SANDIA REPORT

SAND2014-0916
Unlimited Release
Printed February 2014

Milestones for Selection, Characterization, and Analysis of the Performance of a Repository for Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain

Rob P. Rechard

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Approved for public release; further dissemination unlimited.

Sandia National Laboratories

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof, or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof, or any of their contractors.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865) 576-8401
Facsimile: (865) 576-5728
E-Mail: reports@adonis.osti.gov
Online ordering: http://www.osti.gov/bridge

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd.
Springfield, VA 22161

Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-Mail: orders@ntis.fedworld.gov
Online order: http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online

SAND2014-0916
Unlimited Release
Printed February 2014

Milestones for Selection, Characterization, and Analysis of the Performance of a Repository for Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain

Rob P. Rechard
Nuclear Waste Disposal Research and Analysis (6222)
Sandia National Laboratories
Albuquerque, NM 87185-0747

Abstract

This report presents a concise history in tabular form of events leading up to site identification in 1978, site selection in 1987, subsequent characterization, and ongoing analysis through 2008 of the performance of a repository for spent nuclear fuel and high-level radioactive waste at Yucca Mountain in southern Nevada. The tabulated events generally occurred in five periods: (1) commitment to mined geologic disposal and identification of sites; (2) site selection and analysis, based on regional geologic characterization through literature and analogous data; (3) feasibility analysis demonstrating calculation procedures and importance of system components, based on rough measures of performance using surface exploration, waste process knowledge, and general laboratory experiments; (4) suitability analysis demonstrating viability of disposal system, based on environment-specific laboratory experiments, *in-situ* experiments, and underground disposal system characterization; and (5) compliance analysis, based on completed site-specific characterization. Because the relationship is important to understanding the evolution of the Yucca Mountain Project, the tabulation also shows the interaction between four broad categories of political bodies and government agencies/institutions: (a) technical milestones of the implementing institutions, (b) development of the regulatory requirements and related federal policy in laws and court decisions, (c) Presidential and agency directives and decisions, and (d) critiques of the Yucca Mountain Project and pertinent national and world events related to nuclear energy and radioactive waste.

Preface

The historical progression of technical milestones for the Yucca Mountain Project was originally developed for 10 journal articles in a special issue of *Reliability Engineering System Safety* on the performance assessment for the Yucca Mountain license application [1-10]. The listing of milestones, a distinct feature of those articles, has been collected and tabulated here. Although a brief description is presented here (based on the summaries in the 10 journal articles), the emphasis remains on the tabulation because of its usefulness in providing a comprehensive but concise history of the Yucca Mountain Project. Yet, the tabulation presented here is more elaborate than originally presented in that many of the interactions that occurred between the technical realm and policy realm can be depicted in separate columns.

The usefulness of the milestones table is due in part to L.A. Connolly, for editorial and reference support, and S.K. Best, Raytheon, and L. Mays, Sandia National Laboratories (SNL), for illustration support. Reviewers P.N. Swift, SNL, and K. Gupta, University of Oklahoma, helped improve the discussion. The historical perspective presented is that of the author and is not necessarily held by reviewers, Sandia National Laboratories, and the US Department of Energy. As a historic perspective, the author is reporting on the work of others; however, any interpretative errors of the documentation are those of the author alone. The characterization and modeling of the Yucca Mountain disposal system required numerous participants with expertise in many areas of science and technology, as evident from the extensive reference list. Their diligent efforts are generally acknowledged here, but the 10 journal articles acknowledge by name many of the numerous participants that contributed to the Yucca Mountain Project.

Contents

Figures

Tables

Acronyms and Abbreviations

1-D, 2-D, 3-D – One-, two-, and three-dimensional

AEC – Atomic Energy Commission; formed by *Atomic Energy Act of 1946* [11] and a forerunner of ERDA, DOE, and NRC

ALARA – As Low As Reasonably Achievable with costs and benefits taken into account is a basic policy of radiation protection initially proposed in 1948 and promulgated by NRC in 1975.

Am – Americium actinide element

AMR – Analysis/Model Report; the primary support documents for PA-SR, PA-LA, and SAR/LA

ANL – Argonne National Laboratory; a DOE multi-program laboratory near Chicago, IL, which traditionally teamed with LLNL to conduct CSNF and HLW degradation studies for YMP

ASLB – Atomic Safety Licensing Board of the NRC was to conduct formal hearings on the SAR/LA submitted for Yucca Mountain repository.

BRC – Blue Ribbon Commission, formed by Presidential direction in 2010 to review current US waste management policy, BRC recommended changes in 2012 [12].

BSC – Bechtel SAIC Company; M&O for YMP between 2002 and 2009

CEDE – Committed Effective Dose Equivalent; defined as dose received over 50 years from 1 year of external exposure and ingestion of radionuclides by an individual, using the methods of the ICRP.

CFR – Code of Federal Regulations

CHn – Calico Hills, non-welded volcanic tuff modeling layer

^{36}Cl – Chlorine radionuclide activation product

CSNF – Commercial SNF

DSNF – DOE-owned SNF

DKM – Dual-Permeability Model for flow of water through fractures and matrix

DOE – US Department of Energy, formed by *DOE Organization Act* [13], replaced the Energy Research and Development Agency (ERDA).

DOE-EM – Environment Management Office of DOE

DOI – US Department of the Interior

DST – Drift-Scale Test; 4-year thermal test conducted in ESF, with heat applied between December 1997 and January 2002

EA – Environmental Assessment, as specified in NWPA. This designation in NWPA initially caused confusion since it was not related to an EA defined in 40 CFR 1501 regulations promulgated in 1979 to implement NEPA.

EBS – Engineered Barrier System, as defined by NRC in 10 CFR 63, “means the waste packages, including engineered components and systems other than the waste package, and the underground facility” where the “underground facility means the underground structure, backfill materials, if any, and openings that penetrate the underground structure (e.g., ramps, shafts, and boreholes, including their seals)” [14].

ECM – Equivalent Continuum Model was proposed in the 1980s to evaluate percolation in the matrix and fractures of the volcanic tuff [15].

ECRB – Enhanced Characterization of the Repository Block drift excavated to Solitario Canyon Fault between March and October 1998

EIS – Environmental Impact Statement; environmental documentation required by NEPA for large, federally funded programs [16]

EPA – US Environmental Protection Agency; formed by Congress in December 1970 in Reorganization Plan No. 3 of 1970 [17]. In this act, Congress transferred to EPA the tasks of monitoring research, setting standards, and performed enforcement activities related to pollution abatement and control such that the environment could be considered as a single, interrelated system.

EPRI – Electric 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 the Atomic Energy Commission (AEC) [18].

ERMYN – Environmental Radiation Model for Yucca Mountain, Nevada was used for PA-LA. ERMYN was based on the GoldSim® simulation tool and used the underlying equations of GENII-S.

ESF – Exploratory Studies Facility; the experimental area at Yucca Mountain was originally called the exploratory shaft facility (e.g., [19]), but the name was changed in March 1991 to exploratory studies facility to reflect its larger size and purpose [20, p. 1-1].

FEHM – Finite-Element Heat and Mass transport code developed by LANL

FEP – Features, Events (natural and anthropogenic phenomena of short duration), and Processes (natural phenomena of long duration)

Fm – Geologic Formation

FY – Fiscal Year

GAO– Government Accountability Office

GCD – Greater Confinement Disposal; disposed of LLW tritium, sealed sources, and classified TRU waste in 36-m deep boreholes in a 90-m thick UZ layer of tuff alluvium at NTS.

GENII-S – SNL adaption of GENII where the latter was developed by PNNL for evaluating radiation dose [21].

GRHA – *Gramm-Rudman-Hollings Act* is common name of *Balanced Budget and Emergency Deficit Control Act* first passed in 1985 and amended in 1987 to include appropriations for YMP [22].

GTCC – Greater-Than-Class-C LLW

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…" [23, Section 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 also includes SNF in its definition of HLW. Most HLW has been generated by the DOE in reprocessing spent nuclear fuel from experimental and military reactors. Because the possibility of commercial reprocessing was stopped under the Ford Administration in 1976 and never initiated thereafter, only 275 canisters of commercial HLW exist from reprocessing 640 MTHM of SNF at the West Valley Demonstration Project in New York [24, p. 1.5.1.30].

^{129}I – Iodine radionuclide; fission product

IAEA – International Atomic Energy Agency, Vienna, Austria was established in 1957 as an autonomous member by General Assembly of the United Nations to foster research and development in the peaceful uses of nuclear energy.

ICRP – International Commission of Radiation Protection, Ottawa CA.

INL – Idaho National Laboratory is a multi-program DOE laboratory in Idaho Falls, ID. Related to YMP, INL has responsibility for managing DSNF (and storing a portion) destined for geologic disposal.

IPA – Iterative Performance Assessment modeling conducted by NRC

IRG – Interagency Review Group on Nuclear Waste Management was formed by the Carter Administration in March 1978 on the recommendation of Secretary of Energy Schlesinger. The group, with DOE as the chair, consisted of 14 federal agencies together with several entities within the Executive Branch, including the Council on Environmental Quality.

IVRT – Independent Validation Review Team formed by BSC M&O to evaluate the various iterations of PA leading up to PA-LA (the PA supporting SAR/LA).

KTI – Key Technical Issue; 9 categories of issues defined by NRC to be resolved for the sufficiency review prior to SAR/LA

LA – License Application for YM repository to NRC

LADS – License Application Design Selection study conducted between December 1998 and April 1999.

LANL – Los Alamos National Laboratory is a multi-program DOE laboratory in Los Alamos, NM. For YMP, LANL traditionally had responsibility for study of volcanism, mineralogy, petrology, and geochemistry but evolved into analysis of SZ modeling. Early on, LANL also managed many of the experiments at NTS related to YMP.

LBNL – Lawrence Berkeley National Laboratory is a multi-program DOE laboratory in Berkeley, CA. For YMP, LBNL traditionally teamed with the USGS to test and model UZ hydrology.

LBT – Large Block Test; thermal test conducted at Fran Ridge near Yucca Mountain; heat applied between February 1996 and September 1997

LLNL – Lawrence Livermore National Laboratory is a multi-program DOE laboratory in Livermore, CA. LLNL traditionally had responsibility for characterization and testing of the EBS, including initial waste container design, waste container performance analysis and HLW/CSNF degradation.

LLW – Low-Level Waste is radioactive waste that is not SNF, HLW, TRU waste, mill tailings, or byproduct material (as defined in the *Atomic Energy Act of 1954*) [25; 26]. In the US, LLW is divided into 4 classes, A, B, C, and GTCC.

LLWPA –*Low-Level Waste Policy Act of 1980* in which Congress assigned the disposal responsibility for LLW to the states [25].

LLWPAA – *Low-Level Waste Policy Amendments Act of 1985* assigned the responsibility for disposal of GTCC LLW category to the federal government.

LSN – Licensing Support Network was defined by NRC in 10 CFR 2 for documents related to YMP for ASLB hearings.

M&O – Management and Operator contractor team for YMP. First M&O operated between January 1992 and December 2001 and was led by TRW Environmental Safety systems (TRW) and consisted of INTERA, Duke Engineering & Services, B&W Fuel Company, Fluor Daniel, Morrison-Knudsen, Woodward-Clyde, Logicon RDA, ER Johnson Associates, and JK Research Associates; the second team operated between January 2002 and 2009 and was led by BSC. M&O traditionally was responsible for YMP management such as records, technical data, project control, repository design, waste package design including criticality analysis, ESF and ECRB construction, and regulatory interactions.

MOX – Mixed-Oxide fuel consists of oxides of both ^{235}U and ^{239}Pu fissile material.

MPC – multi-purpose canister proposed in 1994 and evaluated in PA-95 to eliminate repeated handling of SNF rods. The MPC was to be loaded at the nuclear reactor, overpacked for transportation, overpacked for dry storage, and overpacked for disposal.

MRS – Monitored Retrievable Storage Facility for CSNF, proposed in 1982 in NWPA and discussed in 1987 in NWPAA (see also RSSF)

MTHM – Metric Tons of Heavy Metal; regulatory mass unit in 40 CFR 191 and 40 CFR 1971 where heavy metal is all the uranium, plutonium, and thorium initially placed in a nuclear power reactor

NAS – National Academy of Sciences, a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research. The 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 organization of the National Academy that conducts the studies requested by Congress is the National Research Council (NA/NRC), which is composed of several standing committees of NA members. Keeping with tradition, this report uses the NAS designation for studies conducted by NA/NRC.

NC-EWDP – Nye County – Early Warning Drilling Program

NEA – Nuclear Energy Agency formed in 1958 as body of the Organisation for Economic Co-operation and Development (OECD) for the safe, environmentally friendly, and economical use of nuclear energy for peaceful purposes. The activities and members of the Radioactive Waste Management Committee of NEA, formed in 1975 to foster exchange of information on nuclear waste disposal, are of most interest in this summary.

NEPA – *National Environmental Policy Act of 1969* was the federal law that set environmental policy by requiring an environmental impact statement on all major federal projects [16].

^{237}Np – Neptunium actinide radionuclide

NNSS – Nevada National Security Site (formally known as the Nevada Test Site or NTS)

NNWSI – Nevada Nuclear Waste Storage Investigations was the name of YMP prior to NWPAA of 1987.

NRC – US Nuclear Regulatory Commission, formed as an independent agency from a portion of the AEC by the 1974 *Energy Reorganization Act* [18]

NTS – Nevada Test Site; first designated as Nevada Proving Grounds in December 1950 with first nuclear weapons test in January 1951. Currently designated as the Nevada National Security Site (NNSS). Because the area was known as the Nevada Test Site during most of the disposal system characterization of Yucca Mountain, the tabulation uses NTS rather than the current NNSS acronym.

NWPA – *Nuclear Waste Policy Act of 1982* provides a national policy for the interim storage, monitored retrievable storage, and eventual disposal of radioactive waste [23].

NWPAA – *Nuclear Waste Policy Amendments Act of 1987* amended the *Nuclear Waste Policy Act of 1982* by specifying that only a repository site at Yucca Mountain was to be characterized by the DOE and placing less emphasis on the monitored retrievable storage option [27].

NWPO – Nuclear Waste Project Office, Nevada was created by state legislature and placed in the Governor's Office.

NWTS – Nuclear Waste Terminal Storage. In the 1970s, a mined, geologic repository was categorized as a storage option and a repository was called nuclear waste terminal storage facility. Storage referred to waste isolation with 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 referred to waste isolation with no initial provision or intention for retrieval, such as deep borehole disposal.

NWTRB – Nuclear Waste Technical Review Board; consists of 11 members appointed by the President from a slate of candidates nominated by NAS. NWTRB was created in NWPAA to review activities of YMP and advise Congress and DOE.

PA – Performance Assessment, as defined in EPA's 40 CFR 197 [28] "means an analysis that (1) identifies features, events, processes, (except human intrusion), and sequences of events and processes the processes (except human intrusion) that might affect the Yucca Mountain disposal system and their probabilities of occurring: (2) examines the effects of these features, events, processes and sequences of events and process upon the performance of the Yucca Mountain disposal system; and (3) estimates the annual committed effective dose equivalent incurred by the reasonably maximally exposed individual, including the associated uncertainties, as a result of releases caused by all the significant features, events, processes and sequences of events and processes, weighted by their probability of occurrence." The YMP called its PAs "total-system performance assessments" or TSPAs. The adjective "total-system" serves to emphasize that the assessment includes all major systems of the disposal system. Yet, because the EPA Standard defines a PA as an analysis of the Yucca Mountain disposal system the adjective is redundant and omitted here since the acronym must be repeated frequently.

PFS – Private Fuel Storage was a consortium of private utilities that contracted with Goshute Indian Tribe in Utah to store CSNF.

PNNL – Pacific Northwest National Laboratory is a DOE multi-program laboratory in Richland, WA For YMP, PNNL traditionally teamed with LLNL to conduct CSNF characterization and degradation studies.

PRA – Probabilistic Risk Assessment is the process of assessing, through a stochastic simulation, the risks from a system. A PRA is equivalent to a performance assessment (PA) in the United States; however, the connotations of the two terms differ. A PRA usually connotes (a) a system composed solely of human-engineered components and (b) performance criteria that include risk to health over a short time (e.g., human lifetime) relative to geologic time. A PA usually connotes a system composed of both natural and human-engineered components over geologic time. Because the time frame is different, many phenomena for a PRA can be termed events (short-term phenomena); because the components are all human engineered, measured failure rates of components are often available. The modeling tools in a PRA can include elaborate event and fault trees and can substitute empirical data for mechanistic models. For YMP PAs, the event trees are simper, fault trees are not usually used, and simplifications of mechanistic models are used.

PSHA – Probabilistic Seismic Hazard Assessment; expert elicitation on seismic hazards at Yucca Mountain conducted between April 1995 and September 1998

PTn – Paintbrush non-welded modeling unit above the repository horizon

PVHA – Probabilistic Volcanic Hazard Assessment; expert elicitation on volcanic hazards at Yucca Mountain

Pu – Plutonium; actinide with several isotopes

QA – Quality Assurance are all those planned and systemic actions necessary to provide confidence that a structure, system, or component will perform satisfactorily in service.

^{226}Ra – Radium decay product from uranium (^{238}U) decay series

RIP – Repository Integration Program stochastic simulator computational platform for personal computers, the predecessor of GoldSim®, RIP was intended to rapidly simulate disposal system behavior.

RSSF – Retrievable Surface Storage Facility for SNF and HLW proposed in 1972 by AEC

SAB – Science Advisory Board of EPA

SAR – Safety Analysis Report on specific topic for NRC; for example, methodology for evaluating criticality scenario class or support for Yucca Mountain licensing application (SAR/LA)

SCC – Stress Corrosion Cracking

SCP – Site Characterization Plan completed in 1988 for evaluating Yucca Mountain repository as required by NRC regulations prior to extensive characterization of a geologic repository.

SER – Safety Evaluation Report produced by NRC in response to submission of a SAR by the applicant.

SHT – Single Heater Test in ESF; heat applied between May 1996 and May 1997.

SNF – Spent Nuclear Fuel is "…fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated by reprocessing" [23]. Spent fuel can include intact and failed fuel assemblies, consolidated fuel rods, non-fuel components that are a part of a fuel assembly (such as neutron sources, instrumentation, and fuel channels). Although spent nuclear fuel has fissionable ^{235}U, it contains too many radionuclides (primarily short-lived) that adsorb neutrons from the fission process for it to be usefully left in the reactor. Because of spent nuclear fuel's high value, some countries choose to recycle it (recycling becomes more attractive after the short-lived fission products have decayed away). It is also designated separately from HLW and TRU waste by EPA in 40 CFR 191 and 40 CFR 197 [29; 30].

SNL – Sandia National Laboratories is multi-program laboratory located in Albuquerque, NM and Livermore, CA. Since inception of YMP, SNL has been involved with PAs, (including lead laboratory in early PAs and for the license application) and geotechnical studies (including initial repository designs in early PAs).

SR – Site Recommendation

SSPA – Supplemental Science and Performance Analysis was produced by YMP to answer questions posed by NWTRB related to the purposeful conservatism present in PA-SR.

START – Strategic Arms Reduction Treaty. The first treaty, ratified by Congress in 1992, reduced strategic offensive arms by 30% [31].

SZ – Saturated Zone

TAD – Transportation, Aging, and Disposal canister loaded at nuclear reactors to avoid handling of fuel rods by YM repository surface operations

TBM – Tunnel Boring Machine used to excavate ESF and ECRB

^{99}Tc – Technetium; fission product

TEDE – Total Effective Dose Equivalent is the sum of the external and internal doses as defined by NRC. Although the external dose is traditionally calculated differently from the similar EPA CEDE, NRC redefined TEDE so that TEDE and CEDE have the same meaning for the post-closure period of the YM disposal system [32].

TRU – Transuranic are 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 [29]. TRU waste, an EPA waste category, and GTCC LLW, an NRC waste category, are similar to the Intermediate-Level Waste (ILW) category of the IAEA, which is to be disposed in a geologic repository.

TSw – Topopah Spring welded tuff modeling unit that includes the layers for the repository.

U – Uranium; several isotopes

UNLV – University of Nevada at Las Vegas

URL – Underground Research Laboratory

US – United States of America

USGS – US Geological Survey, Department of Interior, had the responsibility for geology, hydrology, climatology, and seismic/tectonic studies for YMP.

UZ – Unsaturated Zone

VA – Viability Assessment, analysis of Yucca Mountain disposal system requested by Congress in 1978

WIPP – Waste Isolation Pilot Plant is a full-scale research/development repository for transuranic wastes near Carlsbad, NM. WIPP was authorized in 1979 for the management, storage, and disposal of waste generated by DOE defense programs that is contaminated with TRU radionuclides and some hazardous chemicals [33; 34].

WP – Waste Package as defined by NRC is "…the waste form and any containers, shielding, packing, and other absorbent materials immediately surrounding an individual waste container" [14]

WT – Water Table

WPDEE – Waste Package Degradation expert elicitation panel formed for PA-VA

YM – Yucca Mountain; initials used as adjective; full name used for geographic location (except in milestone tabulation)

YMP – Yucca Mountain Project. The various names for the project and DOE office administering the project were Nevada Nuclear Waste Storage Investigations (NNSWI) in 1978; Yucca Mountain Site characterization Office (YMSCO) after passage of the NWPAA of 1987 and later office reorganization in 1991; and finally, YMP Office after passage of the *Yucca Mountain Development Act* in 2002.

Milestones for Selection, Characterization, and Analysis of the Performance of a Repository for Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain

Overview

In 1987, the US Congress selected Yucca Mountain as the sole location to characterize for a potential disposal site for high-level radioactive waste (HLW), commercial spent nuclear fuel (SNF), and SNF owned by the US Department of Energy (DSNF) [27]. Yucca Mountain, located at the boundary between the Nellis Air Force Range and the Nevada National Security Site, had been under consideration for a repository since 1978 (Fig. 1). In 2002, 15 years later, President Bush recommended and Congress authorized the Department of Energy (DOE) to seek a license from the US Nuclear Regulatory Commission (NRC) to construct a repository at Yucca Mountain. In 2008, DOE submitted the Safety Analysis Report for the construction License Application (SAR/LA) to NRC [24]. SAR/LA represented a significant milestone in the effort to implement nuclear waste policy that had been in place since passage of the *Nuclear Waste Policy Act of 1982* (NWPA) [23].

This report presents a tabulation of technical events on the progression in understanding of the Yucca Mountain (YM) disposal system described in SAR/LA. Examining the progression, although somewhat tedious, provides a means for future repository programs to grasp the technical uncertainty that exists at various phases. In addition, the tabulation shows the interaction between political bodies and government agencies/institutions because the relationship is important to understanding the evolution of the Yucca Mountain Project (YMP),

Fig. 1. View looking south down Solitario Canyon Fault with Yucca Mountain to the east in southern Nevada [4].

Analysis Iterations

Because of general support for the concept in the 1980s, YMP adopted an iterative approach to refine and focus the large-scale risk performance assessments (PAs) on those aspects most pertinent to the policy issue [35-37]. Seven PAs provide historical markers for the discussion. Four early PA iterations to evaluate selection and feasibility of placing HLW and SNF at Yucca Mountain are mentioned: (1) deterministic evaluations of a volcanic eruption [38], and undisturbed behavior [39; 40] conducted to support the environmental assessment (EA) required by NWPA and collectively designated herein as PA-EA [39; 40]; (2) PA-91, the first stochastic simulation of both undisturbed behavior and disturbed behavior from igneous and human intrusion [41]; (3) PA-93; and (4) PA-95. The latter two evaluations provided guidance on repository design options [42; 43]. These four early PAs were followed by three PAs to support major decisions: (5) PA-VA, a viability assessment in 1998, which evaluated undisturbed performance and explored the influence of igneous and seismic events [44]; (6) PA-SR, an analysis for the site recommendation in 2000, which fully incorporated undisturbed behavior and igneous intrusion events [45]; and (7) PA-LA, the license application analysis in 2008, which analyzed undisturbed, early failure, igneous intrusion, and seismic scenario classes [24; 46]. The early PAs through 1995 provided rough measures of performance based on regional geologic characterization, data acquired from boreholes from the surface, limited site-specific data, and waste process data. The later three PAs made extensive use of environment-specific laboratory experiments, *in-situ* experiments, and disposal system characterization from the underground [2, Table 1].

Interactions between Technical and Policy Realms

Although the emphasis of this report is on the technical activities of YMP, an important aspect of the YMP history is the interplay between the technical realm responsible for implementing site selection, characterizing the fractured tuff media, and developing a corresponding assessment technique for a radioactive waste disposal system and the policy realm responsible for developing a politically acceptable approach for radioactive waste disposal, developing the administrative steps for selecting a site, and developing corresponding safety criteria. That is, while the evaluation of the YM disposal system presented new technical challenges for evaluating a disposal site, it also presented a societal challenge in developing a process for choosing a socially and politically viable site and developing a consensus on criteria under which a disposal system would be considered safe.

Although a traditional step-by-step process of developing policy, developing disposal criteria, selecting a site, characterizing the natural barrier, designing the engineered barrier, and then assessing the designed disposal system may have been preferred by all parties involved, the complexity of the technical and especially the social-political uncertainties were too great to be resolved in a sequential manner. Rather, a lengthy, iterative process was necessary where attempts were made to understand uncertainties, narrow differences, and adjust policy (similar to solving a complex mathematical model by an iterative process of trial and error).

The interaction between the technical realm and the policy realm occurred at three different levels (Fig. 2): (1) interaction with the institutions and political bodies that developed and influenced the evolving policy for disposal of SNF and HLW, (2) interaction with the governmental agencies and institutions that implemented policy, and (3) interaction with the institutions that implemented the technical activities.

Concerning the first level of developing policy, an important aspect was the Congressional decision in 1987 to include the YMP under the general spending caps to balance the federal budget. Hence, Congress and the President had to periodically agree on a broad policy approach and annually agree on authorization and a budget for the YMP, which changed dramatically several times and required the YMP to reassess technical approaches and delay activities (Fig. 2). Another important aspect was the contentious rather than cooperative interaction that occurred between the State of Nevada and the federal government policy bodies. The confrontational state-federal interaction periodically influenced the budgetary policy approach within the federal system. Furthermore, this confrontational interaction required continual participation of the federal and state courts.

Concerning the second level of implementing policy, an important aspect was that Congress allowed for multiple decision points and multiple reviews of technical activities, which allowed multiple avenues for stakeholders at all three levels to influence implementation of federal policy and technical decisions. Although a positive situation for stakeholder participation, it placed DOE in the difficult position of trying to maintain an overly aggressive schedule mandated by NWPA while at the same time attempting to accommodate input from multiple sources.

