design report of WIPP repository layout with ~33% extraction ratio (room layout essentially remained unchanged in implemented design).[158] Various natural backfills proposed such as salt, salt/bentonite, or salt/apatite.[159] **1978:** Sandia begins design of the Transuranic Package Transport (TRUPACT-I) using standard cargo box concept. **Aug:** Sandia completes major geologic investigation report.[125] Sandia builds regional 2D hydrologic and 1D transport model to estimate 250,000 years of radionuclide movement to Pecos River (10 half-lives of ^{239}Pu) for site-selection EIS.[129;148] Hydraulic conductivity assigned for several regions of Culebra dolomite based on 4 wells[125;149] of the 47 boreholes completed by USGS. **1979:** Sandia begins 3-y test program on (1) crushed salt consolidation,[126] and (2) thermal/structural effects in nearby potash mine,[127] and Avery Island salt dome in Louisiana (off site URLs).[128] First permeability measurement of Salado Fm in AEC-7 well using compress air; value 1000 times larger than found when measured in repository in 1988. Based on high salt permeability, DOE cancels all gas generation experiments. DOE drops requirement to incinerate TRU waste. Laboratory measurements of ERDA-9 core permeability.[126] As part of EIS, Sandia develops FEPs/scenarios of radionuclide release.[160] DOE buys oil and gas leases around WIPP site. **Jul:** Bechtel identifies 7 potential repository horizons in Salado Fm. Bechtel completes preliminary Title I design of WIPP.

Table 8. Historical steps in conducting investigations over 9 years for feasibility stage of commercial SNF/HLW repository siting.

Steps	Activities on Social Dimension	Activities on Technical Dimension
4. Feasibility stage: evaluate rough measure of performance of nominated sites and review	*4a. Nominate sites; prepare site investigation plan; initiate state/tribe, scientific, and regulatory review*	*4b. Conduct site investigations using surface exploration methods, waste process knowledge, and general laboratory experiments; evaluate rough measures of performance*
	Nuclear Waste Policy Amendments Act NWPAA)[21] in December 1987 forms Nuclear Waste Technical Review Board (NWTRB) to advise Congress and DOE (following example of NAS Review Panel for WIPP). NWTRB to consist of 11 members appointed by the President from slate of candidates nominated by NAS.[21, §5001] NWPA §113(b)(1)(A): DOE to submit SCP to state or tribe prior to beginning site characterization • **1988 Jan:** DOE publishes draft site characterization plan (SCP) (i.e., investigation plan for feasibility and suitability stage) for state and NRC review. **Jul:** NRC criticizes quality assurance (QA) program, lack of alternative conceptual models, and lack of PA to rank activities/experiments; NRC notes that co-location of URL test facilities with disposal drifts requires that construction of URL meet QA licensing criteria. In turn, QA criteria for URL required heightened scrutiny of experiments to ascertain whether tests would interfere with long-term performance.[136] **Dec:** DOE publishes final 9-volume SCP with ~300 activities/experiments for surface, underground, and laboratory test and corresponding models to answer licensing questions and concerns raised by stakeholders.[161]	**1988 Jul:** DOE employee Szymanski hypotheses that earthquakes force water hundreds of meters above water table ("seismic pumping").[162] **1990 Mar:** First report of NWTRB:[50] (1) criticizes using drilling/blasting to excavate URL region, (2) criticizes lack of progress in PA since YM-PA-EA; (3) suggest replacing shafts with ramps. As part of permeability testing in boreholes started after SCP published, bomb pulse ^{36}Cl found in boreholes which suggests deep fracture flow **Sep:** In response to NWTRB critique, Sandia explores alternatives to shafts to exploratory studies facility;[139] top options out of 34 is ramps; DOE develops conceptual repository design for feasibility stage. **1991 Jun:** Deterministic PA analysis demonstration (PACE-90) completed.[163] **Oct:** In response to NRC critique, DOE conducts Test Prioritization Task to rank SCP tests.[137] **1992** NAS finds no evidence for "seismic pumping"[164] **Jan:** DOE support contractor completes Early Site Suitability Evaluation using 10 CFR 960 criteria for Congress. **Jul:** YM-PA-91 completed;[153] it is the first stochastic simulation of both undisturbed behavior and disturbed behavior. **Dec:** NWTRB urges system study of storage, transportation, disposal such as using large horizontal placement of packages to avoid handling SNF at repository.[132] **1993:** USGS begins drilling SD well series; series completed in 1999. DOE decides to curtail surface experiments and move to underground as exploratory studies facility URL construction begins with tunnel boring machine, based on NWTRB recommendations.[132] **1994 Apr:** YM-PA-93 completed; it provides guidance on characterizing site, selecting options for package placement (either vertical with small packages or horizontal with large packages), and demonstrates both dose and cumulative release measures.[51] **1995:** YM-PA-95 analysis improves modeling of engineered barrier system for evaluating dose.[154]

6 IMPLEMENTING SITE CHARACTERIZATION FOR SUITABILITY STAGE

The IAEA consensus requirements, state

> **Requirement 15: Site characterization for a disposal facility**
>
> The site for a disposal facility shall be characterized at a level of detail sufficient to support a general understanding of both the characteristics of the site and how the site will evolve over time. This shall include its present condition, its probable natural evolution and possible natural events, and also human plans and actions in the vicinity that may affect the safety of the facility over the period of interest. It shall also include a specific understanding of the impact on safety of features, events and processes associated with the site and the facility.

6.1 US Context for Characterization

For the US, §2 of NWPA (with similar definitions at §60.2 and §63.2 in NRC regulations) defines site characterization as environment-specific laboratory experiments and *in-situ* experiments in a test and evaluating facility or URL at a candidate site that occurs during the suitability/viability stage. The definition specifically recognizes that there might be preliminary borings and geophysical testing to assess whether a site qualifies for detailed site characterization and excludes such activities from the definition of site characterization: [e]

> The term "site characterization" means—(A) siting research activities with respect to a test and evaluating facility at a candidate site; and (B) activities, whether in the laboratory or in the field, undertaken to establish the geologic condition and the ranges of the parameters of a candidate site relevant to the location of a repository, including borings, surface excavations, excavations of exploratory shafts, limited subsurface lateral excavations and borings, and in situ testing needed to evaluate the suitability of a candidate site for the location of a repository, but not including preliminary borings and geophysical testing needed to assess whether site characterization should be undertaken.

6.2 WIPP Suitability Stage

Several institutional decisions ushered in the WIPP suitability stage. In December 1979, the enabling legislation for WIPP required DOE negotiate a C&C Agreement with the State of New Mexico (Table 7) Negotiations were begun in 1980; however, progress was slow. In January 1981, DOE published a Record of Decision on the site-selection EIS to proceed with site suitability experiments (i.e., Site Preliminary Design Validation program or SPDV).[165] In May 1981, the SPDV contractor began drilling the first shaft. The State of New Mexico promptly sued without a C&C Agreement (Table 10).[166] The US Secretary of Energy James Edwards flew to New Mexico to meet with Governor King and acceded in a Stipulated Agreement to (1) geotechnical experiments; (2) Sandia reports on 17 technical issues of concern to New Mexico (e.g., disruptive scenarios such as breccia pipe, salt dissolution, salt deformation); (3) state and public review of WIPP; and (4) creation of state/federal task force on TRU waste transportation issues (e.g., emergency response, routes, and highway upgrades). The C&C Agreement was attached as Appendix to the Stipulated Agreement. The US District Court stayed the lawsuit in accordance with Stipulated Agreement and, thus, provided the State of New Mexico with a binding agreement on site characterization studies of interest to the State (Table 10).[166]

As part of the Stipulated Agreement, WIPP-12 borehole north of the WIPP site deepened in 1981 and intersected a pressurized brine pocket/reservoir in November.[167] The discovery had ramifications related to modeling inadvertent intrusion in PA analysis. Based on WIPP-12 evaluation and EEG recommendation, the TRU waste disposal area was moved ~1800 m south in 1982 by flipping the repository layout.

By 1983, Sandia, USGS, and contractors had reported on most of the 17 topics of interest to the State of New Mexico required by the Stipulated Agreement.[168] Based on pump and transport tests of the Culebra dolomite in wells around WIPP, Sandia had concluded by 1987 that single porosity adequately modeled fluid flow but that transport best modeled as a dual porosity media, based on tests at H-3 well.[169-171] However, more tracer testing was needed to derive parameters.