Furthermore, the Congressional selection of NRC to implement the EPA radiation protection standards, and the decision, in turn, of NRC to require formal hearings on applications in a legal setting with trial lawyers meant that even pre-licensing interactions between DOE and NRC were formal and required much preparation by both parties. In turn, the formality limited spontaneity in interactions and participation of the public. The alternative would have been to use a certification process as part of rulemaking under the *Administrative Procedures Act*. Under this process, the interactions of DOE and the regulator are more straightforward, as occurred for the Waste Isolation Pilot Plant (WIPP) in southern New Mexico for transuranic (TRU) waste [47; 48].

Concerning the third level of implementing the technical activities, the number of institutions and the corresponding organizational structure of the institutions changed over time. Specifically, the Management and Operating (M&O) contractor for the DOE changed as new contracts were bid; 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 (as mentioned in the acronym list).

The end result was a siting and evaluation process with numerous and significant opportunities to negotiate which, in turn, required three decades to execute, as summarized in the following sections.

Because of the numerous entities, four broad categories of political bodies and governmental agencies/institutions have been selected to be summarized here and in the tabulation (Fig. 2): (1) Federal policy in laws, court decisions, and regulations; (2) Presidential and DOE federal policy decisions; (3) Technical activities related to YMP; and (4) Critiques of YMP and related nuclear events (where the latter category includes those interactions and external events not included in the first three categories).

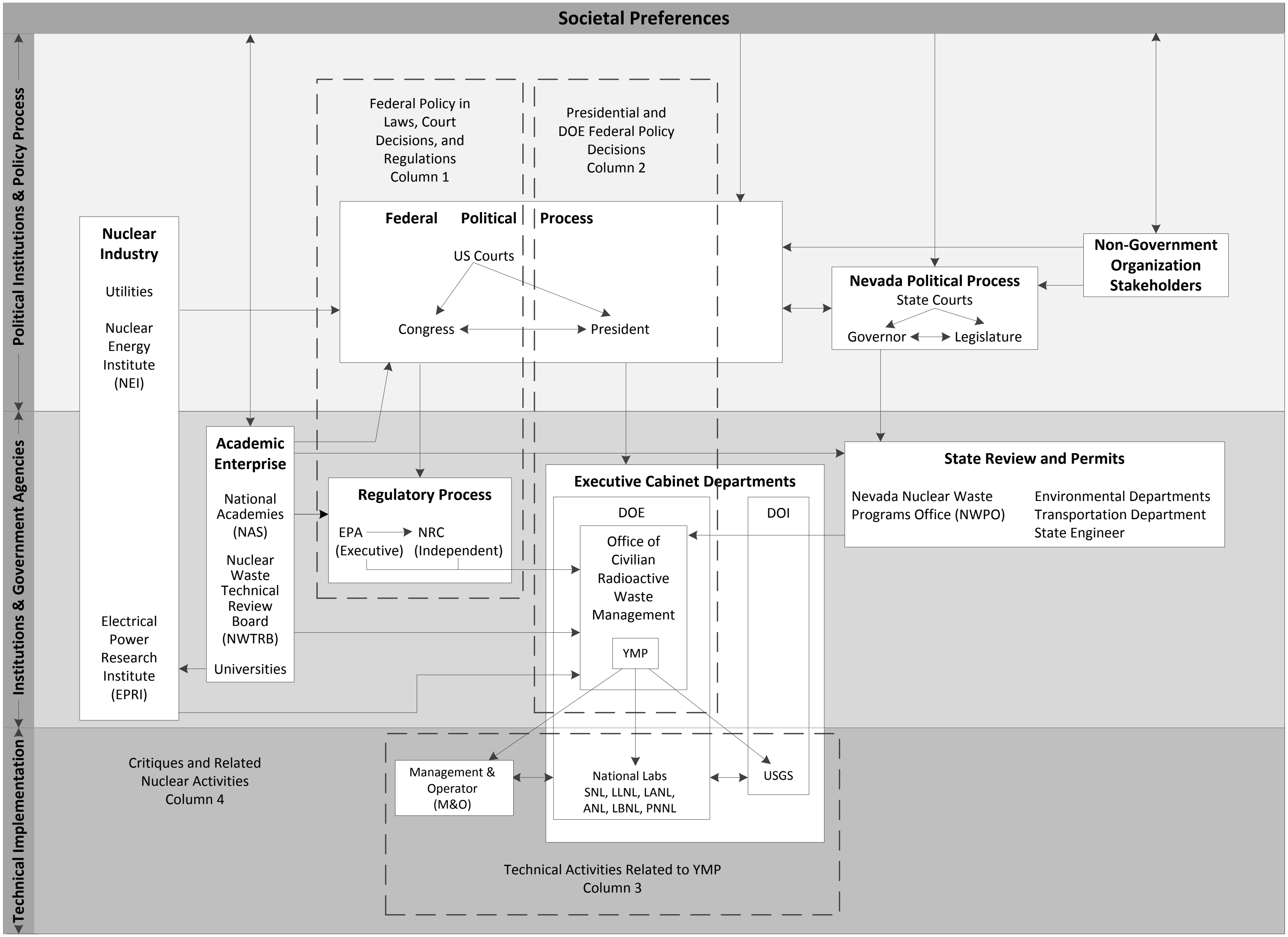


Fig. 2. Interaction between political bodies and institutions and governmental agencies related to evaluation of the disposal system at Yucca Mountain and corresponding four broad categories of interactions shown in milestone tabulation.

Presidential and DOE Federal Policy Decisions

Site Selection

From 1955 through the 1960s, the Atomic Energy Commission (AEC) undertook scientific and engineered studies for disposal of HLW and SNF in salt formations. But the concept of using multiple barriers to build a robust disposal system permitted the Energy Research and Development Administration (ERDA) and DOE, the successors of AEC, to evaluate other geologic formations on land owned by the federal government in the 1970s. In 1976, the US Geological Survey (USGS) noted that the region around the Nevada National Security Site (formally known as the Nevada Test Site or NTS) had several advantages because of its remoteness, past nuclear testing, closed groundwater basin, many suitable host rocks not closely associated with economic resources, and desert conditions. 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. Furthermore, the ability to use large waste packages (WPs), which facilitated direct linkage of the repository to waste management practices at the nuclear reactor, would eventually be appreciated as an additional advantage [3; 7].

The concept of lowering overall program risk by using a portfolio of sites, preferably in different media, was (1) expressed by ERDA in 1976 when searching for up to 6 repository sites, (2) recommended in 1979 by the Interagency Review Group (IRG), (3) required in NWPA in 1982, and (4) codified by the DOE siting guidelines in 1984 in 10 CFR 960 (Title 10 Code of Federal Regulations Part 960). Thus, along with the first ranked YM volcanic tuff site at NTS and third ranked Deaf Smith bedded salt site in Texas, DOE recommended the fifth ranked Hanford basalt site in Washington to add diversity to the three site finalists selected for further characterization beyond 1984.

The diversity of sites being considered in the international community indicates that many different geologic media can safely host a repository. In the future, several sites may need to be simultaneously under consideration to find socially and politically viable sites (e.g., provide regional equity) and, thereby, reduce program risk, but diversity of media should not be particularly necessary as noted as early as 1985 [49, App. B].

Site Recommendation and License Application

In 2001, DOE completed the supplement to the draft Environmental Impact Statement (EIS) on Yucca Mountain [50], the Science & Engineering Report describing PA-SR [45], and the Preliminary Site Suitability Evaluation (SSE) report [51]. After a 9-month personal review of these reports, Energy Secretary Abraham recommended the site to the President in February 2002 [52]; and President Bush recommended the site to Congress. In April of 2002, Nevada Governor Guinn disapproved the Site Recommendation, under the special procedure specified in NWPA [53]. But Congress overrode Nevada's disapproval by July [53] followed by President Bush signing the *Yucca Mountain Development Resolution* [54]. The Court of Appeals for the District of Columbia (DC) Circuit rejected all Nevada lawsuits related to the site selection process in 2004, on the grounds that amendments to NWPA rendered moot challenges on site selection (App. A) [55]. The court did, however, vacate the portion of the EPA radiation protection standards, 10 CFR 97, related to the 10^4-yr regulatory period, as discussed later.

Although DOE submitted and NRC docketed the SAR/LA in September 2008, the election in November brought dramatic changes in 2009 [56]. The Obama Administration reduced funding to a level sufficient only for limited staff to respond to NRC requests for additional information concerning the SAR/LA. Most other work had to cease. In 2010, the Obama Administration declared the YM repository an unworkable solution, eliminated all YMP funding, and filed a motion to withdraw the SAR/LA from NRC.

The Blue Ribbon Commission (BRC) on America's Nuclear Future, formed by Presidential direction in 2010 to review the current waste management policy, endorsed many of the key elements suggested by the IRG, which had provided the foundation for the current policy. However, the BRC recommended in 2012 that the US abandon the approach of first identifying technically suitable sites and then approaching communities, host states, and tribes as outlined in NWPA of 1982. The BRC favored and DOE endorsed in 2013 a "new, consent-based siting approach to siting future nuclear waste management facilities," which is flexible and dependent on a potential host community, in collaboration with the state or tribe, volunteering to be a candidate site [12, p. viii; 57]. Using this approach for identifying a socially acceptable site first, along with sufficient powers for monitoring SNF and HLW disposal, the current generation of citizens in communities, might find that "their interests have been adequately protected and their well-being enhanced" [12, p. xv].

Federal Policy in Laws, Court Decisions, and Regulations

Nuclear Waste Policy Act

In the *Nuclear Waste Policy Act of 1982* (NWPA), 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 safe guard future generations, as expressed by DOE and IRG in the 1970s. To fulfill this stewardship responsibility, Congress sought to (1) set procedures for the siting, development, and operation of a federal repository in order to respond to state concerns about being a host; (2) provide funding for many decades through a fee on nuclear power to dispose of the waste produced by the utilities; and (3) promote stability in waste policy during changes in the executive branch by establishing written contracts between the US government and nuclear utilities to accept ownership and begin disposing of the waste by 1998.

However, the selection process and aggressive schedule for selecting the first repository site between 1983 and 1987 did not soothe fears of the states: the search for a second repository site heightened anxiety in the eastern US and was indefinitely delayed by the executive branch in 1986. Also, Congress included YMP under the budget balancing process in 1987, which introduced uncertainty in financial support.

In the *Nuclear Waste Policy Amendments Act* (NWPAA) passed at the end of 1987 as part of a deficit reduction measure, Congress greatly reduced the scope of the repository siting program and chose the YM site from the three finalists as the only site to initially characterize for the first repository. This choice, in turn, fueled strong opposition in Nevada.

In 2010, the NRC Atomic Safety Licensing Board (ASLB), which was to conduct the hearings, denied DOE's motion to withdraw the SAR/LA and an appeal to the NRC Commissioners upheld the ASLB decision. However, the NRC Commissioners suspended pretrial depositions for the ASLB and the license review by the NRC staff in 2010 when Congress did not appropriate funds. The US Court of Appeals for the DC Circuit ruled in August 2013 that the NRC commissioners did not have the authority to suspend the SAR/LA review, but the programmatic uncertainty and lack of funding has brought a *de facto* stop to YMP.

Standards and Implementing Regulations for SNF and HLW

The US regulatory agencies worked to formulate a notion of safe disposal for SNF, HLW, and TRU waste between 1976, when President Ford directed the US Environmental Protection Agency (EPA) to develop radiation protection standards, and 2008 and 2009, when EPA and NRC finalized their regulations, respectively. In its first 40 CFR 191 standards in 1985, EPA selected the cumulative release of long-lived radionuclides after 10^4 years to a hypothetical large population at the boundary of the controlled area 5 km from the repository as the primary indicator of health impact [29]. EPA required inclusion of uncertainty in the measure, which implied numerical modeling, and, consistent with this requirement, specified the limit for the measure probabilistically. The cumulative release measure was used for PA-EA, PA-91, PA-93, and PA-95 (and WIPP).

In 1992, Congress mandated EPA to seek advice from the National Academies (NAS) and to use individual dose as the indicator of health impact in a site-specific regulation for the YM repository, as suggested by NAS in 1982 [58] and consistent with the international community. Hence, a dose measure was also calculated for PA-93 and PA-95, and solely for PA-VA and thereafter.

In 2001 EPA promulgated the site-specific radiation protection standards, 40 CFR 197. The standards specified the mean peak dose over 10^4 years at the controlled area boundary no further south than the southern edge of NTS, ~18 km from the repository, as the performance measure with a limit of 0.15 mSv/yr. This measure, which was used for PA-SR, prompted changes in the site characterization program since more of the natural barrier had to be characterized for a ~18-km compliance boundary. In response to a court ruling, EPA extended the regulatory period to 10^6 years in 2008. The revised rule had a limit of 1 mSv/yr for the period beyond 10^4 years. This measure was applied to PA-LA.

In both 40 CFR 191 and 40 CFR 197, EPA required reasonable expectation as the standard of proof for the post-closure assessment, a concept that had been affirmed by the courts in 1987 [59].

The early PAs, PA-EA and PA-91, assumed complete failure of the container between 300 and 1000 years, the minimum lifetime requirements for the container, defined by NRC in their generic regulations 10 CFR 60 [1]. In turn, the container lifetime was an important parameter in the analysis. NRC removed subsystem requirements in their site-specific regulations for a YM repository, 10 CFR 63 in 2009, on the advice of NAS. In turn, modeling of waste container degradation progressed to a stochastic description of container breaches when using an individual dose performance measure in later PAs.

The regulatory requirement to treat uncertainty quantitatively through the use of numerical models to evaluate the measure was successfully implemented for PA-LA (and WIPP). Although the site-specific

EPA and NRC regulations for a YM repository will not directly apply to another repository, the 33-yr experience will likely make selection of a health indicator, its measure, the evaluation of uncertainty, and the standard of proof less trying in the future such that the EPA radiation protection standards and NRC implementing regulation can be set prior to development of site selection guidelines and not change substantially during site characterization and, thus, allow a more sequential process for a new repository program.

Related Nuclear Activities and Critiques of YMP

The changes in policy and technical activities were influenced by societal preferences that changed as external events occurred. For example, controversies surrounding the fire at the Rocky Flats Plant near Denver in 1969 (which produced weapon parts), storage of the debris in Idaho in 1970, the attempted disposal in Lyons, KA in 1971, the Arab oil embargo in 1973, and the leakage of HLW from a single-shelled storage tank at Hanford also in 1973 prompted Congress to split the independent AEC in 1974 into [18] (1) an independent regulatory agency, NRC, to regulate civilian use of nuclear materials; and (2) an executive branch agency, ERDA, with a wider energy role but still responsible for radioactive waste.

Also in 1974, EPA and anti-nuclear groups claimed the AEC proposal for a Retrievable Surface Storage Facility (RSSF) was *de facto* disposal in comments on the EIS [60, p. 76]. The criticisms prompted the newly formed ERDA to abandon consolidated surface storage, even as a near-term solution, and emphasize geologic disposal.

Later in 1976, California enacted a moratorium on new nuclear reactors until the federal government approved a method of disposal of radioactive waste. The moratorium, which was upheld by the US Supreme Court [60, p. 86], along with the above events, clearly placed nuclear waste management on the national agenda. In response, President Ford requested that ERDA accelerate the demonstration of waste isolation [61]. That same year, ERDA formed the National Waste Terminal Storage (NWTS) program to develop technology and facilities for storage of HLW and SNF [60, p. 135; 62; 63, p. 2-11].

Also in May 1974, India detonated a plutonium bomb using material and technology supplied by the US for commercial reactors. This event placed nonproliferation issues on the national agenda and the preference for direct disposal of SNF, without reprocessing the SNF to remove the produced ^{239}Pu and remaining ^{235}U. Hence, President Carter asked for a major government evaluation in 1978, a year after he took office, of options for management of radioactive waste by the Interagency Review Group (IRG) of 14 government agencies. In October 1978, the IRG distributed ~15,000 copies of draft recommendations. After considering ~3000 comments, the IRG report suggested mined geologic disposal, use of multiple barriers, looking for sites in variety of media in different regions of US, and not delaying disposal.

The fall of the Berlin Wall in November 1989, signaled the end of the Cold War and reduced the demand for nuclear material. Hence, DOE eventually curtailed production of fissile ^{239}Pu and ^{235}U and adopted direct disposal of SNF from production, experimental, and naval reactors [64-66].

In September 2001, al Qaeda terrorists commandeered 4 commercial jets and flew 2 into World Trade Center and one into the Pentagon. The specter of attacks on nuclear reactors and radioactive waste in transit become of concern. But NRC and the Government Accountability Office (GAO), found that the health risks from accidents and terrorism during transportation of radioactive waste is low [67]. Furthermore and in contrast, the more recent tsunami that severely damaged the Fukushima reactor complex in Japan raised public awareness of the current practice of storing SNF in cooling pools at the reactor and might provide motivation to move more SNF into dry storage and even consolidate SNF at sites away from reactors [68], as previously proposed in 1974 by AEC and 1979 by President Carter.

Following the example set by the establishment of the NAS Review Panel for WIPP, NWPAA established the Nuclear Waste Technical Review Board (NWTRB), with 11 members appointed by the President from a slate of candidates nominated by NAS, to advise Congress and DOE and to ensure scientific credibility through formal outside technical oversight. Many of the changes made in site characterization and engineered barrier design, described in the next section, were made in response or supported by NWTRB comments after their first report in 1990. For example in 1992, NWTB urged (a) horizontal placement of packages, (b) exceeding the NRC container life goal of 1000 years, and (c) use of the MPC (and later the TAD) to limit handling of SNF at the repository [69; 70]. Furthermore in 1997, YMP accepted the NWTRB suggestion for a second test drift: the enhanced characterization of the repository block (ECRB) bored to Solitario Canyon Fault [71].

Also, in response to a request by NWTRB [72], YMP conducted the July 2001 Supplemental Science Performance Analysis (SSPA), which built upon the PA-SR by using more realistic parameter values and more realistic models to better elucidate the relative importance of included features, events, and processes (FEPs). The SSPA also evaluated an alternative cooler repository design [73].

Technical Activities Related to Yucca Mountain Project

Site Characterization of Yucca Mountain Disposal System

Site characterization of the natural barrier consumes much of the time and resources required to evaluate a geologic disposal system. Understanding of the behavior of igneous processes near Yucca Mountain, infiltration in a desert environment, unsaturated flow in fractures, and seepage into an open drift in a thermally perturbed environment was initially lacking in 1984, and, thus YMP expended much site characterization time and expense to improve this understanding. This effort resulted in an impressive body of scientific work.

After the commitment to mined geologic disposal and identification of sites by DOE (phase 1), site characterization at Yucca Mountain progressed through four additional phases: (2) literature search, non-intrusive evaluation, and boreholes completed to determine stratigraphy for the site selection study phase, which supported PA-EA; (3) exploration from the surface through well testing for the feasibility study phase, which supported PA-91, PA-93, and PA-95 (Fig. 3), (4) more extensive well testing and exploration underground to evaluate coupled processes for the suitability phase, which supported PA-VA and PA-SR; and (5) completion and reporting on conclusions of site-specific experimentation for the compliance phase, which supported PA-LA. Once a reasonably good site had been identified in the first phase, the focus of the characterization was on what could go wrong with the YM disposal system and the uncertainty associated with the system.

Most of the wells drilled near the 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 1984 PA-EA and the site selection phase (Fig. 3). However, extensive testing in these wells was not implemented until after completing the Site Characterization Plan (SCP) in 1988, as required by NRC regulations. The proposal to allow temperatures above boiling in the drift for PA-93 and PA-95, in conjunction with the use of large, in-drift disposal containers, also prompted questions about the coupling of thermal, hydrologic, and chemical processes during the ~1000- year thermal period. Hence, YMP conducted much experimental work (e.g., [2]) and code development to advance the science of coupled thermal-hydrologic-chemical modeling thereafter.

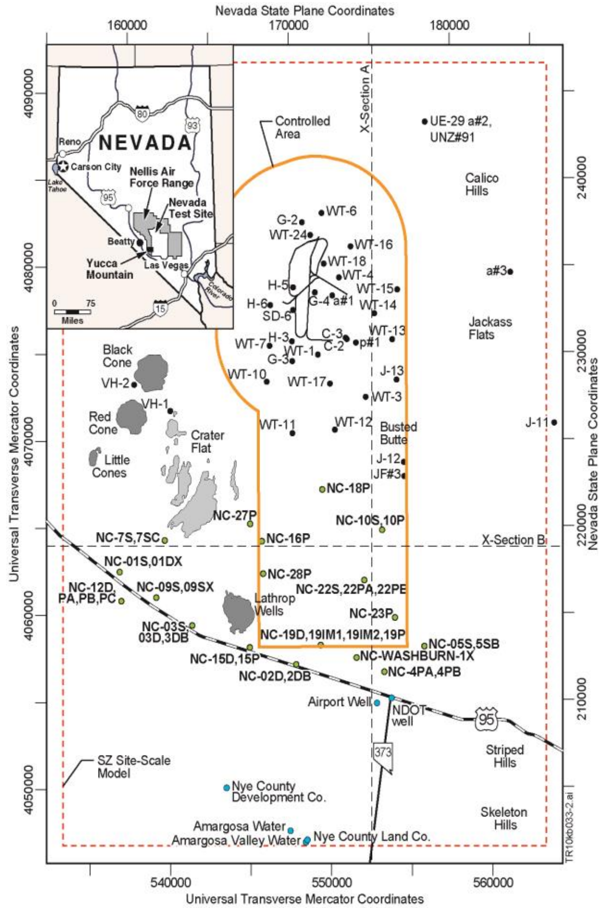


Fig. 3. Location of repository, boundary of controlled area, and pertinent wells at Yucca Mountain [9, Fig. 1].

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

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 PA-VA in 1998. Also for PA-VA, Expert Elicitation Panels were formed to evaluate current models and literature data used in PA-95 and or proposed for PA-VA prior to completion of the experimental program.

By PA-SR, site characterization had evaluated seepage into alcoves and the chemical environment around the Drift-Scale Test (DST), both in the ESF. By PA-LA, Nye County in cooperation with DOE had completed Phases I through IV of a series of wells south of Yucca Mountain to better define fluid flow and radionuclide transport in the saturated zone (SZ) (Fig. 3). The information from these wells permitted a detailed description of the flow path in the SZ in comparison to the simplistic flow paths used in early PAs. By PA-LA, many tests had been completed that allowed PA models to be partially validated. However, an attempt to validate the presence of bomb-pulse ^{36}Cl in fractures within the ESF using different measurement techniques was unsuccessful [74].

NRC initially estimated the cost of *in-situ* characterization of a hard rock repository, such as Yucca Mountain, at less than $40 million in 1982 [75; 76], under the assumption that much knowledge would be acquired during construction, similar to the situation that occurred at WIPP [47; 48]. But after some surface exploration to evaluate the feasibility, the cost of characterization of candidate sites was estimated at ~$1 billion per site in 1987 during hearings for NWPAA [77]. As noted earlier, this cost increase curtailed Congressional support for evaluating multiple repository sites. Under the revised expectation that most knowledge would be acquired prior to construction authorization by NRC, YMP 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 phase. For the licensing compliance phase, the cost had increased further to ~$11 billion (2010 constant dollars), 20 years after NWPAA [78, Tables ES-1 & ES-3]. These large increases made continued Congressional financial support uncertain.

Characterization of future potential repository sites will likely adopt a phased approach, similar to the phases followed informally by YMP, where limited site characterization is conducted during the site identification and feasibility phases. Activities would not proceed to the suitability/viability characterization phase, because of the high costs encountered at Yucca Mountain, until a host community and associated state or tribe have provided preliminary consent to proceed with the repository program.

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 reaches 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 (Fig. 4).

Yet, the limited understanding that existed at Yucca Mountain during PA-91 through PA-95 versus the more complete understanding for PA-VA and PA-SR when *in-situ* underground experimental data were available raises a more subtle question as to the type of laboratory and in-situ experiments to conduct during site identification and site feasibility versus those necessary to conduct for evaluating site suitability/viability and compliance.

Evolution of Repository and Container Designs

Over 30 years of study, from the drilling of borehole UE25a#1 that confirmed thick tuff deposits in 1978 (Fig. 3) to the submission of the LA in 2008, scientists and engineers, with a wide range of expertise, designed engineering features complementary to the characterized attributes of the natural barrier such that YM disposal system would safely isolate radioactive waste over 10^4 to 10^6 years.

Initially, a fairly generic repository layout and engineered barrier design was considered that was applicable to several geologic media. For PA-EA and PA-91, the repository design used vertical floor or horizontal pillar emplacement of small waste containers. Small packages, which held 3 or 4 pressurized-water-reactor assemblies and 6 or 10 boiling-water-reactor assemblies that could be used in various saturated and unsaturated geologic media, were initially adopted in the early 1980s. While ramps were to be constructed using a tunnel boring machine, most of the underground facility was to be constructed with conventional drill and blast technology.

PA-93 considered vertical floor emplacement but also considered in-drift emplacement with large packages (i.e., for PA-93 and afterwards the repository design was gradually adapted to the specific features of Yucca Mountain). The layout of the underground facility was redesigned to facilitate constructing the entire repository with a tunnel boring machine, as supported by NWTRB. Both vertical and in-drift configurations in PA-93 and thereafter considered corrosion resistant material for the containers. The appeal of in-drift emplacement of large packages in PA-95 and thereafter was the ability to more easily receive 3000 metric tons of heavy metal per year (MTHM/yr) of SNF and HLW (a value 50% greater than the ~2000 MTHM annually removed from US reactors) because fewer packages were emplaced. In-drift emplacement also lowered excavation costs. A mountain site facilitated use of large packages since gently inclined ramps could be used to move large, heavy packages into the repository.

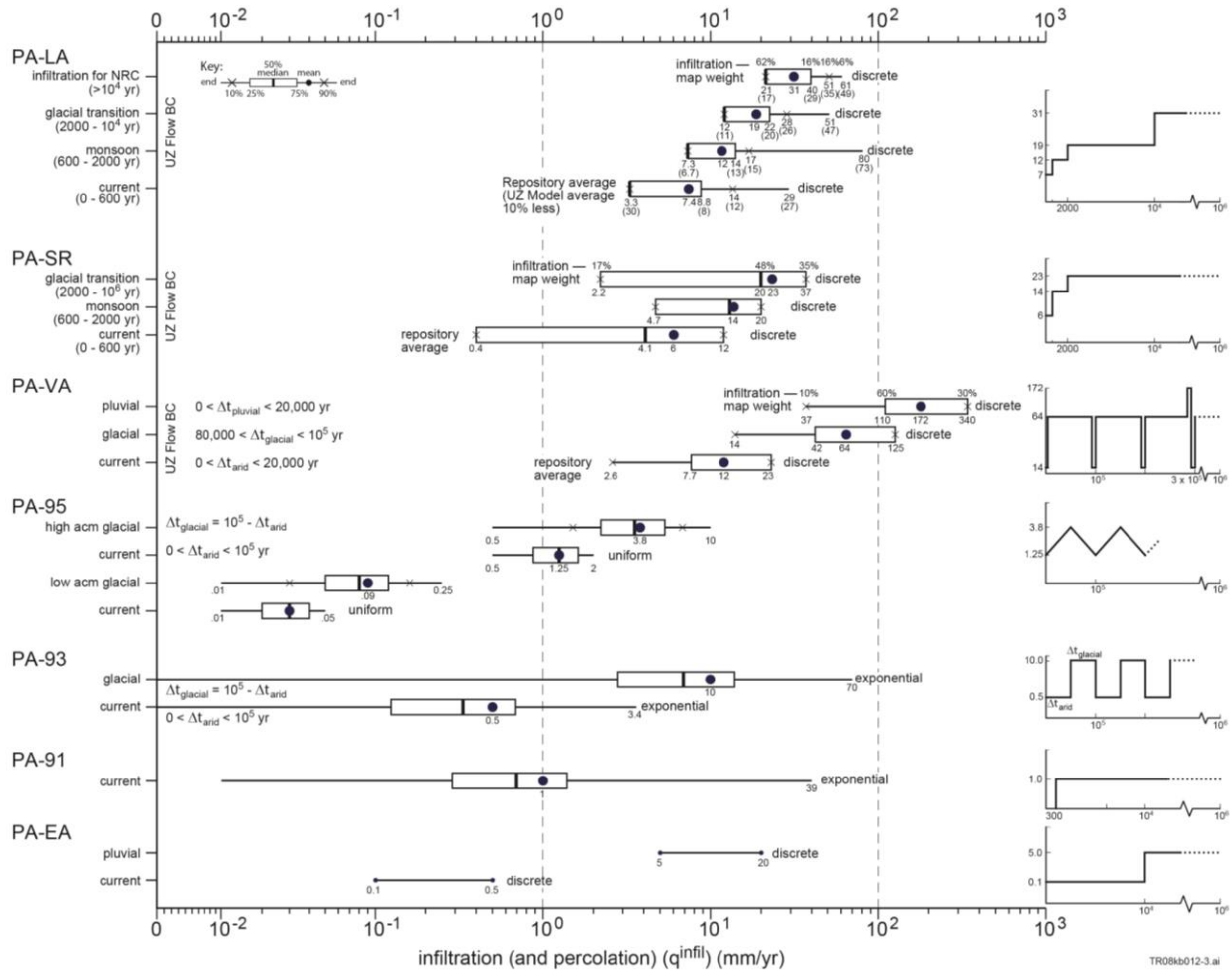


Fig. 4. Infiltration at surface (and percolation at repository horizon prior to PA-VA) as a function of climate states [6, Fig. 5].

Use of the UZ presented YMP the option to not backfill the repository (at least for an extended period) and allow convection and radiative heat transfer in the open drifts to maintain lower temperatures on the large package surface and still thermally load the repository to fairly high values (between 28 W/m^2 in PA-93 and 18 W/m^2 in PA-LA).

Even though a large drift cavity provided a capillary barrier, there was the potential for some flow percolating through fractures to drip into the drifts. Hence, titanium drip shields were added for PA-SR and PA-LA to avoid drips on the package and, thereby, reduce the potential for localized corrosion of the Alloy 22 outer layer of the waste package during the thermal period. Analyzing these new features and processes necessitated an extensive experimental program to resolve phenomena uncertainty.

PA-LA added a 25-mm thick transportation, aging, and disposal (TAD) handling canister loaded and sealed at the utility, which eliminated handling assemblies whenever transporting, storing, or disposing of commercial spent nuclear fuel (CSNF). The TAD was similar in function to the multi-purpose canister (MPC) proposed and evaluated for PA-95.

Although a centralized storage facility could be of great benefit to decouple operations at nuclear reactor from operations at proposed repositories, Congress eliminated this strategy in NWPAA. However, a repository in the UZ at Yucca Mountain was able to directly link CSNF shipments from nuclear reactors and still accommodate the needs for limited disruption of pool storage operations at nuclear reactors, by using a large TAD similar in size to dry storage casks.

Eventually, YMP embraced a staged construction approach for the repository and surface facilities as tentatively proposed in the 1986 EA. In addition, YMP developed a design strategy for the repository underground and surface facilities that was modular (Fig. 5); thus, the design was more flexible and consistent with the annual funding available.

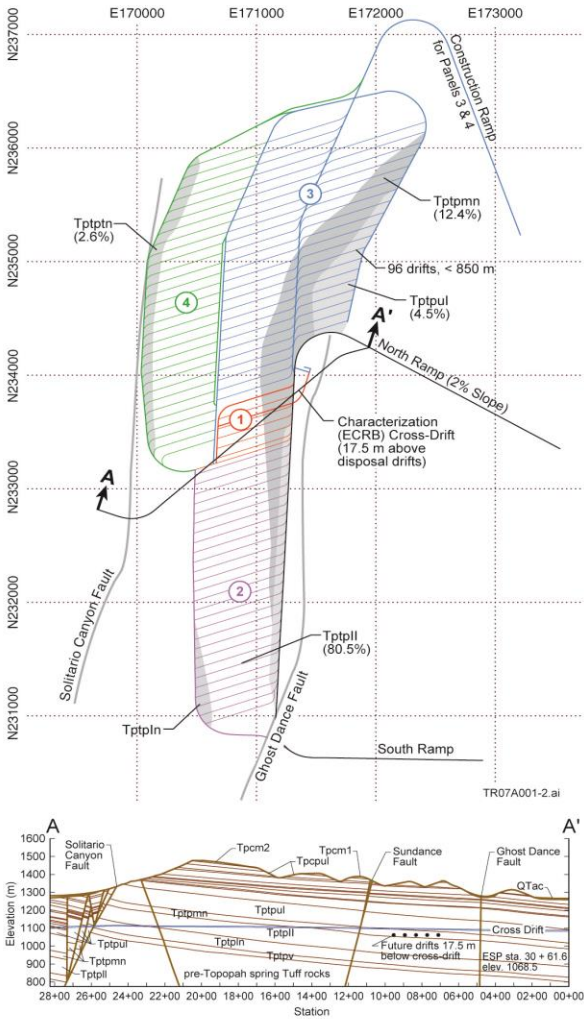


Fig. 5. Modular YM repository concept for PA-LA

In-drift disposal without backfill of a thermally hot package, adopted in 1994 [3], necessitated increased modeling complexity that took a number of years to develop. The most obvious influence of in-drift disposal was the presence of a large cavity such that radiative heat transfer and thermal convection occurred; thus, a major effort to model thermal-hydrologic interactions was added for PA-VA. Also, the detailed modeling of flow percolating through fractures and forming seepage in disposal drifts was added in PA-VA and improved by PA-LA [6]. Furthermore, axial transport and condensation of water vapor in drifts due to repository thermal gradients could cause airflow down the drifts; hence, drift wall condensation was also added in PA-LA [5, Fig. 7; 79].

Drift disposal without backfill, increased the importance of the disruptive events such as seismic and igneous intrusion, as discussed in the next section. The effects of seismic ground motion on in-drift disposal, as modeled in PA-LA, included fault displacement; rockfall damage from a collapsed drift; degraded internal supports (which allowed SNF assemblies to puncture the container); and containers hitting other containers and invert supports. Igneous intrusion into a disposal drift without backfill presented the potential for magma to engulf and, as modeled in PA-LA, completely destroy all the containers and expose the waste form matrix.

Hazards and Scenarios Examined

An important step of the PA methodology is to develop a complete universe of features, events, and processes (FEPs) to consider either as a separate analysis to evaluate the impact or as part of the PA modeling. The more well-known disruptive events and scenario classes considered at Yucca Mountain included igneous intrusion, seismicity, criticality, extensive water table rise, and human intrusion.

Some of the first site evaluations for Yucca Mountain identified igneous activity as a potential hazard to the disposal system. The first analysis in 1982 evaluated the consequences and probability of igneous eruptions. Igneous disruption was evaluated to some extent in all PAs except PA-95. The first estimate of the probability of igneous disruption was established as ~10^{-8}/yr and remained at this value through PA-LA in 2008 (Fig. 6). Hence, the igneous event remained at the threshold of being omitted from the analysis based on the regulatory exclusion criterion [10, Fig. 8].

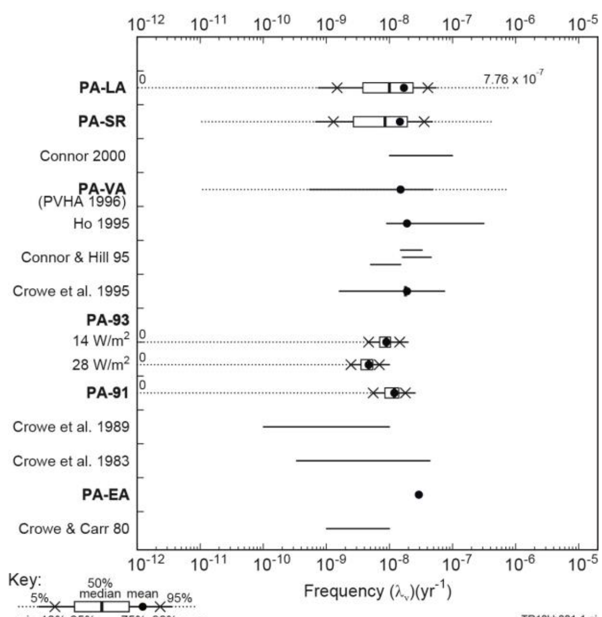


Fig. 6. Estimates of mean frequency of igneous disruption of YM repository have remained fairly constant [4, Fig. 4].

The criticality scenario class was evaluated inside containers at YMP as early as 1983. However, in late 1994, two scientists at Los Alamos National Laboratory (LANL) hypothesized that an atomic explosion via autocatalytic behavior was plausible in tuff. This claim prompted YMP to make a concerted effort to develop a formal methodology for evaluating criticality. In 1995, DOE and NRC agreed to interact via a topical report prior to submitting the LA. YMP excluded criticality by showing the scenario class probability was < 10^4 in 10^4 yr in SAR/LA.

A variable water table rise was included in most PAs (between 50 and 120 m for PA-93, between 80 and 120 for PA-VA, and set at 120 m for PA-SR and PA-LA beyond 600 yr). However, the 1988 hypothesis by DOE employee Szymanski whereby earthquakes force water hundreds of meters above the water table ("seismic pumping") was not included. In 1990 DOE asked the NAS to examine Szymanski's hypothesis. In 1992, the NAS concluded that "…there is no evidence to support the assertion by Szymanski..."

Human intrusion had been an important source of estimated consequences in shallow land burial of radioactive waste and an impetus to search for alternatives to disposal in salt. For the human intrusion scenario class, 40 CFR 191 used the strategy of a stylized calculation that defined the state of human behavior and the intent of intrusion (i.e., current technology and inadvertent exploratory drilling for resources) to avoid speculating on a wide spectrum of futures and technology. In PA-91 and PA-93, inadvertent human intrusion was included in which the release was conditioned by its probability, based on the EPA suggested frequency of exploratory drilling.

However, the treatment of inadvertent human intrusion event evolved. For 40 CFR 197, the inadvertent human intrusion event was a stylized calculation that did not include a probability estimate and, thus, was not included in the probabilistic dose calculations for PA-SR and PA-LA, consistent with an NAS recommendation.

In modeling these and other FEPs, YMP initially constructed scenario sequences that included the timing and order of FEPs. Many elaborate scenario sequence trees were developed and some general sequences that included the igneous and human disruptive events modeled for PA-EA, PA-91, PA-93, and PA-VA. For PA-SR and PA-LA, the process of scenarios development was changed to constructing broad categories of scenarios from combinations of FEPs, similar to the approach used at WIPP. The order and timing of the FEPs were then part of modeling.

FEP and scenario development is an art in that a practical balance is necessary between the detailed description of a FEP and broad categories that reveal important concepts to facilitate meaningful and practical modeling. The approach for PA-SR and PA-LA found this practical balance easier than had occurred when developing elaborate scenario sequences trees, which then had to be grouped afterwards for modeling. Because of the success of the approach for PA-LA, a future repository program would not have to experiment with other procedures.

Progression of Modeling

The construction of the consequence model to simulate the relevant physical phenomena or processes that could influence repository performance is the nuts and bolts of a PA. As noted in the previous section, the first consequence and probability modeling of the proposed YM repository used a deterministic evaluation of the probability of a volcanic eruption scenario and the dose consequences to those living 18 km away in Amargosa Valley (PA-EA) [38] (Fig. 2). The expected volcanic eruptive dose, estimated using average parameter values, was similar to the mean dose calculated for PA-LA in 2008 (i.e., 4×10^{-6} versus 10^{-6} mSv/yr) (Table 1). In addition to the eruptive scenario, a deterministic analysis of the undisturbed scenario using a cumulative release performance measure was conducted in PA-EA [39; 40].

PA-91 demonstrated a full stochastic analysis of cumulative release 5 km from the repository [41] (Table 1). One-dimensional (1-D) UZ flow and transport without lateral dispersion had been used for PA-EA but progressed to a 1-D, dual-porosity transport formulation for the UZ, based on a single equivalent continuum model (ECM), with flow primarily in the matrix [15]. Yet by PA-91, evidence for deep fracture flow had been found. Hence, both PA-91 and PA-93 also considered an alternative conceptual model of flow solely in the fractures. PA-91 used a two-dimensional (2-D) flow model for the SZ, but PA-93 improved SZ flow modeling by progressing to a three-dimensional (3-D) flow model.

PA-93 provided guidance on thermal load options for the repository, and floor and in-drift package placement options [3; 42]. A heat load of either 14 W/m^2 (as used in PA-EA and PA-91) or a hotter 28 W/m^2 were evaluated. The proposal to design a hotter repository necessitated the addition of a thermal module to the consequence model [7]. That is, PA-93 made the first tentative steps toward evaluating the interaction between the engineered barrier and the natural barrier. Each successive PA would evaluate this interaction in more detail.

By PA-93, YMP had settled on a fairly rapid rate for degradation of SNF within the oxygenated environment of Yucca Mountain. Also, YMP used a similarly rapid rate for degradation of HLW in PA-VA and thereafter. Other components of the multi-barrier YM disposal system compensated for the high degradation rates (e.g., while the container was structurally intact, the container provided substantial diffusive and advective resistance to flow regardless of the presence of cladding and a rapid waste form degradation rate [7]).

In general, the thermal load and package placement design options did not have a strong influence on the performance measures for the undisturbed scenario class in PA-93: vertical emplacement was slightly better than horizontal emplacement, and for in-drift emplacement, a cooler repository was somewhat better. In contrast, conceptual model uncertainty related to flow in the UZ (i.e., ECM versus weeps fracture flow) did have a strong influence on dose results for PA-93 (and for PA-91). YMP would devote much resources in the remainder of the 1990s to developing a process model of UZ percolation to accurately match on going characterization experiments [6].

PA-95 also provided guidance on heat loading options for the repository, and floor and in-drift package emplacement options [42]. Furthermore, PA-95 examined the influence of percolation, seepage, and relative humidity on the thermal regime in an expanded thermal-hydrologic module (Table 1). With the proposed change to an individual dose performance measure, PA-95 also took the major step of developing a container degradation module (separate from the waste form degradation model) that used a stochastic description of container breach. Container degradation, as a complex coupling of thermal and chemical processes, presented a significant challenge to the approach adopted for YMP of representing phenomena as a series of abstracted simplified models within the PA simulation.

Partially in response to the change to a dose performance measure, PA-95 also improved modeling of the engineered barrier system (EBS) of the YM disposal system by evaluated 3 modes of transport of radionuclides out of the container [8; 43].

A major step in modeling complexity occurred in PA-VA. The consequence model included more elaborate modeling of UZ percolation. Uncertainty in percolation through the fractured volcanic tuff of Yucca Mountain was usually important in explaining the observed uncertainty in the individual dose measure, and PA-VA was the first to incorporate results of percolation through dual permeability media (both fractures and the matrix) in a 3-D model grid from the surface to the water table.

An important step for incorporating percolation from the surface was to develop an infiltration boundary condition, and, thus, an infiltration module was added in PA-VA [6]. Also prior to PA-VA, evaluating seepage in the disposal drift was fairly rudimentary. The seepage module, introduced for PA-VA, included a detailed, calibrated model of a drift that developed seepage functions for use in the PA from numerous simulations [6].

In addition, the extent of the SZ was greatly expanded from 5 km to 18 km toward the Amargosa Valley for the dose calculations in PA-VA. Finally, a biosphere model was developed to determine individual dose from several exposure pathways in addition to consumption of drinking water for PA-VA, in anticipation of the new site-specific EPA radiation protection standards [9].

For PA-VA, sensitivity studies were conducted to show that the maximum ~0.4 mSv/yr dose over the 10^6-year period from the undisturbed scenario class would not be noticeably changed by inclusion of the igneous intrusion or the seismic disruption scenario classes.

For PA-SR, in which a conservative modeling approach had been adopted, the maximum dose was 4.9 mSv/yr. This maximum occurred at 2.7×10^5 years from neptunium radionuclide (^{237}Np) after corrosion of the container and subsequent groundwater releases.

For PA-SR, the container corrosion module was moved directly into the stochastic calculation and included breach of the newly added drip shield [7] (Table 1). Also, the drift seepage module of the consequence model was more elaborate [6].

For PA-LA, the potential for container damage from drift degradation and container movement during a seismic event was included [80], which, in turn, required the addition of seismic damage process codes [7; 81]. In addition for PA-LA, the calculation of the biological dose conversion factors was determined using a new code to conform to the revised method of evaluating dose, as specified by EPA and NRC. The maximum expected dose of 0.02 mSv/yr occurred at 10^6 years from the contribution of doses from the undisturbed, seismic, and the igneous dike intrusion scenario classes.

As understanding of the YM disposal system increased, the peak doses generally decreased from those calculated in PA-93 through PA-LA in 2008. The change in modeling between PA-93 and PA-VA represented, to some extent, the difference in knowledge based on general data or limited site-specific data from surface boreholes versus knowledge based on site-specific, *in-situ* data such that conceptual model uncertainty could be reduced. However, the plethora of site-specific data was not immediately available and understanding continued to increase between PA-VA and PA-LA. Furthermore, the general decrease in peak dose alos occurred because of the design and modeling changes (summarized in Table 1). For example, the TAD handling canister for CSNF changed the susceptibility of CSNF containers to seismic damage.

Table 1. Summary of PAs evaluating performance of disposal system at Yucca Mountain [10, Table 1].

PA	Purpose	Design and Models	Measure and Key Results
PA-EA [38; 40]	Deterministic PA calculation for site selection in EA [63]	For eruptive dose used Gaussian plume model. For groundwater release, 33,000 stainless WP placed vertically and horizontally in drill/blast panels at 14 W/m^2 in 6-km^2 repository. WP fails at 300 yr, 1000 yr, or exponentially. 1-D model with source term and separate UZ and SZ fracture and matrix transport	Mean peak eruptive dose of 0.004 μSv/yr at 18 km from igneous eruption scenario ($\mathcal{A}_U$) (140 μSv/yr dose with probability of 2.9×10^{-5} in 10^4 yr). Cumulative release at 10 km for undisturbed scenario at 10^4 yr and EPA units released per time. For <1 mm/yr percolation (matrix flow), no release in 1st 10^4 yr. ^{129}I, with no sorption, was important (^{99}Tc adsorbed a little). For >1 mm/yr percolation (fracture flow), ^{240}Pu and ^{239}Pu important with ^{243}Am, ^{242}Pu, and ^{239}Np as minor contributors to release from 0.035 and 0.13.
PACE-90	Deterministic PA calculation exercise		
PA-91 [41]	Demonstrate full stochastic PA capability and site feasibility with preliminary comparison to EPA and NRC criteria using simple models	Repository and WP design similar to PA-EA. WP fails between 500 and 10^4 yr. Two 1-D models of UZ water flow: ECM (most flow in matrix) and a weeps model (flow only in fractures). 1-D transport based on 2-D flow process model. Analysis added gas flow process model that also required WP heat process model.	Cumulative release to 10^4 yr at 5 km from 3 scenarios: undisturbed, igneous eruption, and human intrusion ($\mathcal{A}_U$, $\mathcal{A}_{VE}$, $\mathcal{A}_{HI}$). ^{99}Tc and ^{129}I important for groundwater flow in both ECM and weeps conceptual models. Gaseous releases from ^{14}C > groundwater > human intrusion > volcanic releases. SZ transport time ~1200 yr as in PA-EA. Percolation most important for ECM; fracture aperture parameter most important for weeps model.
PA-PNNL-91	Demonstrate PA with complex codes		
PA-93 [42]	Provide guidance on characterizing site and selecting options for heat and package placement in repository and demonstrate both dose and cumulative release measures	33,000 WPs placed vertically or 8500 WPs with steel and Alloy 825 layers placed horizontally in bored drifts at 14 and 28 W/m^2 heat loads. Percolation change with climate added for 10^6 yr. Added thermal process module for percolation and improved container and waste degradation PA models to evaluate hot repository. 1-D transport based on 3-D flow particle paths. Used ingestion table for calculating dose.	Mean dose to 10^6 yr at 5 km from undisturbed scenario; cumulative release to 10^4 yr at 5 km from 3 scenarios: undisturbed, igneous intrusion, human intrusion. ^{14}C gas largest portion of summed release; ^{99}Tc and ^{129}I important for high probability groundwater releases but ^{237}Np most important for low probability releases and peak dose; ^{237}Np release sensitive to percolation; WP steel layer offers little protection; vertical/horizontal placement and heat loading have only small influence.
PA-M&O-93	Demonstrate PA with Repository Integration Program (RIP) stochastic simulator		
PA-95 [43]	Improve modeling of EBS for comparison to EPA and NRC criteria	9582 WPs with stainless MPC handling canister, an Alloy 825 middle layer, and steel outer layer that are placed horizontally in bored drifts at 6 and 20 W/m^2. Used RIP stochastic simulator and improved modeling of EBS; coupled thermal-hydrology process model; major PA model of container degradation with variability added, and 3 alternative models for EBS transport examined. PA included UZ flow from surface. 1-D transport using RIP based on 2-D flow from PA-91.	Cumulative release to 10^4 yr and dose to 10^6 yr at 5 km from undisturbed scenario. ^{14}C, ^{99}Tc,^{129}I dominate cumulative releases; peak dose of ~300 μSv/yr from ^{237}Np, which depends on its solubility; bulk of container failure by 10^5 yr for either hot or cool repository; furthermore, failure distribution similar (hot repository protects longer but rate higher when resaturated); hence, thermal design only influences time and does not influence value of peak dose.
PA-SNL-95 &97[65; 66]	Demonstrate direct disposal of ~250 types of DSNF and evaluate treatment options for calcine HLW		
PA-96 [82]	Analyze direct disposal of excess Pu from dismantling weapons		
PA-97 [83]	Evaluate design options		

Table 1. Summary of PAs evaluating performance of a disposal system at Yucca Mountain (concluded).

PA	Purpose	Design and Models	Measure and Key Results
PA-VA (1998) [44]	Demonstrate viability to Congress of repository at YM using most current information as interpreted by expert panels	10213 WP with steel and Alloy 22 layers (20 mm thick) at 21 W/m^2, 3 km^2 repository with 28 m drift spacing. Major step in model complexity: added infiltration, drift seepage, EBS chemical environment, and biosphere transport process models. Greatly improved UZ flow (3-D dual permeability), thermal-hydrologic (used several scales), and WP model. Added particle tracking for UZ transport and convolution method for SZ transport.	400 μSv/yr dose to 10^6 yr at 20 km for nominal scenario ($\mathcal{A}_{U+EF}$). In RIP, 177 parameters sampled. Sensitivity studies conducted for igneous eruption, igneous intrusion, igneous disruption of SZ; seismic rockfall, fault disruption of SZ. ^{99}Tc and ^{129}I dominate 1st 10^4 yr but very small; ^{237}Np dominates beyond 10^5 yr. DSNF usually contributes similar dose as HLW (assuming no cladding and fast metallic corrosion rate) but less than CSNF. Doses from all disruptive events very small relative to nominal dose.
LADS (1999) [84]	LA design study to evaluate options	Parameter values in nominal scenario changed to model design options.	Titanium drip shield added. Alloy 22 switched to outer container layer; containers spaced 0.1 m; drift support changed to steel mesh; drift spacing increased to 81 m.
PA-SR (2000) [85]	Analysis to support recommending site under 10 CFR 963 using fully qualified software, parameters, and analysis	11770 WP with Alloy 22 outer layer (20 mm thick for CSNF; 25 mm for DSNF/HLW); stainless replaces carbon steel in 4.6 km^2 repository at 21 W/m^2. Waste blended to 11.8 kW/pkg. Added thermal-hydrologic-chemical process model and drift seepage calibration. Added package chemistry, colloids, and solubility functions to PA waste degradation; and placed WP model inside GoldSim (updated RIP). WP corrosion temperature independent.	Biosphere defined in draft 10 CFR 63 used to calculate dose to 10^6 yr at 20 km for 3 scenarios: $\mathcal{A}_{U+SGclad}$ (undisturbed with seismic cladding failure), $\mathcal{A}_{VE}$, and $\mathcal{A}_{VI}$. Waste particle size reduced, which causes $\mathcal{A}_{VE}$ dose from ^{241}Am (0.04 μSv/yr peak) to dominate for 1st 3000 yr. After 3000 yr, groundwater dose from ^{99}Tc, ^{239}Pu, and ^{237}Np in $\mathcal{A}_{VI}$ dominates until ~40,000 yr when nominal groundwater dose from ^{237}Np dominates with peak of 4900 μSv/yr at 2.7×10^5 yr. Conservative models and parameters (e.g., fast Alloy 22 corrosion) complicate understanding.
SSPA [73] (2001) and PA-EIS (2002) [86]	Examined impact of conservative bias and cool repository for NWTRB and to support EIS on site suitability	Less conservative bias in uncertainty (e.g., lowered Np solubility & Alloy 22 corrosion rate). For PA-EIS, updated WP degradation; conducted thermal-hydrologic process runs for cool repository; improved colloidal transport in SZ; and added climate change beyond 10^4 yr.	Dose at 18 km in 1st 10^4 yr from igneous eruptive ash increase because limit on inhaled particle size decreased, larger maximum wind speed, and larger probability of eruptions. Nominal dose from $\mathcal{A}_{U+EF+SGclad}$ calculated to 10^6 yr; maximum dose of 1500 μSv/yr at 4.8×10^5 yr from ^{237}Np release controlled by solubility.
PA-LA (2008) [24]	Fully qualified and documented compliance analysis for NRC full construction authorization	11629 WP in 5 km^2 repository at 18 W/m^2 with stainless TAD handling canister for CSNF, which added seismic robustness but not corrosion protection. Drift degradation and seismic models incorporated into PA. Improved calibration of seepage and modeling of seepage chemistry; Alloy 22 function of temperature; constrained pH inside package via sorption on immobile Fe; included more uncertainty in solubility; added more transport cells in EBS; and replaced biological module to use ICRP dose method.	Dose to 10^6 yr at 18 km with maximum of 20 μSv/yr at 10^6 yr from advectively released ^{242}Pu, ^{237}Np, ^{226}Ra, and ^{129}I (plus ^{239}Pu in 1st 2×10^5 yr and ^{99}Tc in 1st 7×10^5 yr) in 2 scenarios: igneous intrusion breaching all WP and undisturbed plus seismic breaching ~10% of WP by general corrosion or seismic event ($\mathcal{A}_{VI}$ and $\mathcal{A}_{U+SG}$). Probability of volcanic eruption reduced order of magnitude thus not important. For the portion of analysis run by Goldsim, 392 parameters sampled. Two container parameters important: stress corrosion cracking parameter at 10^4 yr and temperature dependent Alloy 22 corrosion.
PMA (2008) Performance Margin Analysis [24]	Confirm conservative bias collectivity over estimate dose in PA-LA	Like PA-LA but reduced seepage, general corrosion, and uncertainty of Np, U, Pu solubility; larger SCC threshold & SZ sorption; better WP water balance & SZ flow interval	Maximum mean dose of 9 μSv/yr from igneous intrusion scenario in PA-LA and PMA. Small dose of 0.001 μSv/yr from volcanic eruption for both PA-LA and PMA. Only dose from $\mathcal{A}_{U+SG}$ reduced.