As experimental rooms and drifts were excavated, Sandia measured room deformation. By 1985, it was

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[e]In the literature, site characterization can infer a broad, general exploration of site characteristics. However, because NWPA (and NRC in implementing NWPA) narrowly defines site characterization to those activities associated with the suitability/viability stage, this text uses the term site investigation when referring to general exploration of a site in the US context.

evident that observed salt creep in rooms was about three times more than predicted.[172] Results from the creep tests in the circular pillar Room H helped Sandia resolve much of the discrepancy by 1989.[173] Yet, final resolution of the discrepancy did not occur until 2022.[174;175]

In May 1987, Sandia reported that much more brine had migrated to simulated HLW canisters in the experimental rooms than had been expected. By December, the national press was reporting on the issue of brine flow into the repository[176] and environmental groups voiced concern of too much brine seepage into repository. In January 1988, the New Mexico Congressional Delegation asked the full NAS Board on Radioactive Waste Management (full BRWM—not just the NAS WIPP Review Panel) to study potential brine inflow into WIPP after closure. To support the BRWM, Sandia made a concerted effort to explain the seemingly contradictory *in-situ* measurements of low Salado permeability but high brine flow around simulated HLW canisters.[177] Later that year, the BRWM concluded rapid salt creep combined with low salt permeability meant the WIPP repository would be well consolidated before much brine entered; however, NAS suggested an additional brine inflow verification test. Between January and August 1989 Room Q was mined and instrumented for a new brine inflow experiment.[178]

From measured nitrogen gas flow around room drifts in 1984[179] and injected brine flow around room drifts in 1986,[126] the predicted permeability was a factor of 1000 less than previously estimated by compressed air in AEC-7 well in 1979 (Table 7). Thus, gas generated from corrosion and microbial degradation of TRU waste would not dissipate in the host salt. The 1989 Supplemental EIS identified gas generation as an issue to study for compliance analysis.[149]

In December 1990 and 1991, Sandia issued the first and second complete probabilistic PAs (WIPP-PA-90[180] and WIPP-PA-91[181]), which coupled all major models, highlighted rigorous use of scenarios, and used geostatistics for assigning the transmissivity fields of the Culebra dolomite.

6.3 WIPP Construction during Suitability Stage

In March 1983, construction of surface handling facilities began (Table 10). Underground excavation primarily involved the experimental area of the repository since salt creep precluded excavating much of the disposal area prior to operations. Construction of surface handling facilities after the feasibility stage and while scientific studies for suitability/viability were ongoing was a situation unique to WIPP. Opponents might argue that the approach used at WIPP increased the financial commitment at the site and possibly provided a disincentive to abandon the site should unfavorable conditions have been found during *in-situ* site characterization. However, the likelihood of encountering severe problems in salt media was remote after the site identification/feasibility investigation. Furthermore, the financial commitment by the federal government during the suitability/viability stage (1) allowed the local community to directly enjoy financial benefits, such as employment; and (2) strengthened the state/local government position, in some ways, when reviewing WIPP designs and requesting consideration of benefits. For example, on several occasions the Mayor of Carlsbad requested that more benefits accrue to the city. The latter requests resulted in moving staff and WIPP oversight to Carlsbad in 1984 (Table 10). Also, EEG strongly insisted on redesigning the TRUPACT-I container in 1985 (Table 10). In contrast, construction could not begin prior to NRC construction authorization for the YM repository for commercial SNF/HLW.

6.4 Transportation Issues Provided Opportunity for Public Discourse on WIPP

Public opposition to a hypothetical facility handling nuclear material typically increases the closer a respondent is to a hypothetical facility in general surveys of public opinion. The situation is different, however, for an actual nuclear facility. Support is usually high near an existing nuclear facility, and favorable support by New Mexico residents was indeed observed near WIPP.[182, Fig. 4]

Similarly, public opposition to radioactive waste transportation typically increases the closer a respondent is to a hypothetical route. In fact, transporting SNF/HLW through a community piques as much interest as does siting an interim storage facility, based on 2013 national survey (Table 9).

This concern about transportation was evident at the 1989 hearings on the 1989 Supplemental EIS for WIPP where lack of progress by the joint federal/state task force on emergency training along designated transportation routes was criticized;[183] creation of a joint task force had been mandated in the 1981 Stipulated Agreement—Table 10.

Table 9. Concern for transportation similar to concern for a Consolidated Interim Storage Facility in 2013 national survey.[87, Table 8.1]

If a storage site/transportation route for CSNF was proposed within 50 miles of your residence, how likely is it that you would…	**Mean Response** 1~not at all likely 7~extremely likely	
Activity	**Interim Storage**	**Transport Route**
Attend informational meetings	4.37	4.22
Contact your elected representatives	4.20	4.24
Express your opinion on social media	3.96	4.02
Serve on citizen advisory committee	3.92	3.91
Help organize public *support*	3.07	3.09
Help organize public *opposition*	3.05	3.10
Speak at a public hearing in your area	2.97	3.08

As part of the DOE response to comments on the Draft 1989 Supplemental EIS, the joint federal/state task force designated transportation routes and provided funding for emergency equipment and exercises with local first responders. The exercises included simulated accidents that were observed by local media. The exercises provided an opportunity to visibly explain DOE's role for repository disposal with first responders and, indirectly, the public. The training exercises resulted in increased support for WIPP among first responders along transportation routes far from the WIPP repository. Because EMs from state and local police and fire departments, are highly trusted (mean of 6.1 in Fig. 4), their favorable impression from training possibly indirectly increased public trust.

6.5 YM Projected Characterization Costs

After Congress selected the YM disposal system for characterization in NWPAA, the YM Project studied a wide variety of topics under the revised expectation that most knowledge would be acquired prior to construction authorization. Furthermore, studies continued into the licensing stage to demonstrate thoroughness and withstand numerous contentions by State of Nevada. Specifically, YM Project costs for site characterization, repository and package design, PA, and documentation had increased to $8.2 billion (2007 constant dollars) in 2001 for the site suitability/viability stage. Contributing to these cost increases was co-location of the URL test facilities in the main drift of the proposed YM repository, which required that test facility construction meet QA licensing criteria. In turn, QA licensing criteria for the URL required heightened scrutiny of experiments to ascertain whether tests would interfere with long-term performance.[136]

For licensing the proposed YM repository, the cost had increased further to ~$11 billion (2010 constant dollars), 20 years after NWPAA.[184, Tables ES-1 & ES-3]

6.6 YM Site Characterization and Suitability Stage

The YM suitability stage began after SCP tests were re-evaluated, a QA program completed, and state permits issued for *in-situ* experiments for YM site characterization. The decision to allow temperatures above boiling in the disposal drift, in conjunction with the use of large, in-drift disposal containers, prompted questions about the coupling of thermal, hydrologic, and chemical processes during the ~1000-year thermal period. Hence, YM Project conducted much experimental work and code development to advance the science of coupled thermal-hydrologic-chemical modeling during the suitability stage (Table 11).[3]

By the time of the Congressionally mandated 1998 viability assessment (YM-PA-VA), site characterization had collected data on net infiltration into the mountain, bomb-pulse chlorine (^{36}Cl) concentrations in fractures at the repository horizon, and movement of water around a single heater test and a large block test (Table 11). Site characterization had also conducted hydraulic tests on core samples, pneumatic tests in existing wells, and mapped fractures in the exploratory studies facility.

As understanding of the YM disposal system increased through site characterization and *in-situ* testing, modeling of infiltration, percolation, and seepage evolved from simple assumptions in a single model in 1984 to individual modules based on detailed process models by YM-PA-VA in 1998. Also, for YM-PA-VA, five Expert Elicitation Panels were formed to evaluate current models and literature data used in YM-PA-95 and or proposed for YM-PA-VA prior to completion of the experimental program. Site characterization for site suitability lasted ~7 years for the YM repository from 1996 to 2022, when the DOE completed the site-recommendation EIS.[185]

6.7 PA Role During Characterization and Suitability Analysis

Once a site is selected for site characterization, the focus moves to uncertainties in system understanding and whether enough work has been done to resolve uncertainties sufficiently to support subsequent decisions. The data needs related to uncertainty become driving factors, leading to significantly increasing costs and extended schedules, which if unconstrained, could occur at every site that is identified for potential selection. To counteract the tendency to expand site evaluation activities beyond what is necessary for siting and licensing decisions, several approaches were applied.

First, the regulatory environment, noted in §2.1, provided an analysis framework for calculating performance measures, applicable FEPs and scenario classes to consider, and, thus, help constrain data needs.

Second, PAs were used to identify important issues and prioritize data collection needs. One NRC criticism of the YM SCP was not using a PA to guide prioritization and selection of site characterization activities.[136;146] YM-PA-93 and YM-PA-95 were used to examine design options as suggested by NWTRB. WIPP used sensitivity analysis from the WIPP-PA-91 and WIPP-PA-92 to prioritize experimental activities and coupled PA with decision analysis to rank activities in 1994 for the compliance phase in 1994.

Third, PAs showed that sufficient characterization of the disposal system has occurred. For example, when WIPP PAs showed that direct releases from drill cuttings (which was not dependent upon characteristics of the natural barrier) clearly dominated total releases, [15, Fig. 3] it became clear that the WIPP Project had conducted sufficient characterization of the disposal system.[13, p. 39] Likewise, the final YM-PA-LA supporting SAR/LA showed that disruptive events such a volcanism and seismicity dominated releases (for which further characterization could only provide marginal improvement in estimates) and not releases from the normal evolution of the disposal.[11, Fig. 8]

In summary, the YM and WIPP PAs based on early information provided useful insight as to the behavior of the disposal system. Specifically, the rudimentary estimates made for 1984/1986 YM-PA-EA environmental assessment for the proposed YM disposal system and the early WIPP-PA-90 PA identified the range of behavior that would be observed in later more detailed PAs, as discussed more thoroughly in related papers.[11;13]

With the current international experience and knowledge of repository performance in many types of geologic media, early PA bounding estimates on performance for future repositories will likely be reliable and the range of uncertainty about these estimates quite consistent with final PA results required for the licensing case. This finding coupled with[64] (1) the wide use of risk assessments in screening throughout the federal government,[186] (2) the recommendation of expert panels to use risk assessment to recognize hazards early,[144;146] and (3) the fact PAs conveniently synthesis diverse behavior in system components to comprehend the system as a whole, support the use of PAs as an important aspect of site selection and feasibility analysis in addition to suitability and compliance analysis.