Coincident with the decrease in peak doses was the proportional increase to dose from disruptive events, such as seismic damage and especially igneous disruption at Yucca Mountain.

Throughout the PA iterations, most parameters that explained the spread in results were related to the natural barrier. Although conceptual model uncertainty of the natural barrier was reduced in later PA iterations, the epistemic uncertainty in parameter values remained substantial. In addition, parameters related to the corrosion resistant waste container, a major feature in later PAs, had a strong influence on both the absolute value and variability of dose. Coincident with this trend, as the protective function and modeling sophistication of slow enlargement of perforations on the waste container improved, the importance of waste form degradation decreased.

PA Insight

Collectively, the US spent over 30 years selecting a site, and then iteratively developing regulatory concepts of safe disposal over 10^4 to 10^6 years (hundreds to tens of thousands of generations), characterizing the natural barrier, and designing the engineered barrier of the YM disposal system. The iterative PAs interwove this scientific information to analyze the potential behavior of radioactive waste in the engineered and natural barriers of the YM disposal system to assess the compliance with regulatory requirements.

Iterating an analysis allows one to incorporate new information from disposal system characterization through continual updating of FEPs. Also, new hypotheses, even dramatic ones such as large water table rise and criticality, can be examined. Yet, the relative importance of new information and hypotheses is not always apparent. The strength of the PA process is that new information and hypotheses are placed in context to the overall system performance via a quantitative mathematical model rather than given subjective weights in a qualitative mental model.

However, the evaluation of the YM disposal system was very much a public process and some issues garnered more public attention. YMP was not always able to use the PA process to allocate resources to new information and hypotheses according to the understanding of the system as a whole. Rather, YMP had to continue to spend more money to evaluate some potential hazards than was perhaps warranted. Thus, YMP was not able to fully realize the promise of the PA process. Nonetheless, the PA process could identify the significant aspects of FEPs and, more importantly, ensure that other significant but less publicized FEPs were considered in the PA such that the evaluation of the YM disposal system was not driven by only high profile issues.

To elaborate, we as scientists and engineers should not expect too much of our scientific and technological efforts in their ability to gain initial acceptance of a particular activity. The experience of YMP shows that scientists and engineers, and the organizations primarily composed of these professionals could not resolve the social-political concerns of the leaders of the State of Nevada about accepting a radioactive waste disposal facility for the current generation of citizens by presenting scientific arguments as to the minute risks to generations far in the future.

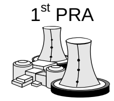
Rather, the radioactive waste management facility must have policy attributes that a community, state, or tribal organization find compelling. Only after the policy attributes of the facility are sufficiently compelling for a plurality of citizens and members of the governing body to entertain hosting a facility, do the scientists, engineers and their organizations have a more prominent role in assuring the feasibility and acceptability of the facility as regards public health and safety such that the initial interest in the facility can be broadened. That is, some policy and technical attributes of a facility are more important in garnering initial acceptance and some policy and technical processes are more important in maintaining credibility and broadening support [87-89].

Interactions and Periods of Yucca Mountain Project

To make the following tabulation tractable, the four categories of political bodies and governmental agencies/institutions summarized above are used to show interactions (Fig. 2): (1) Federal policy in laws, court decisions, and regulations; (2) Presidential and DOE federal policy decisions; (3) Technical activities related to YMP; and (4) Critiques of YMP and related nuclear activities.

The history is also divided into the five major phases of the YMP technical activities [2, Table 1]: (1) Commitment to mined geologic disposal and identification of a site (up to 1982); (2) Site selection analysis (1983-1989); (3) Feasibility analysis (1990-1995); (4) Suitability/viability analysis (1996-2002); and (5) Compliance analysis (2003-2012).

Commitment to Mined Geologic Disposal and Identification of a Site

Federal Policy in Laws, Court Decisions, and Regulations	Presidential and DOE Federal Policy Decisions	Technical Activities Related to Yucca Mountain Project	Critiques of YMP and Related Nuclear Events
	AEC asks NAS for advice **1955 Sep:** Atomic Energy Commission (AEC), formed in 1946, asks National Academies (NAS) to examine disposal of high-level waste (HLW) [90].		
			NAS Suggests Salt Disposal  **1957 Sep:** NAS recommends HLW disposal in salt [90]. US Geological Survey (USGS) begins survey of salt formations [91]. **Dec:** 1st commercial nuclear reactor starts in Shippingport, PA.
EPA Formed **1970: Jan:** *National Environmental Policy Act* (NEPA) signed [16], which requires environmental impact statement (EIS) on major actions. **Jul:** Congress forms Environmental Protection Agency (EPA) [17].	**1970 Jun:** Because of Idaho concern of disposing debris from 1969 Rocky Flats fire, AEC tentatively selects salt mine near Lyons as repository for transuranic (TRU) waste and HLW [60, p. 67; 92]. **Aug:** In 10 CFR 50, AEC requires commercial HLW be solidified within 5 yr and delivered to repository 5 yr afterwards (1st nuclear waste regulation) [93].		**1970:** Up through 1970, AEC spends ~$5 million of 40 million annual budget on waste disposal research: $0.5 million by Oak Ridge National Laboratory (ORNL) on salt disposal using Lyons underground research laboratory (URL); $2 million on solidifying waste; and remainder on other disposal schemes (e.g., granite) [94]
	1972 AEC asks for probabilistic risk assessment (PRA) of a nuclear reactor [95]. **Jan:** Because of troubles at Lyons, AEC develops 3 options: (a) look for another salt site; (b) examine other media; or (c) build surface storage [96, p. 78]. **Feb:** AEC asks USGS to again look for salt sites [49]. **May:** AEC abandons Lyons and plans 100-yr storage in Retrievable Surface Storage Facility (RSSF) [60].	**1972** Winograd of USGS proposes use of thick alluvium in usaturated zone (UZ) for HLW disposal [97].	**1972 May:** Nevada Senator Cannon urges AEC to use Nevada Test Site (NTS) for reprocessing and waste disposal [96, p. 92]. (Nevada Proving Grounds when selected in Dec 1950 for nuclear weapons testing [98] and later Nevada National Security Site or NNSS). **1973 Oct**: Arab oil embargo in retaliation for US support of Israel during Arab attack on Yom Kippur
NRC Formed **1974 Oct:** Congress splits AEC into [18] (1) Nuclear Regulatory Commission (NRC), to regulate civilian use of nuclear material, and (2) Energy, Research, and Development Agency (ERDA), responsible for nuclear weapons, nuclear power research, radioactive waste, and energy role.	**1974** AEC starts Geologic Disposal Evaluation Program for salt disposal. AEC & Pacific Northwest National Laboratory (PNNL) identify 2 options for storage (shallow burial or deep geologic storage) and 6 options for disposal: deep boreholes, sub-seabed, cavities with rock melt, well injection, ice sheets, and space) [99]. **Sep:** AEC issues draft EIS emphasizing reprocessing and RSSF [100].	**1974** Winograd elaborates on use of thick alluvium in UZ for HLW disposal [101]**.**	1st PRA  **1974 May:** India detonates plutonium (Pu) bomb using material and technology supplied for commercial reactor by US. **Aug:** 60 member team completes draft PRA for 2 representative reactors [95]. **Nov:** EPA and anti-nuclear groups claim RSSF *de facto* disposal in comments on EIS [60, p. 76].
1975 May: NRC promulgates guidance on how to provide "reasonable assurance" that nuclear reactors meet as low as reasonably achievable (ALARA) policy for limiting radiation exposure [102].	**1975 Apr:** ERDA abandons RSSF concept [49, App. A].	**1975** USGS develops conceptual model for regional groundwater flow at NTS.	**1975:** Because of unemployment in Nevada, state legislature urges ERDA to choose NTS for storage and processing of nuclear material [103]. **Mar:** Browns Ferry reactor fire. **Oct:** PRA finished for 2 reactors (Surry and Peach Bottom) for NRC [95].
1976 Congress passes Uranium Mill Tailings Policy Act to clean up mill tailings and control future use and disposal (initial appropriation is for 90% federal funding). **Jul:** DC Circuit Court of Appeals rules NRC reactor license must consider confidence of waste disposal; overturned by Supreme Court in 1978 [96, p. 100]. **Dec:** EPA announces intent to develop disposal standards [104]. NRC funds panel of earth scientists to identify events and processes that could disrupt a repository [105].	Ford Asks for EPA Standard  **1976 May:** ERDA adopts 2 options for storage and 6 options for disposal by PNNL: [106]. **Jul:** ERDA hosts conference to bring engineers and geologists together to explore modeling disposal [107]. **Oct:** President Ford orders ERDA to demonstrate disposal and EPA to develop standards for spent nuclear fuel (SNF) and HLW [29].; In response to Indian bomb test, President Ford defers reprocessing [96]. **Nov:** ERDA notifies 36 governors that it will look for sites in their states [60].	USGS Suggests Disposal at NTS  **1976 Feb:** ERDA sets up Nuclear Waste Terminal Storage (NWTS) Program to search for sites in various media for commercial HLW/SNF. USGS urges emplacing HLW at NTS [108]. USGS and Sandia National Laboratories (SNL) 1st look at shale-argillite in Eleana Fm [109]. **Nov:** NWTS proposes 6 repositories to spread burden and minimize impact if site unacceptable.	**1976 Jun:** California enacts moratorium on building nuclear reactors until US demonstrates HLW disposal [60, p. 86]. **Jul:** Facilities built for nuclear rocket program (cancelled in 1971) and weapons effects 425 m below surface in Climax granite at NTS is modified for URL by Lawrence Livermore National Laboratory (LLNL) [110].
DOE Formed **1977 Jan:** Congress forms Department of Energy (DOE), successor of ERDA [13]. **Feb:** EPA conducts public workshop to understand public concerns and technical issues of waste disposal [29]. NRC also begins work on waste disposal issues.	**1977 Apr:** President Carter indefinitely defers reprocessing commercial SNF (CSNF) because of Pu proliferation concern [60, p. 118]. **Aug:** ERDA adds previous land use as criterion for identifying sites [63, p 2-11]. Discontent caused by letters to 36 governors, prompts ERDA to explore Hanford and NTS for sites. President Carter proposes away-from-reactor storage for SNF [96, p. 112].	**1977** Human intrusion event significant contributor to consequences for waste buried at Idaho National Laboratory (INL), Los Alamos National Laboratory (LANL), Savannah River Site, and Hanford [111]. **Oct:** DOE establishes Nevada Nuclear Waste Storage Investigations (NNWSI) Project to continue looking at NTS [63]. Major participants are SNL, LANL, LLNL, and USGS [112].	**1977** NRC funds SNL to evaluate risks of transporting radioactive waste; SNL develops radioactive material transportation model (RADTRAN).

1978 Jan: EPA announces public forum to develop disposal criteria for radioactive wastes [113]. **Nov:** EPA publishes *Criteria for Radioactive Wastes* and seeks comments [114]. NRC publishes general policy for licensing steps and seeks comments [115].

Thick Tuff Found

1978 Mar: President Carter forms Interagency Review Group (IRG), to study nuclear waste disposal [116]. **Apr:** DOE decides repository can be built in 100-km^2 area in southwestern portion of NTS and not disrupt weapon tests [63, p. 2-14]. USGS identifies 5 sites in 100 km^2 area: Calico Hills, Wahmonie, Skull Mt, Jackass Flats, and Yucca Mountain (YM). Granite not within 900 m and argillite structurally too complex at Calico-Hills. Wahmonie granite is too small. Study of thick alluvium at Jackass Flats deferred because of its low thermal conductivity [117]. USGS finds thick tuff deposits at YM in borehole UE25#a-1 [118].

1978 With less reactors planned, NWTS proposes 2 repositories sufficient [119, p. 61]. **Feb:** LLNL evaluates 30 granitic sites in southwestern portion of NTS [120]. USGS plans borehole at YM. **May:** SNL proposes small heater/water-migration and rock mechanic tests in tuff in G-tunnel at NTS as part of URL; SNL along with LANL and Argonne National Laboratory (ANL) also propose nuclide transport tests in tuff [121]; but nuclide tests never completed. **Jun:** USGS begins drilling 1st borehole at YM (UE25#a-1). USGS discusses issues related to characterizing a site, heat perturbation, groundwater movement, and supports using multiple barriers [122].

1978 May-July: Study of argillite and granite locations at NTS are stopped; yet, work at Climax granite continues as URL to determine suitability of granite [117]. **Aug:** At request of NRC, NAS lists 7 characteristics of an ideal repository site and also recommends HLW disposal only (no high-value SNF) [123]. **Oct:** IRG distributes ~15,000 copies of 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, and not delaying disposal.

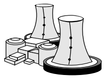
1979 May: DC Circuit Court of Appeals rules NRC must assess degree of confidence that wastes from nuclear reactors can be safely stored until disposed [96, p. 169]. **Oct:** NRC begins deliberations on waste confidence rule [124]. **Dec:** NRC withdraws general policy and proposes licensing steps [125].

1979 Mar: DOE identifies >200 granitic bodies in 17 eastern states. **Sept:** DOE asks SNL and LANL to present suitability of tuff for disposal to NAS [126].

USGS Suggests Yucca Mt

1979 USGS study finds silicic volcanic eruptions near YM ended between 7 and 9 Ma [127]. **Oct:** USGS recommends thick layers of tuff at YM [117].

TMI accident



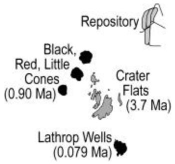
1979 Mar: After considering ~3000 comments, IRG suggests mined geologic disposal, use of multiple barriers, looking for sites in variety of media in different regions of US, not delaying disposal, and demonstrating SNF/HLW disposal at Waste Isolation Pilot Plant (WIPP) [116]. *The China Syndrome* movie released March 16. On March 28, Three Mile Island reactor accident occurs. **Sept:** NAS supports use of volcanic tuff and encourages study [119, p. 148].

1980 Congress authorizes cleanup of West Valley, which produces 275 HLW canisters from 650 MTHM of SNF by 2001 [24, p. 1.5.1.30; 128]. **Dec:** *Low-Level Waste Policy Act* (LLWPA), defines low-level waste (LLW) by what it is not [25].

Mined Repository Selected

1980 Feb: President Carter proposes selecting 1-2 sites from 4-5 candidates with state participation [96, p. 122]. **Oct:** DOE issues EIS on options for CSNF disposal and selects mined repositories with sub-seabed and deep boreholes as backup [129]. EIS examines 4 disruptive events for salt, shale, granitic, and basaltic repositories: meteorite impact, fault, exploratory drilling, and solution mining [129].

Volcanism Frequency Set



1980 LANL/USGS estimate frequency of volcanism (10^{-9} $yr^{-1} < \lambda_V < 10^{-8}$ yr^{-1}) [130]. **Apr:** USGS dates fossil rat middens to delineate climatic changes [131]. **Apr:** USGS drills G-1 geologic well [132]. USGS finds water table <61 m above present position [133]. **Sep:** H-1 hydrologic well drilled into saturated zone (SZ) [134].

1980 SNL identifies 29 features, events, and processes (FEPs) for repositories and develops a screening method for NRC [105]. **May:** 11 CSNF canisters and 6 simulated canisters placed remotely in Climax [135]. By 1982, ~4700 people had visited Climax facility [117, p. 14].

1981 Feb: NRC sets licensing steps in 10 CFR 60, such as trial-like hearings with Atomic Safety Licensing Board (ASLB), and a Site Characterization Plan (SCP) [75]. **Mar:** EPA starts standards for radioactive waste [29,§1.2].

1981 Mar: President Reagan withdraws President Carter's proposed away-from-reactor storage concept and lifts ban on reprocessing CSNF [49, App. A].

1981 Jan: G-2 borehole completed. USGS digs 5 trenches in Crater Flat [136]. USGS completes 5 geologic, 6 hydrologic, 9 UZ, and 16 water-table (WT) wells, and 40 trenches from 1981 to 1984. **Jun:** Winograd again proposes burial in thick desert alluvium [137]. **Nov:** SNL constructs scenarios for repository [138].

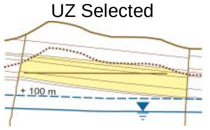
1981 International Atomic Energy Agency (IAEA) includes undetected features along with events and processes (FEPs) in performance assessments (PA) [139]. SNL completes reports to NRC on PA methodology and PA of hypothetical salt repository [140].

EPA Drafts 40 CFR 191

1982 Apr: Congressional Office of Technological Assessment finds no insurmountable technical obstacles for geologic repositories; rather biggest obstacle is erosion of state and public confidence in commitment of Federal government to stick with any policy (i.e., national policy issues overshadow technological problems) [141].**Dec:** EPA proposes disposal standard, 40 CFR 191, for HLW, SNF, and TRU; draft defines performance assessment (PA), sets a population-based release limit for nuclides at 10 km boundary, and requires displaying a complementary cumulative distribution function of uncertain results [142].

1982 Apr: DOE forms Ad Hoc Working Group to evaluate exploratory studies facility (ESF) shaft designs at YM; group selects conventional drill/blast mining [117, p. 14]. **Dec:** Based on NRC draft of 10 CFR 60, DOE requests more robust waste package (WP) for disposal.

UZ Selected



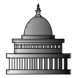
1982 Based on VH-1, USGS finds volcanism declining [143]. Youngest Lathrop Wells cinder cone dated between 80 and 700 ka [144]. USGS suggests variation in groundwater temperature near YM is from percolation of 8 mm/yr [145]. USGS develops 3-D model of stratigraphy of YM [117]. USGS develops 2-D model of regional groundwater flow [146]. **Apr:** SNL evaluates dose after volcanic eruption [38]. **Jun:** Drilling of G-4 begins at proposed location of ESF [147]. **Jul:** USGS suggests and Yucca Mountain Project (YMP) moves repository to 350-m thick Topopah Spring Fm (TSw) in UZ [148]. **Aug:** Site Evaluation Working Group reports that YM remains preferred site [149]. Initial design of ESF completed [150]. **Oct:** Initial design of surface facilities completed [117, p. 19]. **Dec:** Initial design of repository [151].and Initial design of package completed [152].

1982: Washington Public Power Supply System (WPPSS) defaults on debt; construction of 3 reactors at Hanford WA, and 2 reactors at Satsop, WA (76% complete) halted.

Site Selection Analysis

Federal Policy in Laws, Court Decisions, and Regulations

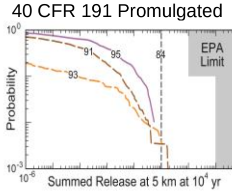
NWPA Passed



1983 Jan: In *Nuclear Waste Policy Act* (NWPA) [23], Congress (a) selects geologic disposal option; (b) sets steps such as environmental assessment (EA); (c) directs promulgation of EPA and NRC regulations; (d) requires NRC to review sufficiency of site characterization; (e) defines state disapproval and override procedure, (f) requires DOE to contract with utilities to dispose waste to provide disincentive for administration policy changes. (g) directs DOE-owned SNF (DSNF) to 70,000-MTHM commercial repository unless President objects; (h) directs DOE to find site for Monitored Retrievable Storage (MRS); and (i) creates Nuclear Waste Trust Fund via 0.1¢ fee on kW-hr of nuclear power produced. **Jun:** NRC promulgates technical criteria on subsystems in 10 CFR 60: 300-1000 yr package life, release limit on engineered barrier, and 1000 yr travel time in geologic barrier [153]. NRC estimates <$40 million for characterizing 300 m of underground drift [75].

1984 Aug: NRC promulgates waste confidence rule; NRC will review in 5 yr [124].

40 CFR 191 Promulgated



1985 Sep: EPA finishes 40 CFR 191 that sets 5 km boundary, defines FEP screening criteria of 10^{-4} in 10^4, clarifies use of uncertainty to estimate "reasonable expectation." [29]. **Dec:** *Gramm-Rudman-Hollings Act* (GRHA) passed to balance budget [22].

Presidential and DOE Federal Policy Decisions

1983 Feb: DOE identifies 9 sites already under consideration (4 bedded salt, 3 salt dome, and 2 sites based on prior land use: 1 tuff site at YM, and 1 basalt site at Hanford) [60, p. 229]. DOE publishes draft guidelines for selecting a site (10 CFR 960) [154]. **Mar:** DOE solicits comments from State of Nevada and public regarding nomination of YM [117]. **Apr:** In 10 CFR 961, DOE publishes contract between DOE, 68 utilities, and 7 other commercial waste owners for disposal of CSNF and HLW and payment of fees into the Nuclear Waste Fund [155]; **Sep:** In response to Swedish concept, DOE asks LLNL to evaluate copper alloys for containers [156].

DOE Nominates 5 of 9 Sites

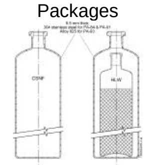
1984 Dec: DOE finalizes 10 CFR 960 site selection guidelines [169]. DOE issues draft EAs on all 9 potential sites and nominates 5 sites for final EAs (YM; Davis Canyon, Utah; Deaf Smith, Texas; Richton Dome, Mississippi; and Hanford, Washington). Criticism of ranking prompts DOE to try multi-attribute utility analysis [170].

1985 President Reagan approves disposal of DSNF with CSNF. DOE closes Climax URL rather than upgrade ventilation to meet more stringent work safety guidance [110]. **Apr:** DOE suggests 3 MRS sites in Tennessee.

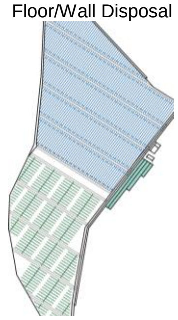
Technical Activities Related to Yucca Mountain Project

1983 Based on fractured outcrops at YM, USGS proposes precipitation percolates directly through UZ [157]. USGS begins water table measurements. High water table/perched water noted northwest of repository. **Feb:** SNL completes evaluation of 4 tuff layers and selects TSw layer [158]. SNL updates scenarios using combinations of 201 FEPs [159]. **Jun:** Small-diameter heater tests completed in G-tunnel on NTS [160]. LANL reports on sorption of nuclides on tuff [161]. **Aug:** Inclined access ramp for waste and tuff adopted for repository [162]. **Sep:** LLNL revises container design using stainless steel sand high-nickel alloys [163]; same design for salt, basalt, tuff [147]. LLNL reports on degradation rates of CSNF and HLW glass [164]. From end of 1983 and through 1984, C-wells, are drilled ~3 km east of repository and permeability estimated [165].

Vertically Placed Packages

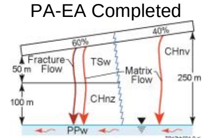


Repository Uses Floor/Wall Disposal



1984 USGS completes geological map of YM [171, p. 9]. To reconcile equivalent continuum model (ECM) with observed fracturing and ~3% infiltration, USGS proposes most percolation (4.5 mm/yr), is diverted laterally to faults and only 0.5 mm/yr moves downward [172, pp. 36-49]. USGS creates new 2-D regional model using wells around YM and Death Valley [173, Fig. 3]. Holes drilled in washes and on crest for infiltration study [174]. Preservation of glass shards in G-4 well suggest that water table never higher than base of TSw. **Feb:** LLNL reports on thermal modeling of vertical and horizontal waste placement [175]. **May:** LLNL reports on tuff/water interaction [176]. SNL reports on area suitable for repository [177]. **Aug:** SNL reports on construction methods for ESF [19]. LANL reports on solubility limits for nuclides [178; 179]. **Sep:** LLNL reports on corrosion process for CSNF cladding [180]. SNL designs stair-step repository to keep horizontal [181]. **Dec:** SNL completes PA-EA that shows compliance with 1982 draft 40 CFR 191 [39].

PA-EA Completed



1985 FEPs and scenarios developed for SCP [182]. LANL finds calcite and opal on fracture surfaces from well core that suggest deep fracture flow [183]. **Sept:** SNL proposes 2 stages over 8 yr for excavating repository; changes to 1984 design include use of 2 ramps at north end rather than one [184]; concepts adopted by final 1986 EA. Study of metal dry storage casks completed for DOE [185]. **Oct:** SNL defines stratigraphy for thermal-hydrologic modeling; similar to USGS 1975 and 1984 model layers [186].

Critiques of YMP and Related Nuclear Events

1983 Jan-Sep: EPA Science Advisory Board (SAB) holds 9 public meetings on 40 CFR 191 [166]. **Apr:** Governor Bryan declares nomination an unfair burden, Nevada already has NTS and waste might discourage growth of Las Vegas [167]. **Mar:** 3-yr test of CSNF at Climax completed; all 11 CSNF canisters removed; one cut open and 2 rods tested; rock temperature and displacements monitored for 6 months [117, p. 21]. **Dec:** Strontium (^{90}Sr), tritium, and other nuclear waste placed in in 36 m deep boreholes in tuff alluvium in Greater Confinement Disposal (GCD) test borehole at NTS [168, §1.2].

1984 Jan: SAB endorses probabilistic, population-limit approach and 10^4-yr regulatory period of 40 CFR 191 but recommends (1) screening criteria for FEPs be increased by a factor of 10 to median probability of 10^{-3} in 10^4, (2) nuclide limits (L_i) be increased a factor of 10; and (3) probability for first level be increased from 0.01 in draft to 0.5 [166]. **May:** Disposal of 330 Ci of ^{239}Pu in 60 Mg of classified TRU waste from cleanup begins at GCD [168, §1.2].

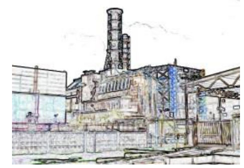
1985 Aug: Tennessee sues DOE since state not consulted on MRS as per NWPA. **Oct:** Tennessee Clinch River Task Force supports MRS if several stipulations adopted.

1986 NRC licenses DOE/utility demonstration of dry casks for storing CSNF. Congress assigns responsibility for greater-than-class-C (GTCC) LLW to federal government in *Low-Level Waste Policy Amendments Act of 1985* [187]. **Jul:** NRC revises licensing steps in 10 CFR 60 to agree with steps in NWPA [188]. **Aug:** NRC promulgates probabilistic safety goals for nuclear reactors that continues trend started with probabilistic 40 CFR 191 [189]. **Nov:** 6th Appeals Court rules DOE does not have to initially consult with Tennessee for MRS.

1986 May: DOE recommends 3 sites (YM [63], Deaf Smith, and Hanford with ranking of 1, 3 and 5 by multi-attribute study) to characterize for 1st repository [190]. DOE uses portfolio of sites to lower program risk. President Reagan approves portfolio. From 1979 list of regions in 17 states, DOE recommends 12 granitic sites in 7 states for 2nd repository but postpones characterization because new reactors not being built [191], high characterization costs, and great concern in the east [192].

1986 Seismic hazard estimated for repository [193]. **May:** Final 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. Construction by either drill/blast and tunnel boring machine (TBM) considered [63]. **Jul:** USGS/LBNL (Lawrence Berkeley National Lab) develop 2-D, ECM, site-scale model [194]. **Aug:** SNL estimates travel time to accessible boundary to compare with limit in 10 CFR 60 [195]. Travel time is sensitive to UZ flow, which is sensitive to percolation.

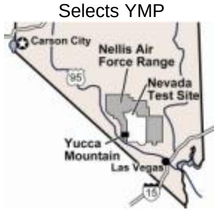
Chernobyl reactor accident



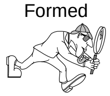
1986 Jan: Tennessee Governor formally rejects MRS because unnecessary and stigma (not safety) [196, p. 146]. **Apr:** Major accident at Soviet's Chernobyl reactor occurs during shut-down test; when many emergency controls turned off.

1987 GRHA amendments place YMP under spending cap [197]. **Jul**: 1st Court of Appeals remands 40 CFR 191 but leaves Containment Requirements and affirms use of "reasonable expectation" [59]. **Dec**: *Nuclear Waste Policy Amendments Act* (NWPAA) [27], (a) selects YM to characterize (b) affirms decision to delay 2nd repository; (d) nullifies choice of Tennessee for MRS (e) sets up voluntary siting program for MRS or repository; (c) sets up compensation; (f) adopts 15,000-MTHM size and links MRS to repository schedule; (g) establishes MRS Review Commission; (h) forms Nuclear Waste Technical Review Board (NWTRB) to advise [27, §5001]; (i) states Nye County is affected unit, which funds tests such as Early Warning Drilling Program (NC-EWDP).

Congress Selects YMP



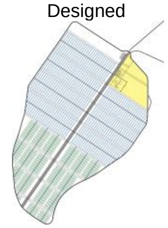
NWTRB Formed



1987 Jan: In hearings before Senate, DOE reports that site characterization now estimated at ~$1 billion per site per site [77]. **Mar:** DOE recommends 3 MRS sites, all in Tennessee for a 15,000-MTHM facility to consolidate CSNF rods and pack into small handling canister; MRS construction linked to repository [198].

1987 SNL develops site-scale model, based on STAFF2D [199], to investigate effect on SZ transport of permeability change from (1) volcanic/seismic activity, and (2) leakage from carbonate aquifer [200]. **Apr:** LANL measures chlorine ($^{36}Cl/^{35}Cl$) ratios in water extracted from UZ and proposes using data to evaluate percolation [201]. **Apr & Nov:** PNNL reports on radionuclide release from bare CSNF in batch tests [202]. **Sep:** SNL describes repository design for SCP. The 5.6-km^2 repository follows the ~6° down dip and remains <183 m above water table. Again, both floor and pillar emplacement considered. CSNF and HLW commingled to keep uniform heat load of 14 W/m^2. Design assumes CSNF consolidated so that 6 pressurized water reactor or 18 boiling water reactor fuel rods fit into canister [203]. **Dec:** LANL models kinetic sorption [204] and traditional sorption [205] on tuff using 1977-1985 test results [206].

SCP Repository/ Package Designed



1987 Apr: In hearings for *Nuclear Waste Policy Amendments Act* (NWPAA), former Director of Oak Ridge National Laboratory, Weinberg, proposes US use Swedish approach of long-lived containers (<300,000 yr) [207].

1988: Jul: As required by NWPA, NRC comments on draft SCP; NRC criticizes quality assurance (QA) program and lack of alternative conceptual models; NRC notes possibility of test interference and that co-location of test facilities with disposal drifts requires that construction of test facility meet QA licensing criteria.

1988 Jan: DOE publishes draft SCP. **Dec:** DOE publishes final 9-volume SCP with ~300 activities for surface, underground, and laboratory test and corresponding models to answer licensing questions and concerns raised by stakeholders, but no PA available to rank studies; however several aspects of PA such as scenario development described [208; 209].

1988 FEPs unique to repository in UZ at YM developed to demonstrate SNL/NRC FEP screening methodology [210]. **Feb:** ANL reports on degradation of HLW glass during gamma irradiation [211]. **May:** LANL finds that calcite and opal mineral deposits in trenches not from upwelling of water [212]. **Dec:** SCP describes 91 FEPs [208; 213, V7, §8.3.5.13].

Seismic Pumping Proposed

1988 Jan: DOE employee, Szymanski, asserts earthquakes could force water hundreds of meter above water table ("seismic pumping"). Szymanski's draft report sent to State of Nevada [214]. **Dec:** Sub-seabed Disposal Program publishes favorable final PA on concept [215].

1989 In response to LLWPAA, NRC amends 10 CFR 61, regulation for LLW, to require disposal of GTCC LLW in geologic repository. **Apr:** NRC promulgates in 10 CFR 2 (a) procedures for licensing hearings, and (b) process of submitting documents related to LA electronically in a Licensing Support System (later called Licensing Support Network or LSN) "to permit early submission of better focused contentions."[216] **Jul:** NRC clarifies need in 10 CFR 60 to update EIS when applying for authorization to construct, operate, or close [217]. **Aug:** NRC publishes final comments on SCP [218].

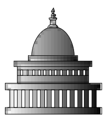
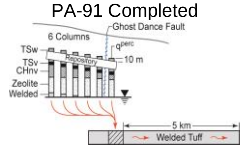
1989 May: DOE, EPA, and State of Washington negotiate the Tri-Party Agreement concerning mixed radioactive and hazardous waste at Hanford; 2018 original date for removal of HLW; current date is 2040. **Jun:** Based on NWPAA, DOE re-evaluates MRS and decides MRS advantage is flexibility but at increased cost [219]. Also, DOE decides to not consolidate rods based on PNNL analysis. **Aug:** Internal DOE review concludes Szymanski assertion without basis [45, p. 4-397].

1989 Artificial colloids tested in lab columns; results suggest that colloid transport not significant at YM [220]. YMP stops thermal testing in G-tunnel to move to ESF [221]. **Feb:** LANL reports that eruptions from 7 Quaternary cinder cones located near YM were of small volume (< 1 km^3) and are declining over time [222]. **Jul:** In response to NRC critique of SCP, YMP studies excavating the Calico Hills Fm (CHn) since CHn thought useful natural barrier; study finds that YM will meet 40 CFR 191 without testing but suggests testing could reduce program risks [223]. **Sep:** ANL reports secondary uranium minerals formed in drip tests on CSNF [224]. **Oct:** PNNL presents deterministic risk assessment of YM repository using literature data and 0.5 to 0.75 mm/yr percolation [225].

Berlin Wall Falls

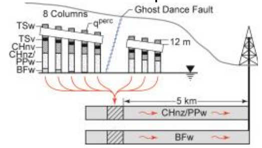
1989 Jun: SNL conducts PA on hypothetical basalt site [226]. PNNL analysis of risks associated with operations for managing radioactive (i.e., storage, transportation, and disposal) finds consolidation noticeably increased worker doses using the technology currently available [227]. **Aug:** Last of 2.3 MCi of LLW tritium disposed at GCD [168, §1.2]. **Nov:** Berlin Wall falls, signaling end of Cold War and demands for nuclear material. MRS Review Commission notes flexibility and cost savings if MRS decoupled from repository schedule. **Dec:** SNL demonstrates PA for disposal of TRU waste in bedded salt at WIPP [228].

Feasibility Analysis

Federal Policy in Laws, Court Decisions, and Regulations	Presidential and DOE Federal Policy Decisions	Technical Activities Related to Yucca Mountain Project	Critiques of YMP and Related Nuclear Events
1990 May: NRC states DOE may take credit for a package lasting longer than 1000 yr (i.e., 300-1000 yr requirement in 10 CFR 60 is a minimum range) [229]. **Sep:** NRC reaffirms confidence in geologic waste disposal; will review in 10 yr [230].	**1990** DOE asks NAS to examine Szymanski assertion [231]. **Sep:** DOE decides to use conservative approach for PAs with no sorption in fractures and smallest measured sorption for matrix. LANL finds that americium (Am), plutonium (Pu and other nuclides with sorption coefficients > 0.5 m^3/kg will comply (retardation of 200-500); only technetium (Tc), Iodine (I), uranium (U), and neptunium (Np) adsorb poorly [223; 232].	**1990** LBNL extends ECM to multiphase, non-isothermal conditions in TOUGH [233]. LANL finds ^{36}Cl in well UZ-6 [234] and USGS finds drilling fluids in dry-drilled UZ-1 from well G-1, 300 m to southeast, which suggest deep fracture flow [235]. **Jun:** Based on morphologic data, LANL suggests that portion of Lathrop Wells cinder cone is < 20 ka [236]. **Sep:** In response to NWTRB and NRC critique of SCP, SNL explores alternatives to shafts in ESF [20]; top 2 options out of 34 are (a) ramps to TSw and lower CHn; or (b) ramp to TSw and internal shaft to CHn.	**1990** Electrical Power Research Institute (EPRI), funded by utilities, completes 1st PA using logic-tree approach [237]. **Mar:** 1st NWTRB report [238] (a) criticizes using drilling/blasting to excavate ESF; (b) criticizes lack of progress in PA since PA-EA (c) suggests replacing ESF shaft with ramp; (d) suggests excavating a 2nd east-west drift. **May:** **Nov:** International Commission of Radiation Protection (ICRP) sets limit of 1 mSv/yr (average at sea level excluding radon) [239, ¶191]. Press reports on Szymanski hypothesis [240]. **Dec:** SNL conducts 1st full PA of WIPP [241].
1991 Mar: Based on refusal of Supreme Court to review decision, US District Court orders State of Nevada to take action on 3 permits for characterizing YM [242]. **Sep:** 9th Court of Appeals rules ban on nuclear waste shipments into state is illegal (imposed by Idaho Governor Andrus because of impasse on WIPP land-withdrawal legislation) [243].	**1991 Jun:** DOE asks SNL to complete stochastic PA by end of year [41, §1.3]. DOE workshop explores package designs that last >10^3 yr. Ideas adopted include (a) multi-barrier materials to reduce uncertainty; (b) multi-purpose canister (MPC) to reduce handling; and (c) simplified design to ease fabrication [242]. **Dec:** In response to $30 million funding cut for fiscal year 1992 (FY92), DOE curtails engineered barrier system (EBS) study, postpones EBS design until FY93, and postpones boring ESF until FY94 [242]. Lack of state permits and NRC compliant QA program also contribute to postponement [242] (i.e., co-locating ESF with the repository necessitates a NRC compliant QA program).	USGS & LANL disagree on age of Lathrop Wells  **1991** SNL finds changes in water table <20 m from earthquakes [244, p 11]. USGS finds that U and Sr nuclides in caliche at repository level not from water far below repository [245, pp. 551-554]. **Apr:** Dating by USGS suggest lava flows at Lathrop Wells are between 119 and 141 ka [246]. **Jun:** Deterministic PACE-90 Completed  PA analysis (PACE-90) completed by SNL, PNNL, and LANL. Little nuclide movement in UZ over 10^4 yr with 0.01 mm/yr percolation [247, §3.4.5]. **Oct:** YMP conducts Test Prioritization Task to rank SCP tests. [242]..	**1991 May:** In 3rd report [223], NWTRB (a) praises ESF Alternative Study; (b) recommends evaluating other alternative heat loads; (c) again requests minimizing waste handling during storage, transportation, and disposal. **Jun:** State of Nevada issues air quality permit for site investigations [242]. **Jul:** SNL demonstrates PA methodology for tuff for NRC [248]. State issues underground injection control permit and State Engineer sets Sept hearing for water permit [242]. **Dec:** SNL completes 2nd PA of WIPP [249]. External majority report concludes Szymanski assertion without basis [45, p. 4-397]. In 4th report [242]**,** NWTRB notes progress made in PA development but criticizes decision to postpone ESF and suggests an ESF with smaller diameter to cut costs.
Congress Requires New EPA Standard  **1992** Congress ratifies *Strategic Arms Reduction Treaty* (START) [31]. NRC and DOE agree on interaction protocol prior to licensing [250]. **May:** NRC completes iterative PA (IPA-1) [251] on effect of igneous/ seismic events and higher recharge on water table [252]. Water table rise small for volcanic/seismic events; yet rises by 45 and 87 m when increasing recharge by factor of 10 and 20 [252]. **Oct:** In *Energy Policy Act* [253], Congress requires (a) EPA to set a site-specific standard for YM using dose, (b) EPA seek advice from NAS, and (c) NRC to revise 10 CFR 60.	**1992 Jan:** For Congress, DOE completes Early Site Suitability Evaluation started in Spring of 1991 using 10 CFR 960 criteria. Evaluation finds no disqualifying conditions [254]. In response to START and need to upgrade reprocessing facilities to meet current environmental regulations, DOE halts reprocessing and proposes direct disposal of DSNF. Also, 50 metric ton Pu declared surplus [255].	**1992** PNNL completes tests on CSNF degradation; data used in PA-95 and thereafter [256]. **May:** ANL reports that HLW glass forms colloids as it degrades [257]. LANL evaluates structural controls on basaltic volcanism [258]. **Jul:** SNL completes PA-91 Completed  1st stochastic PA-91 that shows feasibility of repository at YM [41, §4]. Summed releases to 5 km boundary evaluated for undisturbed and 2 disruptive (volcanic eruption and human intrusion) scenario classes. SNL uses 2 conceptual models of UZ flow: ECM and Weeps [259].	NAS Finds No Evidence for Seismic Pumping  **1992** NAS concludes "…there is no evidence to support the assertion by Szymanski..." [231]. **May:** EPRI completes 2nd PA [260]. **Jun:** NWTRB [69], (a) requests study of heat loads; (b) urges horizontal placement of packages; (c) urges exceeding NRC container life goal of 10^3 yr. **Jun:** 5.4 magnitude earthquake, largest recorded at YM, occurs beneath Little Skull Mt ~20 km to the east [261]. **Aug:** WY Gov declines MRS, citing *de facto* disposal. **Dec:** NWTRB urges (a) system study of storage, transportation, disposal; (b) high capacity MPCs; (c) PA sensitivity analysis [70]. NWTRB supports less drilling, and shifting tests to ESF. SNL completes 3rd PA of WIPP [262].
1993 Feb: EPA announces intent to draft 40 CFR 194 to implement 40 CFR 191 at WIPP [263]. **Dec:** In response to court remand [59] and *WIPP Land Withdrawal Act*, EPA revises 40 CFR 191 and sets the dose limit at 0.15 mSv/yr over 10^4 yr [264].	**1993** DOE changes construction method to TBM with mildly inclined access drifts [42, §4.4]. DOE decides to reduce surface drilling and move to underground once ESF completed [70].	**1993** SNL completes scenarios for igneous activity near YM [265]. USGS develops regional-scale, quasi 3-D model that includes deep carbonate aquifer [266]. USGS begins drilling SD well series; completed in 1999. PNNL completes PA-PNNL-91, which uses more complex models than PA-91, but uses percolation <0.5 mm/yr; thus, no nuclides reach SZ in 10^4 yr [267, Ch. 10]. LLNL models drifts and water that contacts packages and waste [268]. **Mar:** After 10 months, UZ-16 hole completed with new air drill rig (LM-300) to avoid contaminating borehole. It would take ~29 yr to complete 40 boreholes at cost of ~$5.6 ×$10^6$/yr [221]. LLNL suggests using high heat load to dry tuff around drifts to enhance performance [269]. **Dec:** SNL completes PA of waste form options for DSNF in salt and granite showing repository mitigates differences in waste behavior [64]. Estimated degradation of DSNF used in PA-95.	**1993 Mar:** NWTRB reports that three policy issues are influencing technical aspects [270]: (a) unrealistic deadlines set by Congress, (b) lack of overall DOE strategy for storage, transportation, disposal of waste, and (c) organizational structure of DOE and contractors. **Jun:** SNL completes 1st PA on disposal of LLW, tritium, sealed sources, and classified TRU at GCD [271]. **Oct:** NWTRB suggests [272] (a) DOE integrate testing with excavation of ESF, (b) underground testing as soon as possible, and (c) establishing a geo-engineering board to advise on industry practices in constructing ESF. **Nov:** In Congressional subcommittee hearing, NWTRB notes that while it is interested in MPC, the speed with which DOE will have to design and procure MPC to meet 1998 deadline for receipt of waste, will preclude thorough study of alternatives [221].

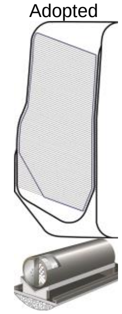
1994 Jun: DOE plans EIS on disposal options for surplus weapons-grade Pu because of START. Options include Pu use in mixed-oxide (MOX) fuels, disposal with HLW; deep borehole disposal; and accelerator destruction [255]. **Sep:** YMP decides to use a moderately high heat-loading (21 W/m^2) to save costs of boring ~200 km of drifts, which allows repository to fit west of Ghost Dance Fault [273]. DOE completes MPC evaluation to better integrate waste management [274]. **Dec:** In periodic program plan required by NWPA, DOE restructures SCP test program and sets 3 milestones: (1) publish findings on suitability in 1998; (2) assuming favorable EIS, recommend site in 2000; and (3) submit license application (LA) for construction to NRC in 2001 [275].

PA-93 Completed



1994 ANL reports on actinides and colloids in CSNF drip tests [276]. **Apr:** SNL completes PA-93 for guidance on design options [42]. Thermal module added to evaluate hot repository. Release over 10^4 yr and dose over 10^6 yr calculated at 5 km boundary. New management contractor (M&O) also conducts PA [277] using RIP to simulate behavior with simple models [278].

In-Drift Disposal and High Heat Load Adopted



May: USGS preliminary results suggests very low infiltration (0.02 and 1.2 m/yr) [279], values used for PA-95. **Jun:** YMP specifies package and repository design [280]: (a) in-drift emplacement; (b) designed for 100 yr retrievability; (c) no backfill; (d) container lifetime >10^3 yr; (d) container for high-temperature repository has inner layer of Alloy 825; (f) package transported by rail underground; (g) no self-shielding package; (h) burn-up credit considered for criticality control; and (i) period of concern for criticality is 10^4 yr. **Sep:** M&O uses TBM to bore large 7.6-m diameter ESF; progress is slow [273]. To avoid influencing experiments, little water is used to suppress silica dust. **Nov:** USGS begins tests of gas permeability in several wells [281, Table 6-4].

1994 May: NWTRB encourages DOE to [221] (a) evaluate CSNF cladding as a barrier; (b) extend retrievability period to 100 yr; (c) make better use of PA results to guide program; and (d) characterize Ghost Dance Fault. NWTRB criticizes (a) progress on the ESF and rejection of previous contractor's plans to purchase conveyer, (b) ignoring NWTRB suggestion to adopt standard industry construction practices; (c) lack of coordination between in-situ thermal tests, repository design, and package design; (d) lack of experts outside the YMP; and (e) YMP avoidance of data qualification under the assumption that YMP will have sufficient time and funding to produce new data under its own QA program. **Apr:** SNL completes 2nd PA on GCD [282]. **Aug:** Planning begins on probabilistic seismic hazard assessment (PSHA) for pre- and post-closure periods. **Dec:** Bowman and Venneri of LANL circulate paper speculating that an atomic

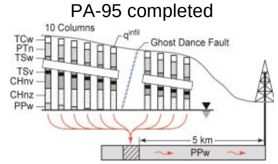
Atomic Explosion Hypothesized

explosion could occur at YM [283]. NWTRB outlines activities to assess site suitability:[284, App G] (a) most important goal is to evaluate percolation flux, and thus place more emphasis on ^{36}Cl; (b) evaluate various thermal loads and conduct more in-situ tests; (d) develop a realistic source term, consistent with effort in other countries; (e) develop procedures for expert elicitation; and (f) understand cause of the steep hydrologic gradient to north of repository. NWTRB also asks for independent assessment of DOE and contractor organization related to YM

1995 Jan: Congress lets **v**oluntary repository/MRS siting office expire. **Jun:** NRC policy statement calls for detailed modeling with unbiased parameters when conducting analysis for NRC, including PAs [285]. Scientists for NRC estimate alternative frequency of igneous disruption for consideration [286; 287]. **Oct:** YMP budget cut from $630 million to $315 million. Congress stops MPC development because of cost for transportation, added handling costs to utilities, and perceived lack of fairness in bidding for only one vender [288]. NRC completes 2nd PA of YM (IPA-2) showing importance of waste container corrosion and infiltration [251].

1995 May: DOE notifies utilities that based on its interpretation of the standard contract DOE does not have an obligation to accept CSNF by 1998 [289].

PA-95 completed



1995 USGS/LBNL develop 1st 3-D UZ model with TOUGH (UZ-95) [290]. One column of model is used for PA-95 [43]. **Feb:** SNL shows feasibility of disposal without treatment of DSNF in separate section of repository [65]. **Mar:** USGS completes mapping of inactive Ghost Dance Fault; [284]. **Apr:** Calcite, ^{36}Cl, and moisture sampling begin in ESF as boring progresses [74, §2]. LANL reports that Sr date of calcite in wellbores and U date of spring deposits suggest water table rise of 80 to 115 m during last glaciation [42, §8.8]. Progress in boring ESF improves after YMP finds money to add conveyer to TBM [291]. Boring of ESF averages ~26 m/day in Sep, Oct, and Nov [273]. **May-Jun:** USGS conducts interference test at C-wells [292]. **Sep:** USGS reports on infiltration in 99 neutron holes [293]; infiltration much larger than reported in 1994. **Nov:** YMP completes PA-95 to evaluate release and doses to 10^6 yr at 5 km boundary [43]. PA-95 uses new container model that includes corrosion variability. **Dec:** Boring of ESF sets a world record of 218 m in 5 days.

NAS advises risk for YMP regulation

1995 Jan: Because MRS office closed, Goshute Skull Valley Indian tribe in Utah starts negotiating directly with utilities. **Mar:** For site-specific regulation, NAS advises (a) risk calculation to whenever dose is largest (likely within 10^6-yr), (b) eliminating subsystem requirements, and (c) making human intrusion a modeling case and not part of PA [294]. Press reports on Bowman and Venneri's claim [295]. NWTRB [284], notes that (a) DOE has no studies that support the thermal load strategy; (b) simplicity of source term in PAs does not support greater emphasis of EBS in new program plan; and (c) DOE has provided no evidence that PA is guiding YMP. **Apr:** YMP starts expert elicitation for PSHA. **May:** YMP starts expert elicitation for probabilistic volcanic hazard assessment (PVHA) [296]. **Jul:** Management review of YMP notes (a) little chance of meeting milestones since schedule does not include sufficient flexibility; (b) YMP reluctant to heed external reviews and industry experts; and (c) M&O lacks incentives to perform cost-effectively [291; 297].

	Federal Policy in Laws, Court Decisions, and Regulations	Presidential and DOE Federal Policy Decisions	Technical Activities Related to Yucca Mountain Project	Critiques of YMP and Related Nuclear Events

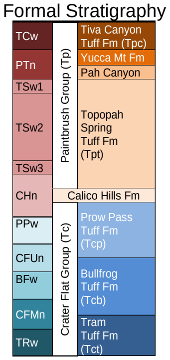
Suitability/Viability Analysis

Federal Policy in Laws, Court Decisions, and Regulations

1996 Jul: DC Circuit Court of Appeals vacates DOE interpretation and rules that DOE will be liable for missing 1998 contract deadline [298]. **Dec:** NRC clarifies terms in 10 CFR 60 [299].

Technical Activities Related to Yucca Mountain Project

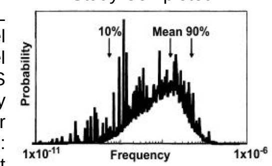
USGS defines Formal Stratigraphy



1996 SNL completes scenarios for tectonic processes [300]. LANL develops site-scale SZ model using dual-permeability model (DKM) in FEHM [301]. USGS publishes formal stratigraphy of YM: upgrades member units to formations [302]. **Feb**: USGS conducts pumping test in c#3. LLNL turns on heaters at large-block test (LBT), located at Fran Ridge to track water movement and deposition in fractures [303]. Boring slows to 15 m/day as TBM encounters unstable rock [291]. **May:** YMP begins single heater test (SHT) with 3.86 kW output in ESF: [304, Ch. 10]. **May-Nov:** Tracers injected into borehole c#2 while pumping c#3 (first tracer test) [305]. **Sep:** Based on LBT, SNL concludes DKM more accurately models percolation than ECM [306]. WP corrosion tests begin at LLNL after funds found to complete facility [273]. YMP stops TBM to suppress dust and require full-face masks because silica dust exceeds safe limits [273]. **Dec:** USGS completes infiltration model, INFIL [307].