Table 10. Historical steps in conducting investigations over 11 years for site suitability of repository for defense TRU waste.

Steps	Activities on Social Dimension	Activities on Technical Dimension
5. Implement suitability stage demonstrating viability of disposal	*5a. Negotiate cooperative agreement on topics of interest to state/community or tribe for suitability site characterization*	*5b. Conduct site characterization for suitability stage using environment-specific laboratory experiments, underground disposal system characterization, and in-situ experiments*
	1981 Jan: DOE publishes Record of Decision to proceed with SPDV to validate that designed dimensions of rooms and drifts will be stable.[165] **May:** Without C&C agreement, NM sues DOE and DOI.[166] Secretary of Energy, Edwards, travels to NM to meet with Gov. King and accedes in Stipulated Agreement to (1) geotechnical experiments; (2) Sandia reports on 17 technical issues (e.g., disruptive scenarios such as breccia pipe, salt dissolution, salt deformation); (3) state and public review of WIPP; and (4) creation of state/federal task force on TRU waste transportation issues. C&C Agreement attached to agreement. US District Court stays lawsuit in accordance with Stipulated Agreement.[166] **1982 Jun:** Army Corps of Engineers assumes responsibility for construction management. **Dec:** Supplemental Stipulated Agreement signed that commits DOE to (1) seek funds for upgrading NM highways; (2) conduct more geotechnical studies; and (3) liability for WIPP-related accidents. **1983 May:** EEG concludes that WIPP site has been characterized in sufficient detail to warrant confidence in suitability for disposal but recommends additional evaluation of brine pockets.[187] **Jun:** DOI approves land withdrawal for 8-y to construct WIPP. **Jul:** DOE decides to proceed with WIPP construction.[188] **1984 Mar:** Manager of DOE Albuquerque Operations Office moves WIPP Project Office to Carlsbad NM. **Nov:** C&C Agreement amended to limit remote-handled TRU waste to $5.1{\times}10^6$ Ci. **1985 Feb:** EEG notifies DOE that single-shelled vented TRUPACT-1 unacceptable.[189] **Sep:** Project focuses on near-field hydrology model with definition of 5-km disposal system boundary in 40 CFR 191. **1986 Aug:** DOE asks Sandia to assess WIPP compliance against 40 CFR 191.[190] **Oct:** In preparation for operations, Westinghouse awarded M&O contract. Army Corp of Engineers relieved of construction management. **1987 Jul:** DOE signs agreement with Department of Labor for mine inspections.[191] **Aug:** In 2nd amendment to C&C Agreement, NRC given jurisdiction over container for shipping radioactive waste to WIPP and commits DOE to comply with all applicable laws and regulations, and discourage WIPP compliance by way of grandfathering, variances, or exemptions. **Oct:** Nuclear Packaging become A/E for the TRUPACT-II design. Sandia retained as DOE technical advisor. **Dec:** National press reports on brine seepage into WIPP.[176] **1988:** NM Congressional delegation asks NAS to study potential brine inflow into WIPP after closure. **1989:** DOE publishes Draft Supplemental EIS and holds hearings in Carlsbad, Albuquerque, and Santa Fe.[192] **1990 Jan:** DOE publishes Final Supplemental EIS on site suitability.[183] **Jun:** In Record of Decision, DOE states WIPP construction complete and compliance testing pilot phase should proceed.[193;194] **1991 Jan:** DOI modifies administrative land withdrawal to allow pilot phase of WIPP. NM files 1000-page lawsuit challenging DOI land withdrawal.[195]	**1981 May:** Fenix & Scisson, SPDV construction contractor, begins augering first shaft. **Oct:** 1st shaft completed. **Sept:** Bechtel begins detailed design phase with 38% extraction ratio for panels and 22% overall (Title II). **Nov:** As part of Stipulated Agreement, WIPP-12 borehole north of the WIPP site deepened and intersects pressurized brine pocket.[167] **1982 Mar:** Sandia publishes plans for *in situ* experiments, such as thermal mechanical creep tests.[196;197] 2nd shaft completed. **Nov:** Excavations connect the two existing shafts. Based on WIPP-12 evaluation and EEG recommendation, TRU waste disposal area moved ~1800 m south. **1983: Mar:** DOE gives SPDV reports to NM for review. Sandia, USGS, and contractors complete most reports required by Stipulated Agreement[168] (e.g., USGS dismisses breccia pipe formation[198] and reports on geohydrology around WIPP;[199] Sandia reports on groundwater flow in Culebra dolomite[200] and deformation of evaporites near WIPP[201]). Construction of surface facilities and excavations of experimental rooms begin. **1984 Feb:** 3rd shaft completed. **Apr:** Sandia begins fielding underground experiments.[169] As room excavated, Sandia measures room deformation and nitrogen gas flow around room drifts.[179] Pump tests at DOE-1 suggest fracture flow in Culebra. **1985 Jan:** Sandia reports 3 times more salt creep measured than predicted.[172] **1986 Feb:** Pillar creep test begins in circular experimental Room H. First injected brine flow measurement around drifts.[126] **1987 Mar:** Based on well H-3 tests, Sandia finds single porosity adequately models fluid flow in Culebra but transport best modeled as dual porosity media.[169-171] **1988** Sandia reports *in-situ* salt permeability 1000 times lower than measured in AEC-7 in 1979.[177] NAS concludes rapid salt creep combined with low salt permeability means WIPP repository would be well consolidated before much brine entered; however, NAS suggested an additional brine inflow experiment. **1989 Jan-Aug:** Room Q mined and instrumented for new brine inflow experiment.[178] **Feb** Sandia resolves many discrepancies between measured and predicted salt creep[173] (final resolution in 2022[174;175]). **Mar:** Sandia completes report to support Draft Supplemental EIS, which identifies gas generation as issue to study.[149] DOE funds Sandia to plan new studies of gas generation, which had been cancelled in 1979.[202;203] **Aug:** NRC approves TRUPACT-II for shipping contact-handled (CH-TRU) waste to WIPP. **Dec:** Sandia completes PA demonstration.[204] **1990 Dec:** Sandia issues 1st complete probabilistic PA (WIPP-PA-90) which couples all major detailed models, includes all scenarios, and uses geostatistics for Culebra transmissivity field.[180;205] **1991 Dec:** Sandia issues 2nd PA (WIPP-PA-91) highlighting major modeling components and rigorous use of scenarios and geostatistics for transmissivity fields, 46 parameters sampled.[181]

Table 11. Historical steps in conducting investigations of site suitability over 6 years for commercial SNF/HLW repository in US.

Steps	**Activities on Social Dimension**	**Activities on Technical Dimension**
5. Implement suitability stage demonstrating viability of disposal	*5a. Negotiate cooperative agreement on topics of interest to state/community or tribe for suitability site characterization and obtain Congressional approval*	*5b. Conduct site characterization for suitability stage using environment-specific laboratory experiments, underground disposal system characterization, and in-situ experiments*
	1996 In deference to Russia, DOE decides in programmatic EIS to convert ~34 t non-pit metal surplus Pu to mixed oxide fuel and dispose resulting SNF at YM repository.[206] **1997** In FY97 budget, Congress calls for a viability assessment (VA) that includes (1) YM-PA-VA, (2) design for the repository and package, (3) cost for completing the license application, and (4) cost for constructing, operating, and closing the repository.[207] **Jan:** To meet NWPA requirement to comment on site characterization sufficiency, NRC identifies 9 key technical issues (KTIs) important to repository performance (plus a 10th issue related to promulgating 10 CFR 63). NRC decides to periodically write reports on the 9 KTI topics[208] and conduct technical exchanges with DOE to facilitate resolution. **1999 Feb:** NRC promulgates draft 10 CFR 63. [209] **Aug:** EPA promulgates draft 40 CFR 197. [210] **Nov**: DOE drafts revised guidelines (10 CFR 963) for evaluating YM suitability by using PA, which examines system as a whole, following precedent set by NRC in draft 10 CFR 63.[84]	**1994-1996:** DOE changes construction method to tunnel boring machine with mildly inclined access ramps.[51, §4.4] Main & test drifts bored; fracture maps developed. *In-situ* experiments begun to evaluate coupled processes after SCP tests re-evaluated, QA program completed, and state permits issued. **1994-1996:** Infiltration[211] & ^{36}Cl monitoring in drifts; USGS completes infiltration model, INFIL.[212] **1997-1999:** Seepage tests near main drift.[213, Fig. 4-17] **1996-1997:** Single Heater Test near main drift.[214, Ch. 10;215] **1996-1997:** Large-Block Heater Test at offsite Fran Ridge URL.[216]. **1997-2006:** Drift-Scale Heater Test near main drift to evaluate chemical environment evolution.[215] **1998-2000:** Tracer migration tests at offsite Busted Butte URL.[217] **1998-2004:** Nye Country wells drilled at edge of NNSS to better define fluid flow and radionuclide transport in saturated zone. **1998:** YM-PA-VA completed for viability/suitability analysis for Congress.[218] YM-PA-VA used 5 expert panels to evaluate current information and made major step in model complexity by adding process models for infiltration, drift seepage, chemical environment and biosphere transport. **1999 Apr:** DOE completes conceptual repository and package design for suitability stage,[219] several design options examined in LA Design Study (LADS) using PA; results in adding titanium drip shields to design. **1999 Mar-Oct:** USGS conduct borings in drift to find ^{36}Cl.[220, §3.2] **2000** YM-PA-SR supports site recommendation using conservative parameters and conservative models,[221] which ACNW notes complicates understanding **2001** NAS concludes that after 40-y of study, "geologic disposal remains the only scientifically and technically credible long-term solution available to meet safety needs."[222] As requested by NWTRB, YM-SSPA examines impact of conservative analysis in YM-PA-SR using more realistic models and parameters. YM-SSPA also evaluated alternative cool repository[223] **Dec:** Joint IAEA-NEA (International Atomic Energy Agency and Nuclear Energy Agency) international team completes review of YM-PA-SR[224] and suggests developing a safety case (i.e., the strategy used to achieve safety as distinct from YM-PA-SR showing compliance with regulations). IAEA review of biosphere model suggests updating biosphere model for LA.[225]

7 COMPLIANCE STAGE AND REVIEW/APPROVAL

7.1 WIPP Compliance Analysis

The DOE Record of Decision on 1989/1990 Supplemental EIS and the 1992 LWA ushered in the WIPP compliance stage. Because of the highlighted issue of gas generation in the 1989/1990 Supplemental EIS, DOE funded Sandia to conduct studies of gas generation. The initial plan was to conduct laboratory experiments and confirm the results using bins of real TRU placed within repository rooms during the WIPP pilot phase. However, the State of New Mexico strenuously opposed bringing any TRU waste to WIPP, until compliance with 40 CFR 191 was demonstrated. Hence, the 1992 WIPP LWA required the NAS WIPP Review Panel to certify the need for *in-situ* experiments with real waste at the WIPP repository. In June 1992, the NAS WIPP Review Panel questioned the need for *in-situ* experiments (Table 12). Without an NAS endorsement for a WIPP pilot phase, DOE decided to submit a Draft Compliance Certification Application (CCA) to focus interactions with EPA.

In December 1992, Sandia issued its third PA (Table 12). [226;227] WIPP-PA-92 represents a transition from suitability analysis and compliance analysis. It is included here as part of the compliance analysis because (1) it was the basis of the Draft CCA, and (2) the sensitivity analysis strongly determined the necessary experiments and data collection for the CCA. WIPP-PA-92 was also the basis of System Prioritization Methodology (SPM) that linked PA methodology with decision analysis, whose purpose was to rank the importance of proposed and on-going experiments for completion of the WIPP-PA-CCA.

Experiments identified as important for WIPP-PA-CCA included (1) brine inflow measurements from dewatering disturbed salt in Room Q, which was completed in 1993; (2) tracer tests in the Culebra dolomite to determine parameters for dual porosity transport formulation, which began in February 1995. and (3) laboratory gas generation experiments, which were completed in September 1995.[203;228] Other experiments were stopped and the experimental area of WIPP closed in 1995 (Table 12).

In October 1996, Sandia completed the PA for CCA that included[229-231] (1) MgO backfill, (2) potash mining scenario, and (3) greater intrusion rate. Drill cuttings and cavings were the only releases in WIPP-PA-CCA (except for a few vectors with groundwater release). Hence, the compliance analysis lasted ~4 years.

7.2 WIPP CCA Submittal and EPA Review

WIPP was authorized under the *Administrative Procedures Act* using a regulatory rule-making process. Under this process, DOE submitted a compliance certification application to EPA in October 1996. [232;233] In November, DOE issued the 84,000-page Second Supplemental Draft EIS for WIPP operation and receipt of waste.[234] Also in November, the NAS WIPP Review Panel stated that the WIPP site “excellent choice” geologically.[235]

After submittal of the CCA, EPA conducted extensive review of the justifications for parameter values and mathematical models in WIPP-PA-CCA. In response to EPA requests for additional information, more PA analysis and documentation, totaling 20,000 pages, were provided to EPA.

In January 1997, the Conceptual Model Peer Review Group (formed in response to 40 CFR 194) concluded 22 of 24 conceptual models adequate. However, the spallings model (i.e., estimate of contaminated particles carried to surface in drilling mud) lacked sufficient realism (i.e., wildly conservative[236]) and needed to be redone and MgO backfill description needed to be improved (Table 12).

In May 1997, EPA required a PA verification test (PAVT) using EPA’s own assumptions for the spallings model and changes in distributions for 26 parameters with more pessimistic bias added.[236, §2.6;237] In October, EPA proposed a draft finding of compliance for WIPP.[238] EPA then responded to comments on the proposed rule-making submitted by other government agencies, non-government environmental organizations, and the public.

In January 1998, EPA certified WIPP with conditions:[238;239] (1) panel seals are required, (2) QA program required for waste generators, (3) DOE must abide by listed requirements for using process knowledge to characterize waste, (4) DOE must provide schedule for installing passive controls. In addition, EPA denied DOE the option to take credit for passive controls that reduced the frequency and timing of inadvertent drilling into the repository in WIPP-PA-CCA.

In March 1999, the District Court lifted the injunction on WIPP placed in 1992 related to mixed RCRA waste. Later that month, the first shipment of TRU waste arrived at WIPP from Los Alamos.[240;241] In October of that same year, the New Mexico Environmental Department issued the permit for WIPP to accept RCRA waste mixed with TRU waste (Table 12).

7.3 Regulatory Viewpoint for Public

IAEA, in its consensus standard, makes 36 basic suggestions on establishing a governmental, legal, and regulatory framework. The last suggestion concerns communication [242]:

> **Requirement 36: Communication and consultation with interested parties**
>
> The regulatory body shall promote the establishment of appropriate means of informing and consulting interested parties and the public about the possible radiation risk associated with facilities and activities, and about the processes and decisions of the regulatory body

EPA first promulgated the regulatory standards for radioactive waste disposal in 1985 (Table 1); however, EPA was not designated as the regulatory implementor until the WIPP LWA in 1992 (Table 1), 19 years after site investigations began in southern New Mexico in 1973 (Table 5). Although, the appearance of the regulator at the end of a 19-year siting process had the potential to be problematic, other aspects of the WIPP project communication compensated for this lack of EPA regulatory communication with the public. These other aspects included (1) extensive early communication with the public by the science advisor (Sandia) for DOE; (2) hearings on the WIPP EIS in 1980, 1990, and 1997;[38;183;243] (3) opportunities for the public to observe the NAS WIPP Panel Review of scientific studies (§5.3, Table 7); and (4) State of New Mexico participation in WIPP review through EEG ((§5.3, Table 7) and RCRA permit (Table 12).

In §60.61 and §60.62, NRC recognized the value of providing a regulatory viewpoint early in the licensing process, but it was upon request of state and affected local and tribal governments and after a site had been approved for detailed site characterization; that is:

> **§60.61 Site review**
>
> Upon publication in the Federal Register of a notice that the DOE has selected a site for site characterization, in accordance with §60.11(b), and upon the request of a State, the Director shall make available NRC staff to consult with representatives of State, Indian tribal and local governments to keep them informed of the Director's view on the progress of site characterization and to notify them of any subsequent meetings or further consultations with the DOE.

This communication is important, because the public is not always attentive to US policy for managing the radioactive waste produced from nuclear power (Fig. 5). Attention tends to ebb and flow over time. For example, noteworthy events such as the tsunami-initiated reactor damage and hydrogen gas explosions at the Fukushima nuclear complex in Japan, can increase public awareness. However, this knowledge may decay with time.

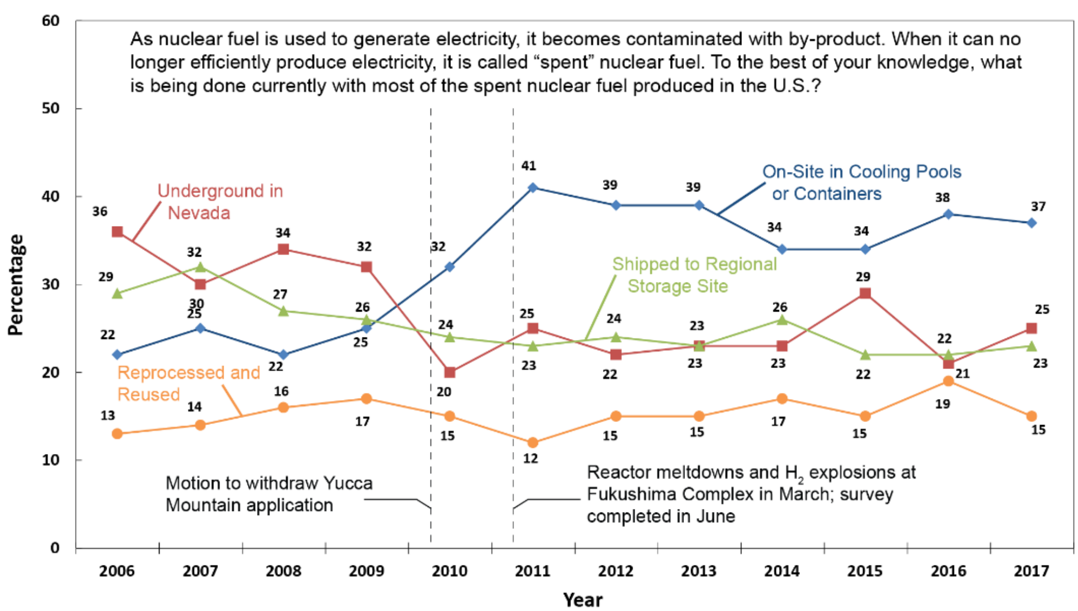

Fig. 5. Since nuclear accident at Japan Fukushima Complex, awareness of current US policy of storing commercial spent nuclear at reactor sites increased from 22% in 2006 to 41% in 2011 but occasionally dropped thereafter to 34% up through 2017.[134, Figure E-6]

7.4 YM Compliance Analysis

The YM compliance stage lasted for ~7 years between December 2001 (when YM-PA-EIS and the supplement to the site recommendation EIS was completed) and January 2009 (when DOE submitted an updated SAR/LA to NRC). As many experiments were completed, the YM Project transitioned to fully qualifying analysis, parameters, and software for the YM-PA-LA.