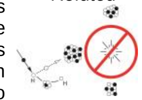
Critiques of YMP and Related Nuclear Events

Volcanic Hazard Study Completed



1996 Ten experts complete PVHA [308], resulting in a mean for λ_V: of 10^{-8} yr^{-1}. LANL estimates age of Lathrop Wells at 0.79 Ma, Little Cones, 0.90 Ma, and Crater Flats, 3.7 Ma. EPRI completes 3rd PA of YM [309]. **May:** Bowman and Venneri paper published along with papers refuting criticality [283; 310]. LANL reports on small energy release from autocatalytic criticality in homogenous system with instantaneous water removal [311]. **Sep:** Berkeley echoes low probability of criticality, but agree hypothesis possible for Pu in UZ in a heterogeneous system with slow water removal [312]. **Nov:** In anticipation of Congressionally mandated analysis, YMP forms 5 expert panels to examine (1) UZ flow, (2) flow and transport in SZ, (3) waste container degradation, (4) waste form degradation, (5) near-field/altered-zone coupled effects [303].YMP forms UZ panel first (7 experts with 4 from outside DOE and USGS) [313].

Criticality & Explosion Refuted

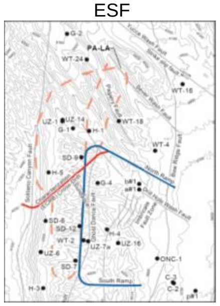


Federal Policy in Laws, Court Decisions, and Regulations

1997 In FY97 budget, Congress calls for a viability assessment (VA) that includes (1) a PA-VA, (2) a design for the repository and package, (3) cost for completing the LA, and (4) cost for constructing, operating, and closing the repository [314]. **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 [229] and conduct technical exchanges with DOE to facilitate resolution. **Nov:** DC Circuit Court of Appeals reaffirms that DOE will be liable for the missed deadline. Court does not require DOE to physically move waste to a storage site, nor allow utilities to suspend payments into the Nuclear Waste Fund. Court states remedy is to sue for damages [315].

Presidential and DOE Federal Policy Decisions

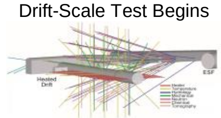
DOE Decides to bore ECRB after completing ESF



1997 Aug: DOE accepts NWTRB suggestion made in 1st report and thereafter for a 2nd test drift: the enhanced characterization of the repository block (ECRB) bored to Solitario Canyon Fault [71, p.92].

Technical Activities Related to Yucca Mountain Project

Drift-Scale Test Begins



1997 USGS develops a 3-layer, 3-D, steady-state regional flow model of SZ for the closed Death Valley basin [316]. For PA-VA, USGS develops a site-scale model with boundary conditions set by regional model [317]. USGS uses FEHM code to model steady flow in SZ at site scale, using 16 zones, one no-flow fault, and minor recharge from Forty-Mile Wash [317]. **Jan:** New conservative tracer test begins at C-wells. Test ends in Nov. **Mar:** YMP conducts workshop to discuss a methodology to evaluate criticality [318]. **Apr:** Boring of 8-km ESF is completed (12 m/day average). **May:** Heat turned off in SHT; test shows conduction rather than convection is dominant heat transfer process [319]. DKM matches temperatures better than ECM [303; 320, §3.4.5]. **Jun:** YMP completes survey of dietary habits of residents within 80 km [44, Vol. 3 Table 3-23]. **Jul:** Drilling of WT-24 begins with vacuum-reverse air circulation; completed May 1998 [321]. **Sep:** YMP publishes summary of criticality probability and consequences [322]. LANL and LLNL report on migration of 0.8 pCi of Pu via colloids 1.6 km from 1.15-million ton Benham bomb test detonated in 1968 below water table at NTS [323]. LBT concluded. **Nov:** LBNL reports on seepage tests in niche at Station 3650 of ESF [45, Fig. 4-17]. Drilling of SD-6 begins with similar rig as WT-24; completed April 1998 [321]. **Dec:** YMP begins $50-million drift-scale test (DST) in 48-m long section of ESF with 9 package-sized heaters, 50 heaters in walls to simulate adjacent drifts, and ~3500 sensors [303]. LANL summarizes ^{36}Cl data [324].

Critiques of YMP and Related Nuclear Events

ICRP Advises 1 mSv/yr

ICRP

1997 Apr: NWTRB suggests [273] (a) small-diameter exploratory drift parallel to the proposed emplacement drifts to obtain hydrologic data; (b) evaluating the use of concrete tunnel lining; (c) evaluating drip/radiation shields; (d) long-term ventilation to keep repository cool; (e) improving transparency to help with public communication about PA; (f) deferring decision on centralized waste storage site until site recommendation (SR). **May:** ICRP recommends dose limit of 1 mSv/yr (from a single source such as radioactive waste disposal) and suggests a target of 0.3 mSv/yr. [325]. UZ expert elicitation completed and agree (a) percolation equal to infiltration above repository; (b) percolation 10 times greater than PA-95; (c) flow in TSw mostly in fractures based on presence of bomb-pulse ^{36}Cl; and (d) capillary barrier would exist around drifts and divert water [326]. **Aug:** Waste Package Degradation expert elicitation (WPDEE) panel (6 experts with 4 from outside DOE complex) completes evaluation of container corrosion, (started in Mar) [327, §5.3]. Experts reluctant to define localized corrosion rates of Alloy 625, which replaced Alloy 825 in 1996 [328]. **Oct:** SNL completes PA for Compliance Certification Application for WIPP using generic EPA Standard 40 CFR 191 [329]. **Nov-Dec:** Waste Form expert elicitation panel (6 experts with 3 outside DOE complex) complete 1st and 2nd workshop on degradation of SNF and HLW. Experts conclude information on waste degradation adequate for PA-VA. Experts find insufficient data on localized corrosion of cladding; hence, no suggestion on role of cladding.

1998 Feb: In NRC funded study, researchers report that, based on Global Positioning System (GPS) data, the earth's crust is deforming 51 nanostrains/yr near YM vs. average of 12 nanostrains/yr in Basin and Range, which suggests either a large earthquake or igneous activity could occur in the future [330]. **Sep 97 & Aug:** Evolution of the Near-Field Environment KTI technical exchange [250]; **Feb:** NRC completes 1st version and 1st revision of 9 reports on KTIs. **Mar & Nov:** Container Life and Source Term KTI [331]; **Apr & Nov:** Total System Performance Assessment and Integration KTI [332].

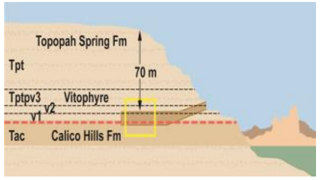
1998: DOE funds USGS over 5 yr to update regional flow model. In DOE audit of documents supporting VA, auditors find problems (e.g., parameter values that could not be traced back to original source data and models that had not followed validation requirements) [333]; QA procedures will have to be followed for site recommendation. **Dec:** DOE estimates that LA (site characterization, repository design, and documentation) will cost $6 billion [44, Sum]. LANL summarizes more ^{36}Cl data [334]. In 5 volume report to Congress, DOE concludes that YM remains a viable site based on PA-VA using a dose measure [44]. Doses from igneous and seismic disruptive events very small [44, Vol. 3 §4.4.3]. Environment Management Office of DOE (DOE-EM) supports YMP so that DSNF is included in PA-VA. Assuming metallic degradation rate and no cladding, DSNF contributes about same dose as HLW; both less than CSNF [44, Vol. 3 Fig. 4-22].

1998 DKM used in thermal-hydrologic models supporting PA-VA [44, Vol. 3 §3.2.1] to predict conditions in near-field. **1998** For PA-VA, USGS defines future climate at YM based on precipitation at analog sites: Rainer Mesa on NTS and South Lake, CA [44, p 3-14]. USGS updates geologic bedrock map first created in 1984 [335]. Testing at C-wells shows aquifer permeability ~2 orders of magnitude greater than single-well tests [292].

Drip Tests Conducted

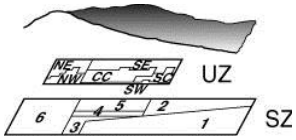
Jan: LBNL conducts seepage tests at Niche 3650. **Feb:** YMP replaces Alloy 825 with Alloy 22 to increase container lifetime. **Mar:** YMP starts boring 2.8-km long, 5-m diameter ECRB cross drift; ECRB is 15 to 27 m above ESF and penetrates lower lithophysal unit where majority of repository will exist [303]. **Jul:** Because of lack of funding for TBM to bore to CHn. LANL begins 3-yr test on flow/ transport in 5 m block of CHn 70 m below the surface at Busted Butte 8 km southeast of YM [336].

LANL begins Busted Butte Tests in Calico Hills Fm

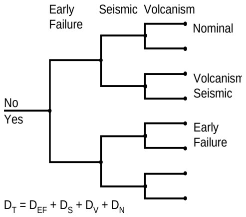


Sep: For DOE-EM, SNL updates PA to examine viability of direct disposal of DSNF at YM [66]. **Oct:** ECRB completed to Solitario Canyon fault [337]. LBNL injects water at fault in Paintbrush non-welded modeling unit (PTn); water imbibed into matrix; thus, episodic fracture flow attenuated [338]. **Nov:** VA shows YM remains a viable site [44]. PA-VA transitioned to SNL/NRC methodology for FEPs [339, §10.2]. PA-VA studies undisturbed scenario class and evaluates influence of (a) seismic rock fall on package and fault altering SZ permeability; and (b) igneous eruption, igneous dike enhancing source term, [44, Vol. 3, §4.4] YMP completes criticality report with two parts [340]: Part 1 is to show low probability. If low probability cannot be shown, then Part 2 is to show low consequences. **Dec:** License Application Design Selection (LADS) study begins to select repository - package design [84].

PA-VA Completed

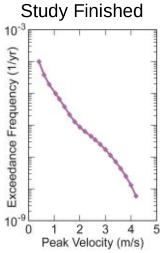


SNL/NRC Method Used for Scenarios



1998: Expert elicitation of 5 experts (4 from outside DOE complex) on issues related to SZ groundwater flow and transport conducted for PA-VA. The experts examine the high water table northwest of the site; but conclude that identifying the cause is not important to PA. As in PA-EA to PA-95, the experts affirm that water from YM does not reach the deep carbonate aquifer but remains in the 2 tuff aquifers. The experts consider the large dispersion used in the PA-95 unrealistic and estimate dispersion between a factor of 2 and 100 of distance. **Feb:** Utilities petition DC Circuit Court of Appeals to force DOE to accept waste [341]. WPDEE panel holds 1-day meeting to discuss corrosion of Alloy-22 [327, §5.3]. **Apr:** Nevada State Engineer cancels 3-day hearing on water permit based on fact DOE has not officially selected site [342]. **Jun:** Nevada Department of Transportation refuses to cooperate with DOE in upgrading rural roads leading to YM [343]. **Jul:** Based on tests funded by Nevada Nuclear Waste Project Office (NWPO), Russian scientist, Dublyansky, argues that calcite crystals in fractures of ESF formed in hot water [344]. NWTRB completes review of 11 reports submitted by Szymanski including those by Dublyansky and concludes reports do not make credible case that geothermal water flooded YM in the past [45, p. 4-402]. **Aug:** SZ Expert Panel concludes Szymanski assertion without basis [45, p. 4-397]. **Sep:** PSHA is completed (effort stopped in FY97 because funds lacking). PSHA produces hazard curves in terms of peak ground velocity (PGV) and probability of PGV being exceeded annually [303]. **Nov:** EPRI completes 4th PA of YM [345]. **Dec:** Nevada reiterates its opposition to site to Secretary Richardson since (1) humans could intrude into the site, (2) the site is susceptible to seismic and volcanic activity, and (3) groundwater could invade the repository in less than 1000 yr [346].

Seismic Hazard Study Finished



Suitability/Viability Analysis for Site Recommendation

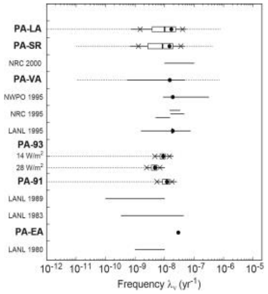
Federal Policy in Laws, Courts Decisions, and Regulations

EPA Drafts 40 CFR 197

1999 Feb: In draft 10 CFR 63 for YM, NRC proposes [347] (a) 10^4-yr regulatory period, (b) total effective dose equivalent (TEDE) limit of 0.25 mSv/yr, (c) critical group 20 km south of emplaced waste of 100 families on 15 to 20 farms using current farming practices under arid and semi-arid conditions (i.e., uncertain dilution); and (d) conditions of climate change from arid to semi-arid. Proposed 10 CFR 63 omits design and siting criteria present in 10 CFR 60, requires identification and description of multiple barriers using PA as technical basis, and uses more conservative "reasonable assurance" compliance concept. **Aug:** In draft 40 CFR 197 for YM, EPA proposes [348] (a) 10^4-yr regulatory period with calculation of peak dose for EIS, (b) 0.15 mSv/yr annual committed effective dose equivalent (CEDE) limit (similar to 40 CFR 191), (c) 0.40 mSv/yr dose limit to protect groundwater, (d) compliance for a reasonably maximally exposed individual (RMEI) at point of compliance rather than critical group member, (e) fixed well withdrawal dilution of 3.7×10^6 m^2/yr, (f) 4 alternative locations for point of compliance, and (g) dictates a "reasonable expectation" compliance concept (similar to 40 CFR 191) and states concept cannot be changed by NRC.

2000 NRC and DOE conduct public meetings to reach 293 agreements in 9 KTI areas on what to resolve and include in LA for the NRC sufficiency review for SR [364, p. 5-1]. **Jan:** NRC scientists estimate frequency of igneous disruption at YM ($10^{-8} < \lambda_V < 10^{-7}$ yr^{-1}) [365]. **Jun:** NRC issues safety evaluation report (SER) on DOE's planned approach for screening criticality. The NRC identifies 28 issues that need to be resolved for LA such as [366] (a) develop a criticality limit that includes bias and uncertainty; (b) develop approach for burn-up credit that includes test validation; (c) validate models that estimate fissile migration external to the package; (d) include more processes in waste degradation; (e) develop consequence analysis.

NRC scientists propose high frequency of volcanic intrusion

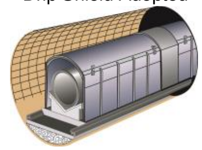


Presidential and DOE Federal Policy Decisions

1999 Feb: Energy Secretary Richardson proposes to take title of CSNF and assume management of onsite storage; cost estimates for storage until 2010 are between \$2 and \$3 $\times10^9$ to be paid by Nuclear Waste Fund. **Jul:** Based on PA-VA, DOE publishes 1400-page draft EIS on either building YM or leaving waste at 77 sites around US [349]. In draft EIS, various repository sizes are considered (70,000 to 105,000 MTHM) [349]. **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 [350].

Technical Activities Related to Yucca Mountain Project

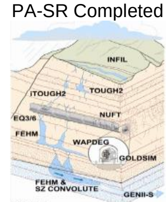
Drip Shield Adopted



1999 Tests start on ¼-scale WP to study condensation under drip shield and water drawn under invert [337]. USGS uses 1997 3-D model developed to evaluate effect of glacial and global-warming climates on SZ regional flow [351]. Results set boundary conditions for site-scale SZ model. USGS reports deformation near YM same as Basin and Range average and propose discrepancy with 1998 NRC work caused by relaxation from 1992 Skull Mt earthquake [352]. USGS conducts magnetic survey of anomalies near YM [353]. **Jan:** LANL dates Lathrop Wells at 77 ka from $^{40}Ar/^{39}Ar$ [354] **Mar-Oct:** USGS/LLNL drill 50 boreholes in ESF at Sundance and Drill Hole Wash faults to validate ^{36}Cl found by LANL [74, §3.2]. **Apr:** YMP completes LADS. Ti drip shield added to protect WP during transition from hot to cool when localized corrosion possible. Alloy 22 switched to outer WP layer. WPs spaced 0.1 m to keep temperatures similar. Drift support changed from concrete to steel mesh. Drift spacing increase to 81 m to lower pillar temperature and allow water to pass. LADS also studies spreading construction costs, which becomes basis of 2001 modular study [84]. **Jun:** ~1 km of ECRB sealed to observe seepage near Solitario Canyon fault. **Jul:** SNL completes database with 310 FEPs for review by April 2000. **Nov:** YMP decides to conservatively estimate uncertainty in SR to ease qualification of data and be consistent with "reasonable assurance" in draft 10 CFR 63 [347].

2000 INL completes 4 studies examining feasibility of critical conditions for DSNF [367]. **Mar:** LBNL concludes (based on 1998-99 flow tests) [368] (a) some UZ percolation is diverted to the faults by non-welded layers: 4% near surface, 15% at PTn, and 35% at CHn; and (b) ~84% of percolation is through fractures. **Mar-Apr:** YMP completes process model reports (PMRs) that summarize various aspects of YM disposal system for site recommendation (PA-SR) [369]. **May-Sep:** AMRs, (Analysis/Model Reports) which provide details summarized in PMRs, are completed during summer. **Jun:** SNL finalizes database of 323 FEPs from various sources [370]. FEP screening rationale for PA-SR developed in 11 reports. **Jul-Nov:** Pump test of NC-19D in alluvium completed [371]. **Oct:** Thermal-hydrologic-chemistry model run for DST [372; 373] and SHT [304, §10]. LANL ends Busted Butte test. Capillary flow dominates water movement [336]. Criticality omitted from PA-SR [374-378]. **Nov:** YMP completes PA-SR for 10^4-yr regulatory period. In PA-SR, only undisturbed and igneous scenario included; damage to WP from seismic scenario omitted [45]. **Dec:** PA-SR is finalized based on DOE comments [85].

PA-SR Completed



Critiques of YMP and Related Nuclear Events

1999 1st 8 wells (Phase I) of NC-EWDP completed [45, Fig. 4-131]. Nuclear opponents reject Sec. Richardson proposal because they want to keep utilities liable for waste; utilities reject idea because it removes pressure to open repository [355]. DOE drills 12 monitoring wells at 7 nuclear test sites based on finding Pu, ^{137}Cs, and ^{60}Co in groundwater around 1968 Benham Test [356]. **Jan:** Government Accountability Office (GAO) criticizes DOE ability to complete large projects, minimize financial waste, and accept outside review [357]. **Feb:** PA Peer Review (PAPR) panel for PA-VA issues final report and concludes that "…at the present time, an assessment of the future probable behavior may beyond the analytic capabilities…" PAPR suggests a different approach: use simple models, sensitivity studies, bounding analysis, and design changes to move into regime of known behavior [358]. **Mar:** Utah Governor Leavitt vows to stop Goshute Indians from obtaining NRC license to store SNF in Skull Valley [359]. Judge Penn lifts injunction placed on WIPP in 1992. First shipment of waste from LANL arrives at WIPP [360]. **Apr:** University of Nevada at Las Vegas (UNLV) begins study of fluid inclusions in tuff to answer claims by Szymanski [361]. **Nov:** In hearing for permanent well permit, Nevada State Engineer finds water use for construction and operation does not infringe upon existing water users. Thus, question is if permit is in public interest [362]. NWTRB notes research needs [363]: (1) seepage into drift under ambient and heated conditions; (2) sorption in CHn to demonstrate "defense-in-depth"; (3) corrosion of Alloy-22; (4) SZ flow/transport, (5) cladding credit; and (6) use of dedicated trains to transport SNF.

2000 Jan: Draft EIS draws criticism on transportation of SNF and lack of specifics on routes at 20 hearings across the US [379]. **Feb:** Nevada State Engineer denies DOE well permit stating permit not in best interest of Nevada public health and tourism-based economy [380]. **Apr:** NWTRB states YM warrants continued study based on PA-VA but states improvements needed for PA-SR: (a) better inclusion of uncertainty in PA, (b) more study of corrosion of Alloy 22, (c) evaluation of hot repository design; (d) acidic condensed water on package from radiolysis; and (e) evaluation of geo-chemistry and hydrology of natural barriers such as ^{36}Cl monitoring, seepage tests, and study of Solitario Canyon fault [381]. NWTRB also reiterates its 1997 recommendation to develop safety case with "multiple lines of evidence," separate from the PA. At same meeting, NRC scientists request more attention to modeling seismic and volcanic events [382]. **Aug:** NWPO funded scientists describe conditions when Alloy 22 might corrode to NWTRB (traces of lead (Pb), arsenic (As), and mercury (Hg) at high temperature) [383]. **Oct:** DOE estimates ~3.4 metric tons of Pu used in 1054 detonations over 40 yr (tests stopped in 1992); of 1054 detonations, 100 atmospheric and 921 underground at NTS [384]. **Nov:** EPRI completes 5th PA of YM [385].

NRC Adopts Reasonable Expectation

2001 Basis of State Engineer denial of DOE well permit ruled unconstitutional by 9^{th} Circuit Court of Appeals. **Apr:** While encouraging more informal hearings, NRC retains formal hearings for construction, receipt, and closure licensing at repositories [386]. **May:** NRC notes 8 technical errors in PA-SR that should be corrected including dose from ash releases from volcanism, chemistry of water around WPs, and how fast material around waste will degrade [387]. In change to 10 CFR 2, NRC adopts DOE suggestion to require electronic access to documents 6 months prior to submission of LA [388]. **Jun:** EPA promulgates 40 CFR 197, which sets accessible environment boundary at southern NTS boundary (~18 km south of emplaced waste) for dominate pathway and 5 km in other directions [30]. **Nov:** NRC promulgates 10 CFR 63, which adopts EPA concept of reasonable expectation, 0.15 mSv/yr dose limit, equates TEDE to annual CEDE for post-closure period, and requirement to describe technical basis of multiple barriers using PA. 10 CFR 63 also defines range of repository percolation to consider for post 10^4 yr period [14]. NRC issues sufficiency review stating confidence that DOE will have sufficient information in LA to resolve issues [364, p. 5-4].

2001 Feb: Condensate found at bulkhead in closed end of ECRB; testing continues to confirm water is condensate and not seepage [389]. Process leading to 328 primary and 1368 secondary FEP list documented [370]. **May:** YMP completes study to increase operation flexibility by using modular surface buildings and subsurface construction [390]. At HLW International conference, USGS scientists summarize findings that calcite in fractures formed by water dripping from the surface as YM cooled and not from thermal water that rose up in recent geologic time [391]. Also, boreholes at paleosprings indicate only a 17 to 30-m rise in the water table during last 2 pluvial cycles [392]. **Jun:** Supplemental Science and Performance Analysis (SSPA) completed to address critique by NWTRB that conservative bias in models and parameters of PA-SR complicates understating. SSPA includes more consistent, unbiased treatment of parameter uncertainty and modeling changes to approximate a cooler repository where drift wall temperatures do not exceed boiling [51]. **Sep:** YMP updates the criticality topical report that adopts a fault tree/event tree approach [393]. **Dec:** PA-EIS completed based on updated SSPA parameters and models that analyze the hot and cool repository designs [50].

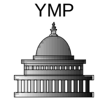
2001 NAS concludes that after 40 yr of study, "geologic disposal remains the only scientifically and technically credible long-term solution available to meet safety needs" [394]. **Jan:** LANL begins $34 million test of accelerator transmutation of radioactive waste [395]. **Apr:** NWTRB notes quantifying uncertainties in the PA should be a priority" [72]. Other needs are (a) understanding package corrosion; (b) evaluating a cooler repository; and (c) explaining bomb-pulse ^{36}Cl in the repository. **May:** At HLW International conference, Dublyansky for NWPO presents his opposing case for formation of calcite in hot water [396]. **Jun:** Nevada petitions DC Circuit Court of Appeals to declare 40 CFR 197 invalid since it does not require geology as primary barrier. **Sep:** al Qaeda terrorists commandeer 4 commercial jets and fly 2 into World Trade Center and 1 into the Pentagon. The specter of attacks on nuclear reactors and nuclear waste in transit become of concern. NRC Advisory Committee on Nuclear Waste (ACNW) issues letter stating "…PA-SR does not lead to a realistic risk-informed result...." and "PA-SR…is not transparent." **Nov:** SNL completes 3^{rd} PA for GCD facility on NTS in tuff alluvium and shows compliance with 40 CFR 191 [168]. **Dec:** Joint IAEA-NEA (International Atomic Energy Agency and Nuclear Energy Agency) team completes review of PA-SR [397] and suggests developing a safety case (i.e., the strategy used to achieve safety as distinct from PA-SR showing compliance with regulations). IAEA review of biosphere model suggests updating biosphere model for LA [398]. Using similar arguments, Nevada petitions DC Circuit Court of Appeals to declare DOE guidelines (10 CFR 963) void.

2002 Jan: NRC study supports plan to store CSNF on Skull Valley Indian Reservation [399]. **Jul:** As part of sufficiency review, NRC issues combined report on status of all 9 KTIs; 293 agreements made related to providing more information or analysis to NRC [400]. **Aug:** Scientists for NRC, propose "dog-leg" scenario in which igneous dike runs down drifts and disrupts large numbers of packages before continuing assent to surface [401].

2002 Feb: In deference to Russia and lack of budget, DOE rejects options to dispose surplus Pu at YM, in deep boreholes, or accelerator destruction and selects option to convert to MOX for reactor use [402]. DOE completes final EIS on site selection (4904-pages including 2864-page response to comments in Vol. 3) [86], based on new PA-EIS [403], which builds upon SSPA. EIS estimates $43 billion for construction and operation and $4 billion for transportation and storage; recommends rail transportation to site. After 9 month personal review of draft, Energy Secretary Abraham recommends YM to President Bush [52]. President Bush recommends YM to Congress. **Sep:** DOE decides to submit license by Dec 2004 (under "Plan B") and conduct PA for only 10^4-yr regulatory period (PA-04-LA) [404].

. **2002** USGS revises regional groundwater flow model of Death Valley Basin [405]. **Jan:** After 4 yr, YMP turns off heaters in DST. During the test, 6-7 m of tuff dried out (drift diameter 5.5 m). **Oct:** Although water levels in a few wells increased in last 10-yr, most of the 43 wells near YM have not changed much since 1960.

Congress Approves YMP



2002 Jan: NWTRB reports :[53; 406] technical basis for PA-SR weak to moderate because of gaps in data and understanding (volcanism basis strong, package corrosion basis weak). **Feb:** Nevada State Engineer denies request to extend temporary ground water permit since site characterization activities are now over [407]. EPRI completes 6^{th} PA of YM, showing capability of natural barrier alone to meet 40 CFR 197 [408]. **Apr:** NWTRB recommends [389] (a) making PA more realistic; and (b) expending more effort on communicating PA conclusions. Using arguments similar to June 2001 lawsuit, Nevada petitions to declare 10 CFR 63 invalid [409]. **Jun:** 4.4 magnitude earthquake occurs in Rock Valley ~30 km east of YM. **Dec:** EPRI completes 7^{th} PA of YM [364].