The experiments completed during this period included zeolite sorption of short-lived radionuclides in the tuff layers below the repository,[217] USGS updates to the regional flow models,[244] and a new aerial magnetic survey of anomalies around YM to resolve remaining questions on igneous history.[245]

In 2003, most of the Analysis Model Reports (AMRs) underlying the PA and SAR/LA were completed. In May 2003, however, an NRC audit found QA procedures were not producing a quality product. Thus, the YM Project was reorganized to form teams to conduct a six-month review of AMRs to improve justification and traceability to sources of information for what was now designated as an interim PA for LA, YM-PA-04.[246]

For the SAR/LA review and hearings in front of the Atomic Safety Licensing Board (ASLB), NRC required that all documents related to the SAR/LA be placed in a Licensing Support Network (LSN) to facilitate access by all parties. DOE placed ~1.2 million documents including ~700,000 e-mails (~5.6 million pages) in 2004.[247] As part of that effort, DOE notified NRC that when reviewing the submittal, e-mails were found between three USGS geo-hydrologists from 1998 to 2004 that raises questions about collection of infiltration data and fabrication of QA records. In October of 2005, DOE directed Sandia to redo the USGS infiltration model, INFIL.[248]

In May 2006, YM-PA-LA was started; it included analysis out to 10^6 years; replaced the near-field chemistry model; replaced USGS INFIL with Sandia MASSIF model; and modeled large in-drift packages. In January 2008, Sandia completed YM-PA-LA,[249] with a maximum dose of 0.02 mSv/y at 10^6 years in two scenarios: igneous intrusion scenario breaching all waste packages and undisturbed/seismic scenario breaching ~10% of waste packages.

NRC staff found the proposed YM repository met regulatory technical requirements in 2015.[250;251] Earlier in 2010, however, the Administration and Congress eliminated funding and brought a *de facto* stop to the hearings necessary for the NRC Commissioners to approve a license (Table 13).

7.5 NRC Hearing on Scientific Basis

As noted in §1.1.1 (Table 2), NRC adopted formal ASLB hearings for approving the YM repository license for construction, waste receipt, and closure. The formal process discusses the science of the repository concept in a formal adjudicatory, "on the record" hearing through live testimony and cross-examination of witnesses (10 CFR §2.101).[42, p. 19624] Even pre-licensing interactions between DOE and NRC were formal and required much preparation by both parties.

As noted by NRC in 2001, however, a formal hearing can thwart spontaneity in interactions and participation of the interested public, since participation must occur through attorneys. Furthermore, an individual or entity must file a contention/objection to the license, and the contention must be admitted to the proceedings prior to the hearing (i.e., have standing). Thus, NRC has adopted an informal adjudicatory process for NRC review of nuclear power plants.[42]

A formal hearing process also thwarts the presentation of a reasonably realistic case for regulatory review because there is little opportunity for either DOE or the regulator to modify their position during deliberations (i.e., the formal hearing process is not designed to facilitate negotiation). Specifically, DOE presented its most legally defensible case for NRC review for the YM repository and not a more realistic performance margin analysis that had also been produced.

Both WIPP and YM geologic disposal systems were far from the regulatory limit and so the need for using a more realistic case to demonstrate compliance did not exist. However, the EPA Standard, 40 CFR 191, asks for reasonable expectation and, thus, providing a more realistic case is conceptually important. One practical reason is that changes to the repository design may be desired to take advantage of technological advances to improve operational safety and/or omit features adopted in the initial design that turn out to be unnecessary during the 50 or more years of disposal operations. During the operation stage of WIPP, the conservative amount of MgO placed in the repository (to eliminate the possibility of forming carbon acid—$H_2CO_3^*$ if gas is generated from microbial degradation) has been reduced substantially based on more realistic analysis. The impact of these changes on long-term performance are more readily interpreted when compared to mean performance (rather than a legally defensible but perhaps pessimistic performance), especially for a system that may behave nonlinearly.[252]

Table 12. Historical steps in implementing compliance analysis over 4 years for TRU waste repository in US

Steps	Activities on Social Dimension	Activities on Technical Dimension
6. Implement compliance stage analysis	*6a. Submit RCRA and certification applications, issue EIS/record of decision under National Environmental Policy Act (NEPA), and approve site for operations* **1992 Aug:** DOE submits Parts A and B of RCRA permit application to State of New Mexico.[253] **Oct:** WIPP LWA: (1) transfers land from DOI to DOE, (2) sets EPA as regulator for WIPP, (3) requires EPA promulgate implementing regulations; (4) requires recertifying WIPP every 5 years, (5) requires DOE cooperate with EEG, (6) authorizes $600 million over 30 years for NM, and (7) requires WIPP Review Panel certify need for placing TRU waste at WIPP in pilot phase. **1993 Oct:** Because of the lack of WIPP Review Panel endorsement, DOE decides not to emplace waste in a pilot phase.[254] Instead, DOE decides to submit Draft CCA to focus interaction with EPA.[255] **1995 Jan:** EPA promulgates draft 40 CFR 194. **Oct:** EPA issues draft Compliance Application Guide on 40 CFR 194. **1996 Feb:** EPA promulgates 40 CFR 194:[40] (1) requires monitoring system; (2) specifies requirements on quality assurance, peer review, and expert judgments; (3) requires peer review on waste characterization, engineered/ natural barriers, and conceptual models of PA; (4) expands human activities to consider in PA (i.e., exploratory boreholes, fluid injection boreholes for oil recovery, development of existing and future oil/gas wells, and potash mining) **Oct:** DOE sends 80,000-page, CCA to EPA.[232;233] **Nov:** DOE issues 84,000-page 2nd Supplemental Draft EIS for WIPP operation and receipt of waste.[234] **Nov:** NAS WIPP Review Panel states WIPP site "excellent choice" geologically.[235] **Dec:** EPA evaluates completeness of CCA.[256] **1997 Jan:** DOE holds hearings on 2nd Draft Supplemental EIS in Carlsbad, Albuquerque, Santa Fe.[257] **May:** After receipt of additional material, EPA decrees CCA complete and ready for review. **Oct:** EPA issues draft rule to approve WIPP. **1998 Jan:** EPA certifies WIPP with conditions:[238;239] panel seals required, QA program required for waste generators, requirements for using process knowledge to characterize waste; schedule required for installing passive controls but denies credit for passive controls. DOE publishes Record of Decision to open WIPP for operations based on 2nd Supplemental EIS. **1999 Feb:** NM Environmental Department holds hearings on RCRA permit for WIPP. **Mar:** District Court lifts injunction on WIPP placed in 1992. **Oct:** NM grants WIPP RCRA permit.	*6b. Complete site characterization for compliance stage and demonstrate compliance with regulations* **1992 Jun:** NAS WIPP Review Panel questions scientific need for *in situ* tests with TRU waste in pilot phase; laboratory tests sufficient.[258] **Dec:** Sandia issues 3rd PA refining (1) models and data, and (2) transmissivity field uncertainty in Culebra dolomite; 49 parameters sampled.[226;227] WIPP-PA-92 becomes bases for SPM—1994 and Draft CCA to EPA (1995). **1993:** Analysis completed of brine inflow measurements from dewatering disturbed salt in Room Q. **1994 Mar-Dec:** Sandia links PA with decision analysis (SPM) to rank value of remaining experiments; SPM confirms results of WIPP-PA-92 sensitivity analysis.[259-261] **1995** URL of WIPP closed. **Feb:** After receiving state permits, Sandia begins drilling wells for tracer tests. **Mar:** DOE submits Draft CCA for review.[255] **Sep:** Laboratory gas generation tests completed;[203;228] results used to set rates for CCA. **1996 Oct:** Sandia completes PA for CCA that includes[229-231] (1) MgO backfill, (2) potash mining scenario, and (3) greater intrusion rate. Drilling debris (cuttings, cavings, and direct brine release) only release (except for a few vectors with groundwater release). 57 parameters sampled. Calculation run three times with 100 samples; each run takes 37,000 CPU h on 40 DEC alpha processors and produces 100 GB of data in 97,000 files. **1997 Jan:** Conceptual Model Peer Review Group (formed in response to 40 CFR 194) concludes 22 of 24 conceptual models adequate. However, spallings model (i.e., estimate of contaminated particles carried to surface in drilling mud) must be redone because it lacked sufficient realism (wildly conservative[262]) and MgO backfill description must be improved. **Mar:** Sandia quantifies conservatism of spallings model and commits to improve by next certification in 5 years. Sandia conducts sensitivity analysis for EPA on PA model parameters. **May:** Sandia runs PA verification test (PAVT) using EPA selected values for 26 parameters with more pessimistic bias and EPA assumptions for spallings model.[236;237] **1999 Mar:** First shipment of TRU non-RCRA waste arrives at WIPP.[240;241]

Table 13. Historical steps in recommending and approving site over 7 years for commercial repository development in US

Steps	***Activities on Social Dimension***	**Activities on Technical Dimension**
6. Review and recommend site for development	*6a. Review technical assessments, recommend final repository site, issue EIS/record of decision under NEPA, and approve site for construction*	*6b. M&O develops technical design for construction license.*
	§114(a)(2): DOE to recommend 1 site for construction with EIS (§114(f)) • **1989 Jul:** NRC clarifies need in 10 CFR 60 to update EIS when applying for authorization to construct, operate, or close [263] • **2002 Feb:** DOE completes Final EIS for site recommendation (4904 pages including 2864-page response to comments).[185] After 9-month personal review of Draft EIS, Energy Secretary Abraham recommends YM repository site to President Bush.[264] NWPA §112(c): President to approve or disapprove sites <60 days after recommendation; President to recommend to Congress • **2002 Feb:** President Bush recommends YM repository site to Congress. NWPA §116(a)(2) and §118(a): State or Tribe disapprove within 60 days of presidential recommendation • **2002 Apr:** Gov. Guinn, State of Nevada, disapproves • **2002 May:** House overrides; **July:** Senate overrides • **2003 May:** NRC Director of Waste Management Division tells DOE that QA procedures are not working ("Quality is not being built into the Project").[265] • **2004 Feb:** ASLB reject initial DOE certification of LSN because ~4 million e-mails from personnel no longer with project had not been submitted. **Nov:** DOE notifies NRC that when reviewing documents for LSN, DOE found e-mails between 3 geo-hydrologists that raise questions about collection of infiltration data and fabrication of QA records for INFIL mode.[246] • **2005 Mar:** DOE Inspector General and Interior Inspector General investigate USGS e-mails.[246]	**2001 Dec:** YM-PA-EIS, builds on YM-SSPA by updating waste package corrosion, improving colloidal transport, and adding climate change to 10^6 y.[266;267] **2002:** USGS revises regional groundwater flow model of Death Valley Basin.[268] **Jan:** YM Project turns off heaters in Drift Scale Heater Test. During the test, 6-7 m of tuff dried out. **Oct:** Most of the 43 wells near YM have not changed much since 1960. **2004:** USGS completes update to regional SZ flow model.[244] **Feb:** In response to NRC request in 2002, YM Project conducts new aerial magnetic survey to resolve remaining questions on igneous history. [245] **Mar:** Based on 2003 NRC audit,[269] YM Project initiates 6-month, $20 million review of analysis model reports (AMRs) to improve justification and traceability for YM-PA-04[246] **2005 Jun:** YM Project completes updates AMRs; seismic model uses maximum peak ground velocity of 4 rather than 12 m/s, which eliminates unrealistic behavior in PA-04-LA.[270] DOE places ~1.2 million documents including ~700,000 e-mails into LSN. **Feb:** 1st evidence of natural seepage found near main entrance. **Aug:** Sandia revises FEP list in response to internal and NRC comments. **2005 Jan:** DOE asks for another interim YM-PA-05 to improve various sub-models in response to comments. **Oct:** DOE directs Sandia to redo USGS infiltration model, INFIL for YM-PA-05.[248] **2006 May:** YM-PA-05 stopped, YM-PA-LA started. **2007 Apr:** Sandia completes analysis with infiltration model, MASSIF; at cost of ~$12.9 million; investigation cost ~$12.7 million.[271]
7. Approve site for construction:	§115: Review of recommendation NWPA §114(b):DOE submits SAR/LA to NRC • **2008 Jun:** DOE submits SAR/LA to NRC, based on YM-PA-LA, which shows compliance with EPA and NRC disposal regulations using fully qualified analysis, parameters, and software. DOE publishes Final Supplemental EIS on construction.[272] NWPA §114(d): NRC staff issues final construction decision, licensing board conducts hearings, and Commission rules on license application • **2008 Sep:** NRC dockets SAR/LA.[273].. • **2009 Jan:** DOE files update to SAR/LA • **2010 Feb:** Administration stops funding for necessary NRC hearings prior to NRC approval. • **2015** NRC staff issues 5-volume Safety Evaluation Report that concludes SAR/LA meets pre- and post-closure requirements.	**2008 Jan:** Sandia completes YM-PA-LA,[249] which considers 152 of 374 FEPs in 4 scenario classes; it also replaces biological module to use ICRP dose method..[274] Maximum dose of 0.02 mSv/y at 10^6 y from released ^{242}Pu, ^{237}Np, ^{226}Ra, and ^{129}I (plus ^{239}Pu in 1st 2×10^5 y and ^{99}Tc in 1st 7×10^5 y) in 2 scenarios: igneous intrusion breaching all waste packages and undisturbed plus seismic breaching ~10% of waste packages by general corrosion or seismic event.
	The Negotiator shall submit to the Congress any proposed agreement between the United States and a State or Indian tribe negotiated under subsection (a) of this section and an environmental assessment prepared under section 10244(a) of this title for the site concerned. (3) (A) No proposed agreement entered into under this section shall have legal effect unless enacted into Federal law.(B) A State or Indian tribe shall enter into an agreement under this section in accordance with the laws of such State or tribe.	**1999 Mar:** Utah Governor Leavitt vows to stop Goshute Indian Tribe from storing SNF.[275] **2005 May:** NRC approves storage license for Private Fuel Storage (PFS) on Skull Valley Indian Reservation in Utah for 40,000 MTHM. [276;277] **2006 Sept:** Bureau of Indian Affairs nullifies lease between Goshute tribe and PFS claiming storage might be permanent and federal, tribal, and local police inadequate to protect.[278]

7.6 State Participation in SAR/LA Review

State/tribal and local participation in review likely helps establish and maintain trust. For example, EEG reviewed the 17 reports produced for the Stipulated Agreement, during the suitability stage to assess the suitability of WIPP for the State of New Mexico (Table 10).

In Subpart C of both 10 CFR 60 and 10 CFR 63, NRC offered, upon request, opportunities for participation of state, affected local, and affected tribal governments in (1) providing information, (2) participating in NRC staff review of site characterization, and (3) participating in review of the license application for construction and subsequent amendments for receipt of waste and decommissioning.

> **§60.62 Filling of proposals for State participation.**
>
> States potentially affected by siting of geologic repository operations area at a site that has been selected for characterization may submit to the Director a proposal for State participation in the review of the Site Characterization Report and/or license application…

The regulations suggest that most proposals for participation in reviews would be accepted provided "…(2) the proposed activities—(i) Will enhance communications between NRC and the State, or affected unit of local government, or affected Indian Tribe; (ii) Will make a productive and timely contribution to the review; and (iii) Are authorized by law." This provision was carried forward from 10 CFR 60 into 10 CFR 63 without modification.

7.7 Institutional Bias

Although some organizations are perceived to accurately assess risks and benefits associated with managing SNF, HLW, and TRU waste, the public, on average, expects to observe systematic bias from personnel within various organizations. Specifically, some organizations are perceived to systematically downplay or exaggerate risks and benefits associated with hosting a nuclear waste facility (Fig. 6). These public perceptions come into play during regulatory review of the compliance certification application (CCA) for WIPP or safety assessment report/license application (SAR/LA) for YM disposal system. The public perceives that DOE will communicate in a manner that is somewhat favorably biased (Fig. 6). The public will not likely credit DOE with bending over backwards to introduce excessive bias to ensure safety whether DOE points to many pessimistic interpretations of repository performance in the SAR/LA.

In comparison, the public perceives that EPA will somewhat exaggerate risk in fulfilling its responsibility to ensure safety (Fig. 6).[f] Thus, the EPA regulator reasonably shouldered the responsibility for introducing a pessimistic bias at WIPP in its PAVT assessment[236] (Table 11).

The situation with the NRC regulator is different. NRC is perceived to have a similar risk bias as DOE. Hence, a formal hearing process may be necessary when initially reviewing a SAR/LA for constructing a repository licensed by NRC, regardless of the advantages of informal hearings (as discussed below in §7.7).

BRC suggested that Congress form a new WMO with the sole purpose of managing storage, transportation, and disposal of radioactive waste. The BRC-suggested structure was a federally-chartered corporation, similar to the Tennessee Valley Authority (TVA), which is overseen by a board of directors appointed by the President and confirmed by the US Senate.[26, p. 61] However, other structures are possible: a private company created by the nuclear power industry, similar to Sweden (Table 3), or a new independent agency with leadership appointed by the President and confirmed by the US Senate, similar to the National Aeronautical and Space Administration (NASA). The latter approach was adopted in proposed legislation introduced in the Senate in 2015 (S854).[280] The US public perceives each structure has a different built-in bias when describing the risk of waste management but all are perceived as more biased than existing agencies in the US (Fig. 6).