Compliance Analysis

Federal Policy in Laws, Court Decisions, and Regulations | Presidential and DOE Federal Policy Decisions | Technical Activities Related to Yucca Mountain Project | Critiques of YMP and Related Nuclear Events

2003

Federal Policy in Laws, Court Decisions, and Regulations

2003 May: NRC Director of Waste Management Division tells DOE that QA procedures are not working ("Quality is not being built into the Project") and orders official response in 30 days.[410]. **Jul:** NRC releases final version of LA review plan, which was developed to maintain consistency during review [411]. US District Court in Boise, Idaho rules DOE cannot reclassify HLW left in Hanford storage tanks after removing the readily pumped liquid to permit disposal in-place [412].

Presidential and DOE Federal Policy Decisions

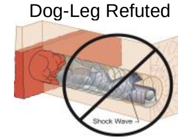
2003 Mar: DOE starts what is to be a long-term Science and Technology program with $1.7 million to improve understanding and develop technology that could reduce uncertainty and costs.

Technical Activities Related to Yucca Mountain Project

2003 Most AMRs completed for PA-04-LA that includes seismic scenario class; better calibration of seepage model; updated near field chemistry model to better evaluate pH, nitrate (NO_3), and chloride (Cl^-) concentration in seepage water to determine localized corrosion on container; updated package chemistry model to simulate when only water vapor available and include sorption of hydrogen (H^+) and hydroxyl (OH^-) ions on rust to constrain pH; and replaced GENII-S with Environmental Radiation Model for Yucca Mountain, Nevada (ERMYN) to calculate dose factors. **Nov:** Based on work at Busted Butte, LANL reports zeolites in CHn below repository readily sorb short-lived strontium (Sr), cesium (Cs), and barium (Ba) [336]. Scientists report that U may form studtite that could trap Pu and Np and prevent nuclide migration [413].

Critiques of YMP and Related Nuclear Events

Shock Wave & Dog-Leg Refuted

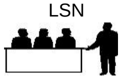


2003 YMP funded expert panel finds, based on numerical modeling, that both dog-leg scenario and hypothesis of pyroclastic flow and shock wave are not plausible [414]. Scientists at UNLV conclude no evidence for past flooding of repository horizon to form calcite [361]. NAS suggests staged repository schedule [415]. **Jul:** GAO concurs with NRC and DOE findings that health risks from accidents and terrorism during transportation of nuclear waste is low [67]. **Nov:** Nevada State Engineer again denies DOE permanent water rights, this time because water for project is not beneficial use since Governor Guinn rejected the project [407]. **Nov:** NWTRB comments that YMP has not convincingly screened out localized corrosion on drip shield or container [416].

2004

Federal Policy in Laws, Court Decisions, and Regulations

Court Vacates 40 CFR 197 & ASLB Rejects LSN



2004 Feb: NRC finds risks from storage of CSNF in reactor pools less than previously thought [417]. **Apr:** NRC issues report (draft available in Jan) on audit of 3 AMRs (Corrosion of WP Outer Barrier, CSNF waste form degradation, Drift Degradation Analysis) that criticizes the lack of clarity and linkage to technical information [418]. **Jul:** DC Circuit Court of Appeals rejects all Nevada petitions on site selection process: NWPAA rendered moot challenges [55]. Except Court states EPA rejected, without sufficient basis, NAS advice [294] for a regulatory period to when risk is largest and vacates 10^4 yr period in 40 CFR 197 [55]. ASLB rejects initial DOE certification of LSN. ASLB notes ~4 million e-mails from personnel no longer with YMP had not been reviewed [419].

Presidential and DOE Federal Policy Decisions

2004 Jun: DOE places ~1.2 million documents including ~700,000 e-mails (~5.6 million pages) in LSN [420]. **Nov:** DOE notifies NRC that when M&O was reviewing old e-mail for LSN, M&O found e-mail between 3 USGS geo-hydrologists from 1998 to 2004 that raise questions about collection of infiltration data, when INFIL installed, fabrication of QA records [333].

Technical Activities Related to Yucca Mountain Project

2004 USGS completes update to regional SZ flow model [421]. **Feb:** In response to NRC request in 2002, YMP conducts new aerial magnetic survey of anomalies around YM to resolve remaining questions on igneous history [422]. **Mar:** Based on NRC audit [418], YMP reorganizes to form Repository Integration Teams and initiates a 6-month, $20 million review of AMRs to improve justification and traceability to sources of information for PA-04-LA [333]. **May:** YMP presents test results to NWTRB that show no localized corrosion of Alloy 22 induced by salt deliquescence [423]. **Sept:** CSNF drip tests at ANL stopped; analysis continues to 2005. **Nov:** 16 new NC-EWDP wells mostly completed (Phases II, III, IV); wells suggest alluvium unconfined [371, Fig. 7-4]. **Dec:** YMP completes PA-04-LA for 10^4-yr regulatory period, but work stops because ASLB rejected certification of LSN.

Critiques of YMP and Related Nuclear Events

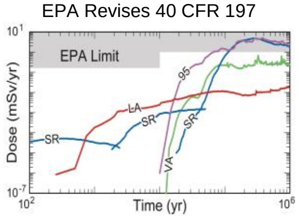
2004 Feb: Nevada state inspectors find tailings from tunnel in "impeccably well kept" and no violations of Clean Air Act for blowing dust that might include silica that might cause silicosis and fiberous erionite mineral that might cause cancer [424]. **Mar:** SNL completes 1st re-certification PA of WIPP [425]. **Jul:** First of potentially 65 trials begins to assess damages incurred by utilities when DOE defaulted on contract to accept waste [426]. **Sep:** Nevada sues DOE over choice of Caliente rail route claiming EIS was not completed before choice [427].

2005

Federal Policy in Laws, Court Decisions, and Regulations

2005 May: NRC approves storage license for Private Fuel Storage (PFS) at Goshute tribe reservation in Utah for 40,000 MTHM [428]. **Aug:** In draft revision of 40 CFR 197 EPA extends period of compliance to 10^6 yr and proposes a peak dose limit of 0.15 mSv/yr for mean of simulations for 1st 10^4 yr and 3.5 mSv/yr for *median* of simulations between 10^4 and 10^6 yr [429]. **Sep:** As requested by EPA, NRC defines model style for climate change after 10^4 yr in draft revision of 10 CFR 63: NRC proposes DOE model a constant average percolation rate reaching the repository that is sampled from a log-uniform distribution between 13 and 64 mm/yr [430].

EPA Revises 40 CFR 197



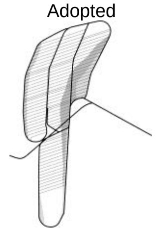
Presidential and DOE Federal Policy Decisions

2005 Jan: While waiting for LSN certification, DOE asks for another interim PA-05-LA to improve various sub-models in response to comments **Mar:** DOE Inspector General and Interior Inspector General investigate USGS e-mails [333]. **Oct:** DOE directs SNL to redo infiltration model and directs INL to review technical merit of INFIL [431]. Because of high cost of handling facility for large volume of CSNF, DOE suggest transportation, aging, and disposal (TAD) handling canister that is loaded at reactor (similar to MPC) [432].

Technical Activities Related to Yucca Mountain Project

2005 Jan-Jun: YMP updates AMRs; seismic model uses maximum peak ground velocity of 4 rather than 12 m/s to eliminate unrealistic behavior in PA-04-LA [433]. **Feb:** 1st evidence of natural seepage found near ESF entrance. **Aug:** SNL publishes revision of FEPs in response to internal comments and NRC; 375 FEPs are listed. Original 328 FEPs are not changed much, but some FEPs are split [434]. FEP screening rationale is contained in 10 reports. **Oct:** Repository moved to northeast with 4 modular panels to increase flexibility in construction. Also, modular surface facilities used and concrete pads added for buffer storage [435]. **Nov:** LANL dispels hypothesis of UNLV scientists: Drilling at magnetic anomalies finds mainly Miocene age basalt (>9.5 Ma). Also, magma composition at Lunar Crater differs from YM [422]. **Dec:** DST completed.

Modular Design Adopted



Critiques of YMP and Related Nuclear Events

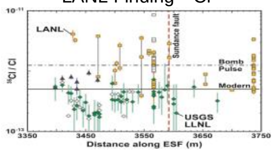
2005 Aug: UNLV scientists hypothesize (a) buried magnetic anomalies near YM are of Pliocene age, which would cause 5 fold increase in igneous rate, and (b) volcanoes near YM may be linked to more active Lunar Crater, California volcanic field 150 km to the NNE [436]. **Aug:** Independent Validation Review Team (IVRT) finds PA-LA-05 is not ready to submit to the NRC.

2006 Jan: In audit, NRC finds that LLNL never calibrated its measurements of humidity in corrosion experiments [373].

TAD Handling Canister Adopted

2006 Bush Administration proposes Global Nuclear Energy Partnership (GNEP) to promote development of advanced reprocessing plants that do not separate Pu and U. **Jan:** Acting Director Golan announces a new path: implement TAD for CSNF. Also, Alloy 22 layer thickness increased from 20 to 25 mm for CSNF. DOE stops corrosion work at LLNL. Eventually, 5 yr and 9.5 yr corrosion work had to be eliminated [71, p.24] **Apr:** DOE and Interior Inspector Generals conclude no criminal charges of misconduct should be filed against USGS geoscientists. Although misconduct was suggested in e-mails, it was not substantiated [333].

USGS/LLNL Cannot Validate LANL Finding ^{36}Cl



2006 Feb: YMP finds infiltration corroborated by other studies in southwest [437]. YMP reports that Eh tests at wells suggest a reducing zone exists down gradient from YM that may retard ^{99}Tc, [432]. **May:** YMP completes most documentation for PA-05-LA, but work stops to prepare PA-LA that addresses remaining IVRT comments; includes analysis out to 10^6 yr; replaces near-field chemistry model; replaces USGS INFIL with SNL MASSIF model; and models TAD **Aug:** No conclusions reached between LANL finding and USGS/LLNL not finding ^{36}Cl in ESF [74, Fig. 6-1].

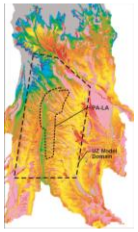
IAEA selects 1 mSv/yr

2006 May: IAEA publishes model standard for geologic disposal that adopts the ICRP recommendation of a maximum exposure dose of 1 mSv/yr and average dose of 0.3 mSv/yr (or health risk of 10^{-5}/yr) over a regulatory period not too long for meaningful evaluation [438]. **Jun:** NWTRB recommends YMP [432] (a) explain the conflicting measurements of ^{36}Cl; (b) explain the source and chemistry of water found in the sealed portion of the ECRB; (c) investigate the potential for secondary minerals to capture Np and Pu; and (d) investigate the veracity of the reducing curtain down gradient of repository. **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 [435].

2007 Dec: ASLB rules that certification of LSN in October is valid and DOE may continue to add important documents to the LSN [439].

2007 Jun: DOE announces requirements for TAD canisters; ~7800 TADs to be built by various vendors for CSNF disposal [440]. Although similar to MPC, dry casks at utilities now exceeds size of TAD [71, p.44]. **Oct:** DOE announces the LSN contains 3.4 million documents related to YMP and is certified to be complete for LA review [441].

SNL Finishes Infiltration Model



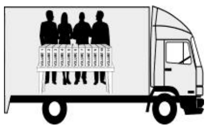
2007 Apr: SNL completes analysis using MASSIF infiltration model. MASSIF predicts 2.5 times more infiltration with more uncertainty. SNL replacement cost ~$12.9 million; and investigation cost another ~$12.7 million [442].

2007 Jun: Nevada State Engineer orders DOE to stop using water for 48 boreholes for seismic and foundation investigations in violation of court-approved agreement that limits groundwater use to safety/sanitary purposes [407]. **Oct:** Nevada petitions ASLB to strike LSN certification because documents, such as PA-LA AMR, have not been completed and will not be available 6 months prior to submitting LA [443]. **Dec:** NWTRB concludes MASSIF represents uncertainties better but did not consider all data previously used by the USGS. NWTRB suggests YMP re-qualify the USGS infiltration data for use in MASSIF [431].

NRC Dockets LA

2008 NRC completes another iterative PA on YM [444]. **Sep:** NRC dockets SAR/LA [445]. EPA repromulgates 40 CFR 197 with 3 changes from draft: dose limit after 10^4 yr lowered to 1 mSv/yr; mean selected as measure of interest throughout regulatory period; and FEP screening criterion restated as annual probability of 10^{-8} [28].

PA-LA Completed



2008 Jun: DOE submits 15 copies of 41 kg, 3 million word, 8578 pp., 16 volume Safety Analysis Report for LA (SAR/LA) to NRC [24]. DOE submits final EIS on repository construction [446].

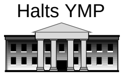
2008 Jan: SNL completes PA-LA [85]. Max dose of 0.02 mSv/yr at 10^6 yr. **Mar:** M&O completes SAR/LA chapters on repository design, pre-closure behavior, and general information. FEP screening rationale updated [447]. PA-LA considers 152 of 374 FEPs in 4 scenario classes. Criticality screened out [24]. **Apr:** SNL completes chapters on post-closure behavior and performance confirmation **Sep:** Updated PVHA, using new aeromagnetic survey, confirms 1996 PVHA [448].

2009 Mar: NRC repromulgates 10 CFR 63 that adopts EPA changes and expands range of repository percolation for post 10^4-yr period to between 10 and 100 mm/yr [32].

2009 Jan: Update to SAR/LA submitted to NRC [449]. **Mar:** Obama Administration funds only limited staff to respond to NRC requests for more information on SAR/LA [56].

2010 Jun: ASLB denies DOE motion [56]. **Aug:** NRC staff releases Vol 1 of Safety Evaluation Report (SER) discussing general information submitted in SAR/LA.

Administration Halts YMP



2010 Feb: Administration zeros budget for YMP. **Mar:** DOE files motion with ASLB to withdraw SAR/LA. DOE forms Blue Ribbon Commission (BRC) to recommend a new plan for nuclear waste [12] .

2010 Mar: South Carolina (SC) and Washington (WA) sue DOE. **Dec:** ~65,200 MTHM of CSNF and 2458 MTHM of DSNF has been generated (includes 25 MTHM of Naval SNF); 3175 HLW canisters poured. Waste is stored in 39 states at 131 sites [446].

2011 Jul: DC Circuit Appeals Court declines to intervene on SC petition but suggests SC and WA sue NRC [450]. **Aug:** NRC releases technical evaluation report (TER) of post-closure safety (SER Vol 3 without conclusions) [451]. **Sep:** NRC releases TER on pre-closure aspects (SER Vol 2) [452]. NRC Commissioners affirm Chairman's decision to close YM activity because no funding.

2011 Apr: About $15 billion spent by DOE for waste management costs required by NWPA of which ~$11 billon spent by YMP for site selection, site characterization, and LA [453].

Fukushima

2011 Mar: After 9.0 earthquake (4th largest in world), 14-m tsunami causes electrical and pump failure leading to meltdown in 3 of 6 reactors at Fukushima, Japan. Fire in storage pool raises safety concern of wet fuel storage **Jul:** SC and WA sue NRC.

2013 Aug: DC Circuit Appeals Court rules NRC Commissioners cannot stop SAR/LA review until all funds exhausted [454]. **Nov:** DC Circuit Appeals Court orders DOE to stop collecting nuclear waste fund fees [454]

2012 Jan: BRC recommends consent-based siting, restarting repository sitting, and building centralized storage to avoid high costs of stranded storage as reactors are decommissioned [12].

References

[1] Rechard RP, Cotton TA, Voegele M. Site selection and regulatory basis for the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste. Reliability Engineering and System Safety. 2014;122(2):7-31.

[2] Rechard RP, Liu HH, Tsang YW, Finsterle S. Site characterization for the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste. Reliability Engineering and System Safety. 2014;122(2):32-52.

[3] Rechard RP, Voegele MD. Evolution of repository and waste package designs for Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste. Reliability Engineering and System Safety. 2014;122(2):53-73.

[4] Rechard RP, Freeze GA, Perry FV. Hazards and scenarios examined for the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste. Reliability Engineering and System Safety. 2014;122(2):74-95.

[5] Rechard RP, Wilson ML, Sevougian SD. Progression of performance assessment modeling for the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste. Reliability Engineering and System Safety 2014;122(2):96-123.

[6] Rechard RP, Birkholzer JT, Wu Y-S, Stein JS, Houseworth JE. Unsaturated flow modeling in performance assessments of the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste. Reliability Engineering and System Safety. 2014;122(2):124-44.

[7] Rechard RP, Lee JH, Hardin E, Bryan CR. Waste package degradation from thermal and chemical processes in performance assessments of the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste. Reliability Engineering and System Safety. 2014;122(2):145-64.

[8] Rechard RP, Stockman CT. Waste degradation and mobilization in performance assessments of the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste. Reliability Engineering and System Safety. 2014;122(2):165-88.

[9] Rechard RP, Arnold BW, Robinson BA, Houseworth JE. Transport modeling in performance assessments for the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste. Reliability Engineering and System Safety. 2014;122(2):189-206.

[10] Rechard RP. Results from past performance assessments of the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste. Reliability Engineering and System Safety. 2014;122(2):207-22.

[11] Pub. L. 585. Atomic Energy Act of 1946. (60 Stat. 755). 1946.

[12] BRC (Blue Ribbon Commission). Report to the Secretary of Energy. Washington, DC: Blue Ribbon Commission on America's Nuclear Future; 2012.

[13] Pub. L. 95-91. Department of Energy Organization Act. (91 Stat. 565; 42 U.S.C. 7101 et seq.). 1977.

[14] NRC (US Nuclear Regulatory Commission). 10 CFR Parts 2, 19, 20, 21, etc.: Disposal of high-level radioactive wastes in a proposed geological repository at Yucca Mountain, Nevada; final rule. Federal Register 2001;66(213):55732-816. US Nuclear Regulatory Commission.

[15] Peters RR, Klavetter EA. A continuum model for water movement in an unsaturated fractured rock mass. Water Resources Research 1988;24(3):416-30.

[16] Pub. L. 91-190. National Environmental Policy Act of 1969. (83 Stat. 852; 42 U.S.C. 4321 et seq.). 1970.

[17] EPA (US Environmental Protection Agency). Reorganization plan No. 3 of 1970, (5 U.S.C. 903, paragraph 301, section 2(a)6; 84 Stat. 2086) Federal Register 1970;35(194):15623-6.

[18] Pub. L. 93-438. Energy Reorganization Act of 1974. (88 Stat. 1233; 42 U.S.C. 5801 et seq.). 1974.

[19] Bertram SG. NNWSI exploratory shaft site and construction method recommendation report. SAND84-1003. Albuquerque, NM: Sandia National Laboratories; 1984.

[20] Dennis AW. Exploratory studies facility alternatives study final report. SAND91-0025. Albuquerque, NM: Sandia National Laboratories; 1991.

[21] Leigh CD, Thompson BM, Campbell JE, Longsine DE, Kennedy RA, Napier BA. User's guide for GENII-S: A code for statistical and deterministic simulations of radiation doses to humans from radionuclides in the environment. SAND91 0561. Albuquerque, NM: Sandia National Laboratories; 1993.

[22] Pub. L. 99-177. Balanced Budget and Emergency Deficit Control Act of 1985. (99 Stat. 1038). 1985.

[23] Pub. L. 97-425. Nuclear Waste Policy Act of 1982. (96 Stat. 2201; 42 U.S.C. 10101 et. seq.). 1983.

[24] DOE (US Department of Energy). Yucca Mountain repository license application, safety analysis report. DOE/RW-0573. Washington, DC: Office of Civilian Radioactive Waste Management, US Department of Energy; 2008.

[25] Pub. L. 96-573. Low-Level Radioactive Waste Policy Act of 1980. (94 Stat. 3347; 42 U.S.C. 2021b et seq.). 1980.

[26] Pub. L. 703. Atomic Energy Act of 1954. (68 Stat. 919). 1954.

[27] Pub. L. 100-203. Nuclear Waste Policy Amendments Act of 1987 as contained in the Omnibus Budget Reconciliation Act of 1987. (101 Stat. 1330; 42 U.S.C. 10101 et seq.). 1987.

[28] EPA (US Environmental Protection Agency). 40 CFR Part 197: Public health and environmental radiation protection standards for Yucca Mountain, Nevada; final rule. Federal Register. 2008;73(200):61256:89. US Environmental Protection Agency.

[29] EPA (US Environmental Protection Agency). 40 CFR Part 191: Environmental standards for the management and disposal of spent nuclear fuel, high-level and transuranic radioactive wastes: final rule. Federal Register. 1985;50(182):38066-89.

[30] EPA (US Environmental Protection Agency). 40 CFR Part 197: Public health and environmental radiation protection standards for Yucca Mountain, Nevada; final rule. Federal Register. 2001;66(114):32074-135. US Environmental Protection Agency.

[31] Congress U. The START Treaty; report of the Committee on Foreign Relations, United States Senate, together with additional views to accompany Treaty Doc. 102-20 and Treaty Doc. 102-32. 102nd Congress, 2nd Session. Executive Report 102-53. Washington, DC: US Government Printing Office; 1992.

[32] NRC (US Nuclear Regulatory Commission). Implementation of a dose standard after 10,000 years; final rule. Federal Register 2009;74(48):10811:30.

[33] Pub. L. 96-164. Department of Energy National Security and Military Applications of Nuclear Energy Authorization Act of 1980. (93 Stat. 1259). 1979.

[34] Pub. L. 102-579. Waste Isolation Pilot Plant Land Withdrawal Act. (106 Stat. 4777). 1992.

[35] Morgan MG, Henrion M. Uncertainty: A guide to dealing with uncertainty in quantitative risk and policy analysis. New York, NY: Cambridge University Press; 1990.

[36] Rechard RP. An introduction to the mechanics of performance assessment using examples of calculations done for the Waste Isolation Pilot Plant between 1990 and 1992, revised. SAND 93-1378. Albuquerque, NM: Sandia National Laboratories; 1996.

[37] Rechard RP, Tierney MS. Assignment of probability distributions for parameters in the 1996 performance assessment for the Waste Isolation Pilot Plant, Part 1: Description of process. Reliability Engineering and System Safety 2005;88(1):1-32.

[38] Link RL, Logan SE, Ng HS, Rockenbach FA, Hong K-J. Parameter studies of radiological consequences of basaltic volcanism. SAND81-2375. Albuquerque, NM: Sandia National Laboratories; 1982.

[39] Sinnock S, Lin YT, Brannen JP. Preliminary bounds on the expected postclosure performance of the Yucca Mountain repository site, southern Nevada. SAND84-1492. Albuquerque, NM: Sandia National Laboratories; 1984.

[40] Sinnock S, Lin YT, Brannen JP. Preliminary bounds on the expected postclosure performance of the Yucca Mountain repository site, southern Nevada. Journal of Geophysical Research 1987;92(B8):7820-42.

[41] Barnard RW, Wilson ML, Dockery HA, Gauthier JH, Kaplan PG, Eaton RR, Bingham FW, Robey TH. TSPA 1991: An initial total-system performance assessment for Yucca Mountain. SAND91-2795. Albuquerque, NM: Sandia National Laboratories; 1992.

[42] Wilson ML, Gauthier JH, Barnard RW, Barr GE, Dockery HA, Dunn E, Eaton RR, Guerin DC, Lu N, Martinez MJ, Nilson R, Rautman CA, Robey TH, Ross B, Ryder EE, Schenker AR, Shannon SA, Skinner LH, Halsey WG, Gansemer JD, Lewis LC, Lamont AD, Triay IR, Meijer A, Morris DE. Total-system performance assessment for Yucca Mountain – SNL second iteration (TSPA-1993). Executive summary and two volumes. SAND93-2675. Albuquerque, NM: Sandia National Laboratories; 1994.

[43] Atkins JE, Andrews RW, Duguid JO, Dunlap BE, Houseworth JE, Kennedy LR, Lee JH, Lingineni S, McNeish JA, Mishra S, Reeves M, Sassani DC, Sevougian SD, Tsai F, Vallikat V, Wang QL, Xiang Y. Total system performance assessment - 1995: An evaluation of the potential Yucca Mountain Repository. B00000000-01717-2200-00136 REV 01. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 1995.

[44] DOE (US Department of Energy). Viability assessment of a repository at Yucca Mountain. DOE/RW-0508. Washington, DC: Office of Civilian Radioactive Waste Management, US Department of Energy; 1998.

[45] DOE (US Department of Energy). Yucca Mountain science and engineering report. DOE/RW-0539. Las Vegas, NV: Office of Civilian Radioactive Waste Management, US Department of Energy; 2001.

[46] SNL (Sandia National Laboratories). Total system performance assessment model/analysis for the license application. MDL-WIS-PA-000005. Las Vegas, NV: Sandia National Laboratories; 2008.

[47] Rechard RP. Historical background on performance assessment for the Waste Isolation Pilot Plant. Reliability Engineering and System Safety. 2000;69(1-3):5-46.

[48] Rechard RP. Milestones for disposal of radioactive waste at the Waste Isolation Pilot Plant (WIPP) in the United States. SAND98-0072, Revised. Albuquerque, NM: Sandia National Laboratories; 2000.

[49] OTA (Office of Technology Assessment). Managing the nation's commercial high-level radioactive waste. OTA-O-171, http://www.fas.org/ota/reports/8514.pdf. Washington, DC: Office of Technology Assessment. US Government Printing Office; 1985.

[50] DOE (US Department of Energy). Supplement to the draft environmental impact statement for a geologic repository for the disposal of spent nuclear fuel and high-level Radioactive waste at Yucca Mountain, Nye County, Nevada. DOE/EIS-0250D-S. Las Vegas, NV: Office of Civilian Radioactive Waste Management, US Department of Energy; 2001.

[51] DOE (US Department of Energy). Yucca Mountain site suitability evaluation. DOE/RW-0549. Las Vegas, NV: Office of Civilian Radioactive Waste Management, US Department of Energy; 2001.

[52] DOE (US Department of Energy). Office of Civilian and Radioactive Waste Management; Nuclear Waste Repository Program: Yucca Mountain site recommendation to the President and availability of supporting documents; notice. Federal Register 2002;67(39):9048-68.

[53] NWTRB (Nuclear Waste Technical Review Board). Report to the US Congress and the Secretary of Energy, January 1, 2002, to December 31, 2002. Arlington, VA: Nuclear Waste Technical Review Board; 2003.