[f] The public does not trust all US government agencies in the same way. Older respondents, and those that perceive nuclear power as providing great benefit are more trusting of NRC, while younger respondents, females, and those that perceive nuclear power and waste management as high-risk endeavors are more trusting of EPA. However, all segments of the United States generally trust NAS.[279]

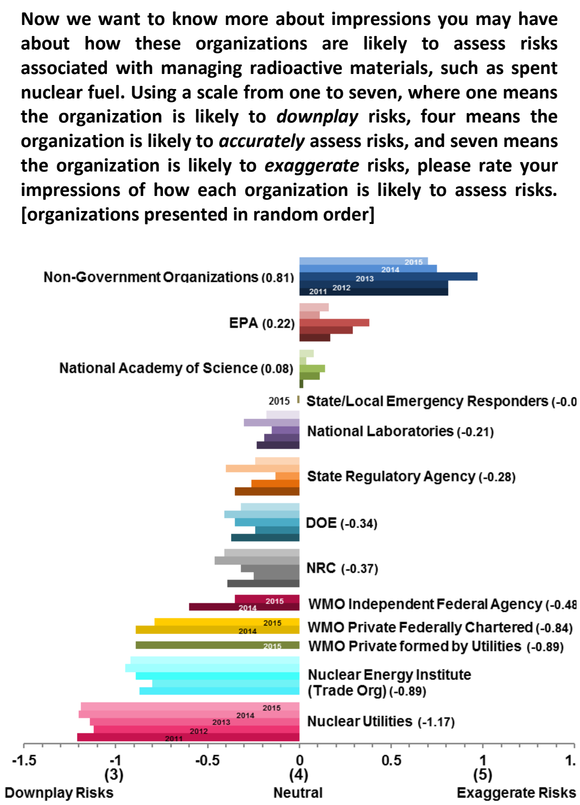

Fig. 6. Annual and overall mean perceived bias of various institutions describing risk associated with managing spent nuclear fuel in national surveys conducted between 2011 and 2015.[31, Figure 18]

7.8 Separating Disposal Concept Review from Design Review

IAEA proposes six design phases for repository development: The first phase is a generic design. [281, Fig. 11] Examples are (a) the WIPP conceptual design in 1977 for the initial environmental assessment (Table 7), (b) the WIPP Title I design in 1979 for feasibility analysis (Table 7), (c) the initial design for YM repository in 1982 (Table 6), and (d) 1990 YM repository design for feasibility analysis (Table 8).

The second phase is conceptual design for evaluating the suitability of potential sites,[281, Fig. 12] Examples are (1) the Title II design for WIPP in 1981 (Table 10) and conceptual design for YM repository in 1999 (Table 11).

The third phase is the technical design for construction license application and regulatory review.[281, Fig. 13] Examples are (a) completion of construction in 1990 for WIPP (Table 10) and (b) YM repository design in SAR/LA (Table 11).

The fourth, fifth, and sixth phases are respectively detailed design for construction authorization;[281, Fig. 14] design updates for waste receipt authorization; and design for closure authorization.[281, Fig. 15]

In this approach, the first critical step of construction licensing of the repository involves producing a SAR/LA for NRC staff review and ASLB hearings that focuses on the scientific basis of the disposal concept, not the operation design details. Once the NRC commissioners had authorized construction of the disposal system, DOE was to begin detailed design of the underground operations (such as waste transport and ventilation), and surface handling facilities.

This approach avoids committing extensive resources to design development and design review for the initial safety analysis report prior to approval of the disposal system concept. Nonetheless, one difficulty is for DOE to discern the technical design detail necessary to show NRC that the repository design is feasible and suitable. DOE preferred to provide extensive designs to avoid requests for more information during NRC staff review.

When promulgating 10 CFR 60, NRC recognized this design approach when they removed detailed design criteria on the ventilation system and shaft/borehole seals that had been in the proposed draft, and thereby, did not require a final repository design for the repository during review of the SAR/LA.[72, p. 28198] Furthermore, the ASLB dismissed a contention submitted by the State of Nevada claiming a final repository design was necessary under 10 CFR 63. Finally, EPA's review of the WIPP Compliance Certification Application focused on the post-closure disposal system performance, not the operational design.

8 SUMMARY AND INSIGHT

8.1 Social Dimension

The evaluation of the WIPP and YM disposal systems presented a societal challenge in developing a process for selecting a socially and politically viable site for radioactive waste disposal and developing a consensus on criteria under which a disposal system would be considered safe. In the social dimension, Congress made a national commitment to mined, geologic disposal for TRU waste from defense atomic activities and commercial SNF/HLW in NWPA.[14] Most of the social dimension in the US delt with institutional stakeholders.[281] The institutional stakeholders in each program were similar but important differences existed (Table 1 and 2).

8.1.1 EPA Standard

EPA set environment standards for each program . Initially, the probabilistic standards were the same for both the WIPP and YM programs (40 CFR 191) with a cumulative release standard for WIPP with a regulatory period of 10^4 years at a 5-km disposal system boundary (Table 1).[63] After 1992,[48] EPA established a site-specific dose standard for the YM repository (40 CFR 197) with a regulatory period of 10^6 years at an 18-km boundary (Table 2).[71]

8.1.2 Standard Implementation

Congress designated NRC as the regulator for SNF/HLW commercial repositories in NWPA and NRC promulgated general implementing regulations starting in 1983 (10 CFR 60—Table 2). In 2001, NRC promulgated the site-specific implementing regulation for the YM repository as mandated by Congress in 1992 (10 CFR 63—Table 2). Also in 1992, Congress designated EPA as the regulator for WIPP,[25] In turn, EPA promulgated the WIPP site-specific implementing regulation in 1996 (40 CFR 194—Table 1).

8.1.3 State of New Mexico

Because of the presence of hazardous chemical waste in the TRU waste for WIPP, EPA hazardous waste regulations also apply.[22;23] EPA granted authority to the State of New Mexico to implement its regulations for WIPP in 1990,[41] thus WIPP had both a federal and state regulator.

8.1.4 DOE Implementor

Congress, in NWPA, required DOE promulgate siting guidelines to select a repository site for commercial SNF/HLW. Like EPA and NRC, DOE promulgated two sets of siting guidelines for evaluating and selecting a repository site: generic guidelines in 10 CFR 960, and YM-specific guidelines in 10 CFR 963 (Table 3). EAs and generic guidelines were used to nominate three sites for a commercial SNF/HLW repository in the feasibility stage from nine potentially acceptable sites. Congress chose the Yucca Mountain from the three finalists for characterization in NWPAA in 1987.

8.1.5 Federal-State Confrontations

An important aspect of siting YM repository for commercial SNF/HLW in the US was the contentious rather than cooperative interaction that occurred between the State of Nevada and the federal government. This confrontational interaction required continual participation of the federal and state courts and influenced the federal budgetary policy.

The situation for WIPP was confrontational but different. Lawsuits between the State of New Mexico and the federal government occurred but the local community, which became an advocate for WIPP, was large enough to have influence in the state legislature, the governor, and the NM congressional delegation such that the state remained open to nuclear waste disposal. The direct negotiation between the Secretary of Energy Edwards and Governor King resulted in a Stipulated Agreement that became part of the resolution of a 1981 state lawsuit. The Stipulated Agreement was enforced by courts and not easily altered by Congress. The codification of the Stipulated Agreement and its amendments in the 1992 WIPP LWA further cemented the agreements. Also, EPA granted the State of New Mexico authorization to enforce RCRA regulations on mixed waste disposed at WIPP.

In its discussion of the social dimension in 2012, BRC noted that a successful siting process would be one in which host communities and states are involved through a series of steps; specifically, (a) they participate in a consultative and cooperative process (e.g., negotiation between Secretary of Energy Edwards and NM Governor King leading to the Consultation/Corporation Agreement of the Stipulated Agreement) (b) they collaborate with repository implementor on site investigations (e.g., site investigations required in Stipulated Agreement); (c) during the conceptual technical development, they have access to the information and resources needed to engage in key decisions and advocate for their interests (e.g., the federally funded EEG in New Mexico that reviewed all DOE documents and, for example, advocated for a much more robust TRUPACT transport container); (d) the implementor is flexible and adaptable to their desires (e.g., New Mexico lawsuits forced adaptation though not an inherit aspect of a Washington-based DOE); and (e) they retain the right to opt out at the end of the conceptual development. Though the last item was not a feature at WIPP, efforts of the Carter Administration to demonstrate SNF/HLW at WIPP were vigorously opposed by the state, by Congress, in general, and the NM Delegation, in particular, that resulted in legislation omitting commercial SNF from WIPP.

8.2 Technical Dimension

Technical investigations for both WIPP and YM Project progressed through four stages that corresponded to analysis of disposal system performance: (1) site identification (2) feasibility analysis based on rough measures of performance using surface exploration, waste process knowledge, and general laboratory experiments; (3) suitability analysis demonstrating viability of the disposal system based on site characterization; and (4) compliance/licensing analysis based on completed site characterization with partially validated models.

8.2.1 Site Identification Stage

In the technical dimension, the site identification stage lasted ~3.5 years for WIPP between 1973 and April 1976 (Table 5) and ~11 years for YM Project between February 1976 and May 1986 (Table 6).[g] Both WIPP and YM Project relied heavily on the USGS identifying potentially acceptable regions and areas for sites. Most of the wells drilled near the YM repository (G-geologic, H-hydrologic, WT-water table, and UZ-unsaturated zone wells and many of the N series neutron probe boreholes) were completed for the site selection phase and accompanying 1984 YM-PA-EA.

8.2.2 Feasibility Stage

The feasibility stage lasted ~4.5 years for WIPP between 1976 and October 1980 (Table 7). During the feasibility stage, the USGS drilled 47 boreholes to define stratigraphy. Sandia developed a conceptual design of repository,[158] conducted laboratory tests on TRU waste behavior and salt consolidation,[126;156;157] and built 2D flow and 1D radionuclide transport models from the repository to Pecos River for the site-selection EIS. [129;148]

The feasibility stage lasted ~9 years for YM Project between 1987 and 1995 (Table 8). Permeability testing began in the boreholes after the SCP was published. In March 1990, bomb pulse ^{36}Cl was measured in some boreholes which suggested deep fracture flow in some locations, which, in turn, influenced modeling. Also in 1990, Sandia developed a conceptual repository layout that used ramps rather than shafts to the repository horizon.[139] In 1992, the YM-PA-91 was completed;[153] it was the first probabilistic simulation of the YM repository behavior. In 1994, YM-PA-93 was completed;[51] it provided guidance on characterizing the site and options for package placement (vertical boreholes with small containers or in-drift placement with large containers). In 1995, YM-PA-95 was completed;[154] it improved modeling of the engineered barrier system for evaluating dose.

8.2.3 Suitability Stage

The suitability stage lasted ~11 years for WIPP between 1981 and 1991 (Table 10). As part of the court enforced Stipulated Agreement signed in 1981 between DOE and State of New Mexico, WIPP-12 borehole north of the WIPP site was deepened and intersected a pressurized brine pocket.[167] The presence of the pressurized pocket would have ramifications for how inadvertent human intrusion was modeled. By March 1983, Sandia and USGS had completed most of the reports on the 17 topics of interest to the State of New Mexico, as specified in the Stipulated Agreement.

Based on pump and transport tests of the Culebra dolomite in wells around WIPP, Sandia had concluded by 1987 that single porosity adequately modeled fluid flow, but that transport was best modeled as a dual porosity media, which required more tracer testing to derive parameters.

By 1985, it was evident that observed salt creep in rooms was about three time more than predicted, which necessitated more in-situ tests and model improvements. Most discrepancies were resolved by 1989[173] but final resolution did not occur until 2022.[174;175]

In May 1987, Sandia reported that much more brine had migrated to simulated HLW canisters in the experimental rooms than had been predicted. By December, the national press was reporting on the issue.[176] Thus, the New Mexico Congressional Delegation asked NAS to study potential brine flow into WIPP. In May 1988, NAS concluded rapid salt creep combined with low salt permeability meant the WIPP repository would be well consolidated before much brine entered (Table 10).[177]

On completion of site suitability stage in 1989, Sandia completed documentation to support the Draft Supplemental EIS to prepare for the compliance phase of WIPP. The Supplemental EIS identified gas generation from corrosion and microbial degradation of TRU waste as an unresolved issue to study during the compliance stage.[149]

The suitability stage lasted ~7 years for YM Project, between 1996 and 2002 (when the DOE completed the site-recommendation EIS)[185] (Table 11). *In-situ* experiments for YM site characterization began between 1994 and 1996 after the importance of tests in the SCP were ranked, the QA program completed, and the State of Nevada issued permits.

The proposal to allow temperatures above boiling in the disposal drift, in conjunction with the use of large,

[g] The uncertainty in the length of time of each stage derives from uncertainty as to when to demark the start and end of each stage since the projects often slowly transitioned between stages.

in-drift disposal containers, prompted questions about the coupling of thermal, hydrologic, and chemical processes during the ~1000-year thermal period. Hence, YM Project conducted much experimental work[3] and code development to advance the science of coupled thermal-hydrologic-chemical modeling (Table 11).

By YM-PA-VA in 1998, site characterization had collected data on net infiltration into the mountain, bomb-pulse chlorine (^{36}Cl) in fractures at the repository horizon, and movement of water around the single heater and large block heater tests (Table 11). Site characterization had also conducted hydraulic tests on core samples, pneumatic tests in existing wells, and mapped fractures in the exploratory studies facility.

As understanding of the YM disposal system increased through site characterization and *in-situ* testing, modeling of infiltration, percolation, and seepage evolved from simple assumptions in a single model for YM-PA-EA in 1984 to individual modules based on detailed process models by YM-PA-VA in 1998.

8.2.4 Compliance Stage

The compliance stage took ~4 years for WIPP between 1992 and 1996 (Table 12) Experiments identified as important for WIPP-PA-CCA included (1) brine inflow measurements from dewatering disturbed salt in Room Q; (2) tracer tests in the Culebra dolomite to determine parameters for dual porosity transport formulation. and (3) laboratory gas generation experiments.[203;228]

The initial plan for the gas generation experiments was to conduct laboratory experiments and confirm the results using bins of real TRU placed within repository rooms during the WIPP pilot phase. The State of New Mexico strenuously opposed bringing any TRU waste to WIPP until compliance with 40 CFR 191 was demonstrated. Hence, the 1992 WIPP LWA required the NAS WIPP Review Panel to certify the need for *in-situ* experiments with real waste at the WIPP repository. In June 1992, the NAS WIPP Review Panel questioned usefulness of *in-situ* experiments (Table 11). Without an endorsement of a pilot phase for WIPP, DOE submitted a Draft CCA in March 1995.[255] In October 1996, Sandia completed the PA for CCA.[230;231]

The compliance analysis period for the YM repository lasted for ~7 years between December 2001 (when YM-PA-EIS and the supplement to the site recommendation EIS was completed) and January 2009 (when DOE submitted an updated SAR/LA to NRC) (Table 13).

As experiments were completed, the YM Project transitioned to fully qualifying analysis, parameters, and software for YM-PA-LA. In 2003, most AMRs underlying the PA and SAR/LA were completed. In May 2003, however, an NRC audit found QA procedures were not producing a quality product. Thus, the YM Project was reorganized to conduct a 6-month review of AMRs to improve justification and traceability to sources of information.[246]

For the SAR/LA review and ASLB hearings, NRC required that all documents related to the SAR/LA and ASLB hearings be placed in a LSN. As part of that effort, DOE notified NRC that when reviewing the submittal, e-mails were found between three USGS geo-hydrologists from 1998 to 2004 that raised questions about collection of infiltration data, when USGS infiltration model was installed, and fabrication of QA records. Thus, DOE directed Sandia to redo the USGS infiltration model.[248]

By May 2006 preparations began for YM-PA-LA that included analysis out to 10^6 years; replacement of near-field chemistry model; replacement of USGS INFIL with Sandia MASSIF model; and use of large in-drift packages. In January 2008, Sandia completed YM-PA-LA.[249]

Much micro-scale complexity was discovered during site characterization; yet, Yucca Mountain, on a macro-scale, remained fairly simple and consisted of mildly tilted unsaturated layered strata with mostly vertical water percolation down to the deep-water table from limited amounts of precipitation in a desert environment (Fig. 1). Generally, little water reached the repository horizon under current climate conditions, and then in only small areas connected by fractures. Yet, high infiltration and percolation at the repository horizon was usually considered for a portion of the regulatory period in all PAs, to evaluate the influence of fluctuations in climate on the disposal system performance.

8.2.5 Siting Duration

The elapsed time between selecting a tentative site location and submitting a certification or license application was 23 years for WIPP and 33 years for YM Project. Much of the extra time for the YM Project was spent on site identification: 11 years versus 3.5 years for WIPP. The willingness of city leaders and mine operators to invite DOE to explore the Los Medaños area around Carlsbad, with the tacet approval of the state governor, helped focus the search for WIPP.

The combined time spent on the feasibility and suitability stages was respectively 15.5 years and 15 years for WIPP and YM Projects. However, the resources spent on the technical challenges in these two programs differed substantially. Investigating the unsaturated natural barrier with in-drift disposal (without backfill) of a thermally hot package necessitated increased modeling complexity that took intensive scientific study and personnel on the YM Project. Furthermore, drift disposal without backfill, increased the importance of the natural disruptive events such as seismic and igneous intrusion on the YM Project.

8.3 Technical Review

The technical programs of both WIPP and YM Project were reviewed by national expert panels that made many substantive critiques and recommendations that improved the design and analysis of the respective disposal systems. Both review panels were implemented at the start of the Feasibility Stage: the NAS WIPP Review Panel in 1978 and NWTRB for the YM Project in 1987.[21]

8.4 Role of PA

The YM project made extensive use of PAs during all four stages of site investigations. WIPP also made extensive use of PAs for the suitability and compliance phases but not in earlier stages since these early stages occurred prior to the development of the PA methodology and adoption by EPA in its 1985 environmental standard.

Reasons for using PAs throughout the technical site investigation included (1) PA methodology synthesized diverse information from multiple scientific disciplines to comprehend the WIPP or YM disposal system as a whole; (2) new information and hypotheses (e.g., gas generation at WIPP or seismic damage to drift packages at YM) were placed in context to the overall system performance via a quantitative mathematical model rather than given subjective weights in a qualitative mental model; (3) embedding PA early helped to appropriately assign resources to study FEPs of the WIPP and YM disposal system; (4) demonstrated ability of the early PAs to identify the range of behavior observed in later PAs for the WIPP and YM disposal systems.[15, Figs. 3&4] Thus, PAs can be a component of early site-candidacy selection. Furthermore, early PA estimates will likely be more reliable and the range of uncertainty about these estimates consistent with final PA results because of the international experience and knowledge of repository performance in a variety of geologic media.

The PA and the accompanying scientists/engineers, which reside in the technical dimension, could not resolve state and public lack of interest in accepting the YM repository in the social dimension. On the other hand, WIPP had stable employment attributes in the social dimension that Carlsbad found compelling for a community with a boom/bust resource extraction economy. Thus, Carlsbad community came to embrace the opportunity to host the WIPP repository. With a plurality of local residents finding WIPP compelling, scientists/engineers had a more prominent role in assuring the feasibility and suitability/viability of a mined, geologic repository as regards to long-term public health and safety to citizens throughout the State of New Mexico. In turn, New Mexico citizens came to cautiously welcome its presence.[182;282]

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