[54] Pub. L. 107-200. Approving the site at Yucca Mountain, Nevada, for the development of a repository for the disposal of high-level radioactive waste and spent nuclear fuel, pursuant to the Nuclear Waste Policy Act of 1982. (116 Stat. 735). 2002.

[55] US Courts. Nuclear Energy Institute, Inc. v. Environmental Protection Agency. US Court of Appeals for the District of Columbia Circuit. Decided July 9, 2004. Federal Reporter, 3rd Series 2004;373:1251.

[56] Garvey T. Closing Yucca Mountain: Litigation associated with attempts to abandon the planned nuclear waste repository. R41675. Washington, DC: Congressional Research Service; 2011.

[57] DOE (US Department of Energy). Strategy for the management and disposal of used nuclear fuel and high-level radioactive waste. Available online at www.doe.gov; 2013.

[58] NA/NRC (National Academies/National Research Council). A study of the isolation system for geologic disposal of radioactive wastes. Washington, DC: National Academy Press; 1983.

[59] US Courts. NRDC (National Resources Defense Council) v. US EPA (Environmental Protection Agency). Federal Reporter, 2nd Series 1987;824:1258.

[60] Carter LJ. Nuclear imperatives and public trust: dealing with radioactive waste, Resources for the Future, Inc. Baltimore, MD: John Hopkins University Press; 1987.

[61] Ford GR. The White House fact sheet: President's Nuclear Waste Management Plan. Office of the White House Press Secretary. (On file at Gerald R. Ford Library, 1000 Beal Avenue, Ann Arbor, MI, Telephone: 313/741-2218); 1976.

[62] Cotton TA. Yucca Mountain and the nation's high-level nuclear waste. Nuclear waste story: Setting the stage. In: Uncertainty underground. Macfarlane A.M., Ewing R.C., eds. Cambridge, MA: Massachusetts Institute of Technology Press; 2006.

[63] DOE (US Department of Energy). Nuclear Waste Policy Act (Section 112), environmental assessment, Yucca Mountain Site, Nevada research and development area, Nevada. DOE/RW-0073. Washington, DC: Office of Civilian Radioactive Waste Management, US Department of Energy; 1986.

[64] Rechard RP. Initial performance assessment of the disposal of spent nuclear fuel and high level waste stored at Idaho National Engineering Laboratory. SAND93-2330/1/2, Vols. 1-2. Albuquerque, NM: Sandia National Laboratories; 1993.

[65] Rechard RP. Performance assessment of the direct disposal in unsaturated tuff of spent nuclear fuel and high-level waste owned by US Department of Energy. Volumes 1, 2, and 3. SAND94-2563/1,2,3. Albuquerque, NM: Sandia National Laboratories; 1995.

[66] Rechard RP. Update to assessment of direct disposal in unsaturated tuff of spent nuclear fuel and high-level waste owned by US Department of Energy. DOE/SNF/REP-015, INEEL/EXT-98-00185, SAND98-0795. Washington, DC: US Department of Energy; 1998.

[67] GAO (Government Accountability Office). Spent nuclear fuel: Options exist to further enhance security. GAO-03-426. Washington, DC: Government Accountability Office; 2003.

[68] Jenkins-Smith HC, Silva CL, Herron KG, Bonano EJ, Rechard RP. Designing a process for consent-based siting of used nuclear fuel facilities--analyis of public support. The Bridge, National Academy of Engineering. 2012;42(3):28-39.

[69] NWTRB (Nuclear Waste Technical Review Board). Fifth report to the US Congress and the US Secretary of Energy. Arlington, VA: Nuclear Waste Technical Review Board; 1992.

[70] NWTRB (Nuclear Waste Technical Review Board). Sixth report to the US Congress and the US Secretary of Energy. Arlington, VA:: Nuclear Waste Technical Review Board; 1992.

[71] NWTRB (Nuclear Waste Technical Review Board). Technical advancements and issues associated with the permanent disposal of high-activity wastes, lessons learned from Yucca Mountain and other programs. Arlington, VA: Nuclear Waste Technical Review Board; 2011.

[72] NWTRB (Nuclear Waste Technical Review Board). Report to the US Congress and the Secretary of Energy, January to December 2000. Arlington, VA: Nuclear Waste Technical Review Board; 2001.

[73] BSC (Bechtel SAIC Company). FY01 supplemental science and performance analyses, Volume 2: Performance analyses. TDR-MGR-PA-000001 REV 00 ICN 01. Las Vegas, NV: Bechtel SAIC Company; 2001.

[74] Paces JB, Roback RC. Chlorine-36 validation study at Yucca Mountain, Nevada. TDR-NBS-HS-000017. Denver, CO: US Geological Survey; 2006.

[75] NRC (US Nuclear Regulatory Commission). Disposal of high-level radioactive wastes in geologic repositories: Licensing procedures. Federal Register 1981;46(37):13971-87. US Nuclear Regulatory Commission.

[76] Rechard RP, Perry FV, Cotton TA. Site selection, characterization and research and development for spent nuclear fuel and high-level waste disposal. In: International High-Level Waste Radioactive Waste Management Conference, Albuquerque, NM, April 10-14, 2011. La Grange Park, IL: American Nuclear Society; 2011.

[77] US Senate. Current status of the Department of Energy's civilian nuclear waste activities: Hearings before the Committee on Energy and Natural Resources, United States Senate, January 29, February 4 and 5. S. Hrg. 100-230, Pt.1. http://www.archive.org/stream/nuclearwasteprog01unit/nuclearwasteprog01unit_djvu.txt. 1987.

[78] DOE (US Department of Energy). Analysis of the total system life cycle cost (TSLCC) of the Civilian Radioactive Waste Management Program. DOE/RW-0591: Office of Civilian Radioactive Waste Management, US Department of Energy; 2008.

[79] Webb S. In-drift natural convection and condensation. MDL-EBS-MD-000001 REV 00. Las Vegas, NV: Bechtel SAIC Company; 2004.

[80] SNL (Sandia National Laboratories). Mechanical assessment of degraded waste packages and drip shields subject to vibratory ground motion. MDL-WIS-AC-000001 REV 00. Las Vegas, NV: Sandia National Laboratories; 2007.

[81] Kicker DC. Drift degradation analysis. ANL-EBS-MD-000027 REV 03. Las Vegas, NV: Bechtel SAIC Company; 2004.

[82] CRWMS (Civilian Radioactive Waste Management System). Total system performance assessment of a geologic repository containing plutonium waste forms. A00000000-01717-5705-00011 REV 00. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 1996.

[83] CRWMS (Civilian Radioactive Waste Management System). Total system performance assessment sensitivity studies of US Department of Energy spent nuclear fuel. A00000000-01717-5705-00017 REV 01. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 1997.

[84] CRWMS (Civilian Radioactive Waste Management System). License application design selection report. B00000000-01717-4600-00123 REV 01 ICN 01. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 1999.

[85] McNeish JE, et al. Total system performance assessment for the site recommendation. TDR-WIS-PA-000001 REV 00, ICN 01. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 2000.

[86] DOE (US Department of Energy). Final environmental impact statement for a geologic repository for the disposal of spent nuclear fuel and high-level radioactive waste at Yucca Mountain, Nye County, Nevada. DOE/EIS-0250F. Las Vegas, NV: Office of Civilian Radioactive Waste Management, US Department of Energy; 2002.

[87] Jenkins-Smith HC, Silva CL, Herron KG, Rechard RP, Gupta K, Nowlin M, Ripberger J, Collins S, James M, Song G, Trousett S. Perspectives on nuclear waste management. FCRD-USED-2011-000334. Idaho Falls, ID: US Department of Energy Fuel Cycle Technology Program; 2011.

[88] Jenkins-Smith HC, Silva CL, Herron KG, Trousset SR, Rechard RP. Enhancing acceptability and credibility of a repository for spent nuclear fuel. The Bridge, National Academy of Engineering. 2012;42(2):49-58.

[89] Jenkins-Smith HC, Silva C. The role of risk perception and technical information in scientific debates over nuclear waste storage. Reliability Engineering and System Safety. 1998;59:107-22.

[90] NA/NRC (National Academies/National Research Council). The disposal of radioactive waste on land. Publication 519. Washington, DC: National Academy Press. National Academies/National Research Council; 1957.

[91] Pierce WG, Rich EI. Summary of rock salt deposits in the United States as possible storage sites for radioactive waste materials. Geologic Survey Bulletin 1148. Washington, DC: US Department of Interior, Geological Survey; 1962.

[92] AEC (US Atomic Energy Commission). Environmental statement: Radioactive waste repository Lyons, Kansas. WASH-1503. (On file in the SWCF as WPO 47929). Washington, DC: US Atomic Energy Commission; 1971.

[93] NRC (US Nuclear Regulatory Commission). Title 10—Atomic Energy Chapter I—Atomic Energy Commission Part 50—licensing of production and utilization facilities, siting of fuel reprocessing plants and related waste management facilities. Federal Register 1970;35(222):17530-3.

[94] Kubo AS, Rose DJ. Disposal of nuclear wastes. Science. 1973;182(4118):1205-11.

[95] Rasmussen NC. Reactor safety study: An assessment of accident risks in US commercial nuclear power plants. Vols. 1-8. NUREG 75/014, WASH 1400. Washington, DC: US Nuclear Regulatory Commission; 1975.

[96] Walker JS. The road to Yucca Mountain. Berkeley, CA: University of California Press; 2009.

[97] Winograd IJ. Near surface storage of solidified high-level radioactive wastes in thick (400-2,000 foot) unsaturated zones in the Southwest. Abstracts with Programs, Geological Society of America. 1972;4(7):708.

[98] Winograd IJ, Thordarson W. Hydrogeologic and hydrochemical framework, south-central Great Basin, Nevada-California, with special reference to the Nevada Test Site. Professional Paper 712-C. Washington, DC: US Geological Survey; 1975.

[99] Schneider KJ, Platt AM. High-level radioactive waste management alternatives. WASH-1297. Washington, DC: Atomic Energy Commission; 1974.

[100] AEC (US Atomic Energy Commission). Management of commercial high level and transuranic-contaminated radioactive waste. Draft environmental statement. WASH-1539. Washington, DC: US Atomic Energy Commission; 1974.

[101] Winograd IJ. Radioactive waste storage in the arid zone. EOS, Transactions, American Geophysical Union 1974;55(10):834-94.

[102] NRC (US Nuclear Regulatory Commission). 10 CFR Part 50, Appendix I: Numerical guides for design objectives and limiting conditions for operation to meet the criterion 'as low as practicable' for radioactive material in light-water-cooled nuclear power reactor effluents. Federal Register 1975;40(87):19442-3.

[103] Morrison JA. State politicians once courted nuclear waste. Las Vegas Review-Journal, March 24, 2002.

[104] EPA (US Environmental Protection Agency). 40 CFR Part 260: Environmental radiation protection standards for high-level radioactive wastes: Advance notice of proposed rulemaking. Federal Register. 1976;41(235):53363.

[105] Cranwell RM, Guzowski RV, Campbell JE, Ortiz NR. Risk methodology for geologic disposal of radioactive waste: Scenario selection procedure. SAND80-1429, NUREG/CR-1667. Albuquerque, NM: Sandia National Laboratories; 1990.

[106] ERDA (Energy Research and Development Administration). Alternatives for managing waste from reactors and post-fission operation in the LWR fuel cycle. ERDA-76-43. Washington, DC: Energy Research and Development Administration; 1976.

[107] Ewing RC, Tierney MS, Konikow LF, Rechard RP. Performance assessment of nuclear waste repositories: A dialogue on their value and limitations. Risk Analysis. 1999;19(5):933-57.

[108] McKelvey V. Major assets and liabilities of the Nevada Test Site as a high-level radioactive waste repository. Letter from Dr. V. McKelvey (USGS) to R.W. Roberts (US Energy Research and Development Administration), July 9, 1976, with enclosure: Table 1. Assets and liabilities of Nevada Test Site as potential high-level radioactive waste repository. 1976.

[109] Lappin AR, Cuderman JF. Eleana Argillite—Nevada Test Site, National Waste Terminal Storage Program progress report for period October 1, 1976 to September 30, 1977. Report Y/OWI-9. Oak Ridge, TN: Office of Waste Isolation, Union Carbide Corporation; 1978. p. 223-30.

[110] Patrick W. Spent fuel test—climax: An evaluation of the technical feasibility of geologic storage of spent nuclear fuel in granite, final report. UCRL-53702. Livermore, CA: Lawrence Livermore National Laboratory; 1986.

[111] Smith T. Risk and safety analyses for the disposal of alpha-contaminated waste in INEL. CONF-820845. In: Proceedings of Alpha-Contaminated Waste Management Workshop, Gaithersburg, MD, August 10-13, 1982. Oak Ridge, TN: Oak Ridge National Laboratory; 1982, p. 47-58.

[112] Lynch RW, Hunter RL, Anderson DR, Bingham FW, Covan JM, Hohnstrieter GF, Hunter TO, Klett RD, Ryder EE, Sanders TL, Weart WD. Deep geologic disposal in the United States: The Waste Isolation Pilot Plant and Yucca Mountain Projects. SAND90-1656. Albuquerque, NM: Sandia National Laboratories; 1991.

[113] EPA (US Environmental Protection Agency). Environmental protection criteria for radioactive wastes: Announcement of public forum. Federal Register 1978;43(10):2223.

[114] EPA (US Environmental Protection Agency). Criteria for radioactive wastes; invitation for comment: Environmental protection. Federal Register 1978;43(221):53262-8.

[115] NRC (US Nuclear Regulatory Commission). Licensing procedures for geologic repositories for high-level radioactive wastes. Federal Register 1978;43(223):53869-70.

[116] IRG (Interagency Review Group). Report to the President by the Interagency Review Group on Nuclear Waste Management. TID-29442. Washington, DC: US Department of Energy; 1979.

[117] DOE (US Department of Energy). Bibliography of the published reports, papers, and articles on the Nevada nuclear waste storage investigations. NVO-196-24 (Rev. 5). Las Vegas, NV: Nevada Operations Office, US Department of Energy; 1985.

[118] Spengler RW, Muller DC, Livermore RB. Preliminary report on the geology and geophysics of drill hole UE25a-1, Yucca Mountain, Nevada Test Site. Open-File Report 79-1244. Denver, CO: US Geological Survey; 1979.

[119] Lomenick TF. The siting record: An account of the programs of federal agencies and events that have led to the selection of a potential site for a geologic repository for high-level radioactive waste. ORNL-TM-12940. Oak Ridge, TN: Oak Ridge National Laboratory; 1996.

[120] Boardman CR, Knutson CF. Preliminary evaluation of 30 potential granite rock sites for a radioactive waste storage facility in southern Nevada. Livermore, CA: Lawrence Livermore Laboratory; 1978.

[121] Tyler LD, Zimmerman RM, Langkopf BS, Johnstone JK, Erdal BR, Friedman AM. Field experiment program for tuff in G-Tunnel. In: 1980 National Waste Terminal Storage Program Information Meeting, Columbus, OH, December 9-11, 1980. Columbus, OH: Office of Nuclear Waste Isolation, Battelle Memorial Institute; 1980.

[122] Bredehoeft JD, England AW, Stewart DB, Trask NJ, Winograd IJ. Geologic disposal of high-level radioactive waste: Earth-science perspectives. US Geological Survey. 1978;Circular 779.

[123] NA/NRC (National Academies/National Research Council). Geological criteria for repositories for high-level radioactive wastes. Washington, DC: National Academy Press; 1978.

[124] NRC (US Nuclear Regulatory Commission). Waste confidence decision. Federal Register 1984;49(171):34658-95.

[125] NRC (US Nuclear Regulatory Commission). Disposal of high-level radioactive wastes in geologic repositories: Licensing procedures. Federal Register 1979;44(234):70408-35.

[126] Johnstone JK, Wolfsberg K. Evaluation of tuff as a medium for a nuclear waste repository: Interim status report on the properties of tuff. SAND80-1464. Albuquerque, NM: Sandia National Laboratories; 1980.

[127] Crowe BM, Sargent KA. Major-element geochemistry of the Silent Canyon-Black Mountain Peralkaline Volcanic Centers, northwestern Nevada Test Site: Applications to an assessment of renewed volcanism. Open-File Report 79-926. Denver, CO: US Geological Survey; 1979.

[128] Pub. L. 96-368. West Valley Demonstration Project Act of 1980. (94 Stat. 1347; 42 U.S.C. 2021 et seq.). 1980.

[129] DOE (US Department of Energy). Final environmental impact statement, management of commercially generated radioactive waste. DOE/EIS-0046F. Washington, DC: US Department of Energy; 1980.

[130] Crowe BM, Carr WJ. Preliminary assessment of the risk of volcanism at a proposed nuclear waste repository in the Southern Great Basin. Open-File Report 80-357. Denver, CO: US Department of the Interior, Geological Survey; 1980.

[131] Spaulding WG. Vegetation and climates of the last 45,000 years in the vicinity of the Nevada Test Site, south-central Nevada. Professional Paper 1329. Washington, DC: US Geological Survey; 1985.

[132] Spengler RW, Byers J, R.M., Warner JW. Stratigraphy and structure of volcanic rocks in drill hole USW-G1, Yucca Mountain, Nye County, Nevada. Open-File Report 81-1349. Denver, CO: US Geological Survey; 1981.

[133] Winograd IJ, Doty GC. Paleohydrology of the Southern Great Basin with special reference to water table fluctuations beneath the Nevada Test Site during the late (?) Pleistocene. Open File Report 80-569. Denver, CO: US Geological Survey; 1980.

[134] Rush FE, Thordarson W, Bruckheimer L. Geohydrologic and drill-hole data for test well USW H-1, adjacent to Nevada Test Site, Nye County, Nevada. Open-File Report 83-141. Denver, CO: US Geological Survey; 1983.

[135] Duncan JE, House PA, Wright GW. Spent fuel handling system for a geologic storage test at the Nevada Test Site. In: Proceedings of the American Nuclear Society, Las Vegas, NV, June, 1980. La Grange Park, IL: American Nuclear Society; 1980.

[136] Swadley WC, Hoover DL. Geology of fault trenches in Crater Flat, Nye County, Nevada. Open-File Report 83-535. Denver, CO: US Department of the Interior, Geological Survey; 1983.

[137] Winograd IJ. Radioactive waste disposal in thick unsaturated zones. Science. 1981;212(4502):1457-64.

[138] Hunter RL, Barr GE, Bingham FW. Preliminary scenarios for consequence assessments of radioactive waste repositories at the Nevada Test Site. SAND82-0426. Albuquerque, NM: Sandia National Laboratories; 1982.

[139] IAEA (International Atomic Energy Agency). Safety assessment for the underground disposal of radioactive wastes. Safety Series No. 56. Vienna, Austria: International Atomic Energy Agency; 1981.

[140] Campbell JE, Cranwell RM. Performance assessment of radioactive waste repositories. Science 1988;239(4846):1389-92.

[141] OTA (Office of Technology Assessment). Managing commercial high-level radioactive waste. Washington, DC: Office of Technology Assessment. US Government Printing Office; 1982.

[142] EPA (US Environmental Protection Agency). 40 CFR Part 191: Environmental radiation protection standards for the management and disposal of spent nuclear fuel, high-level and transuranic radioactive wastes; proposed rule. Federal Register. 1982;47(250):58196-206. US Environmental Protection Agency.

[143] Carr WJ. Volcano-Tectonic history of Crater Flat, southwestern Nevada, as suggested by new evidence from drill hole USW-VH1 and vicinity. Open-File Report 82-457. Denver, CO: US Geological Survey; 1982.

[144] Sinnock S, Easterling RG. Empirically determined uncertainty in potassium-argon ages for Plio-Pleistocene basalts from Crater Flat, Nye County, Nevada. SAND 82-2441. Albuquerque, NM: Sandia National Laboratories; 1982.

[145] Sass JH, Lachenbruch AH. Preliminary interpretation of thermal data from the Nevada Test Site. Open-File Report 82-973. Denver, CO: US Geological Survey; 1982.

[146] Waddell RK. Two-dimensional, steady-state model of ground-water flow, Nevada Test Site and vicinity, Nevada-California. Water-Resources Investigations Report 82-4085. Denver, CO: US Geological Survey; 1982.

[147] Gregg DW, O'Neal WC. Initial specifications for nuclear waste package external dimensions and materials. UCID-19926. Livermore, CA: Lawrence Livermore National Laboratory; 1983.

[148] Roseboom EH. Disposal of high-level nuclear waste above the water table in arid regions. Circular 903. Denver, CO: US Department of the Interior, Geological Survey; 1983.

[149] Sinnock S, Fernandez JA. Summary and conclusions of the NNWSI area-to-location screening activity. SAND82-0650; NVO-247. Las Vegas, NV: Nevada Operations Office, US Department of Energy; 1982.

[150] DOE (US Department of Energy). Project management plan for exploratory shaft at Yucca Mountain, Nevada nuclear waste storage investigation. NVO-255. Las Vegas, NV: Nevada Operations Office, US Department of Energy; 1983.

[151] Scully LW, Rothman AJ. Repository and engineering barriers design. DOE/NWTS-30. In: 1982 National Waste Terminal Storage Program Information Meeting, Las Vegas, NV, December 14-16, 1982. Las Vegas, NV: US Department of Energy; 1982.

[152] Rothman AJ. Development of waste packages for tuff. DOE/NWTS-30. In: 1982 National Waste Terminal Storage Program Information Meeting, Las Vegas, NV, December 14-16, 1982. Las Vegas, NV: US Department of Energy; 1982.

[153] NRC (US Nuclear Regulatory Commission). 10 CFR Part 60: Disposal of high-level radioactive wastes in geologic repositories, technical vriteria; final rule. Federal Register 1983;48(120):28194-230. US Nuclear Regulatory Commission.

[154] DOE (US Department of Energy). 10 CFR Part 960: Nuclear Waste Policy Act of 1982; proposed general guidelines for recommendation of sites for nuclear waste repositories. Federal Register 1983;48(26):40638-82.

[155] DOE (US Department of Energy). 10 CFR Part 961: Standard contract for disposal of spent nuclear fuel and/or high-level radioactive waste; final rule. Federal Register 1983;48:16599.

[156] McCright RD. An annotated history of container candidate material selection. Livermore, CA: Lawrence Livermore National Laboratory; 1988.

[157] Scott RB, Spengler RW, Diehl S, Lappin AR, Chornack MP. Geologic character of tuffs in the unsaturated zone of Yucca Mountain, Southern Nevada. In: Role of the Unsaturated Zone in Radioactive and Hazardous Waste Disposal. Mercer J.W., Rao P.S.C., Marine I.W., eds. Ann Arbor, MI: Ann Arbor Science; 1983. p. 289-335.

[158] Johnstone JK, Peters RR, Gnirk PF. Unit evaluation at Yucca Mountain, Nevada Test Site: Summary report and recommendations. SAND83-0372. Albuquerque, NM: Sandia National Laboratories; 1984.

[159] Hunter RL, Barr GE, Bingham FW. Scenarios for consequence assessments of radioactive-waste repositories at Yucca Mountain. SAND82-1277. Albuquerque, NM: Sandia National Laboratories; 1983.

[160] Zimmerman RM, Finley RE. Summary of geomechanical measurements taken in and around the G-Tunnel Underground Facility, NTS. SAND86-1015. Albuquerque, NM: Sandia National Laboratories; 1987.

[161] Ogard AE, Wolfsberg K, Daniels WR, Kerrisk JR, Rundberg RS, Thomas KW. Retardation of radionuclides by rock units along the path to the accessible environment. LA-UR-83-1953. In: Materials Research Society Annual Meeting, Boston, MA, November 13-18, 1983. Materials Research Society; 1983.

[162] Scully LW, Hunter TO. NNWSI repository design approach. SAND84-0104C. In: 1983 Civilian Radioactive Waste Management Information Meeting, Washington, DC, December 12-15, 1983. Washington, DC: US Department of Energy; 1983.

[163] Russel EW, McCright RD, O'Neal WC. Containment barrier metals for high-level waste packages in a tuff repository. UCRL-53449. Livermore, CA: Lawrence Livermore National Laboratory; 1983.

[164] Oversby VM. Performance testing of waste forms in a tuff environment. In: 1983 Civilian Radioactive Waste Management Information Meeting, Washington, DC, December 12-15m 1873. Washington, DC: US Department of Energy; 1983, p. 265-9.

[165] Geldon AL. Results and interpretation of preliminary aquifer tests in boreholes UE-25c#1, UE-25c#2, and UE-25c#3, Yucca Mountain, Nye County, Nevada. Water-Resources Investigation Report 94-4177. Denver, CO: US Geological Survey; 1996.

[166] SAB (Science Advisory Board). Report on the review of proposed environmental standards for the management and disposal of spent nuclear fuel, high-level and transuranic radioactive wastes (40 CFR 191). Washington, DC: US Environ¬mental Protection Agency, High-Level Radioactive Waste Disposal Subcommittee, Science Advisory Board; 1984.

[167] McCracken. Nuclear waste and Nye County: Part I. Pahrump Valley Times, April 30, 2004.

[168] Cochran JR, Beyeler WE, Brosseau DA, Brush LH, Brown TJ, Crowe BM, Conrad SH, Davis PA, Ehrhorn T, Feeney T, Fogleman B, Gallegos DP, Haaker R, Kalinina E, Price LL, Thomas DP, Wirth S. Compliance assessment document for the transuranic wastes in the greater confinement disposal boreholes at the Nevada Test Site, Volume 2: Performance assessment. SAND2001-2977. Albuquerque, NM: Sandia National Laboratories; 2001.

[169] DOE (US Department of Energy). 10 CFR Part 960: Nuclear Waste Policy Act; general guidelines for the recommendation of sites for nuclear waste repositories. Federal Register 1984;49(236):47714-70.

[170] Merkhofer MW, Keeney RL. A multiattribute utility analysis of alternative sites for the disposal of nuclear waste. Risk Analysis 1987;7(2):173-94.

[171] Scott RB, Bonk J. Preliminary geologic map of Yucca Mountain, Nye County, Nevada, with geologic sections. Open-File Report 84-494. Denver, CO: US Geological Survey; 1984.

[172] Montazer P, Wilson WE. Conceptual hydrologic model of flow in the unsaturated zone, Yucca Mountain, Nevada. Water-Resources Investigations Report 84-4345. Lakewood, CO: US Geological Survey; 1984.

[173] Czarnecki JB, Waddell RK. Finite-element simulation of ground-water flow in the vicinity of Yucca Mountain, Nevada-California. Water-Resources Investigations Report 84-4349. Denver, CO: US Geological Survey; 1984.

[174] Flint AL, Flint LE, Bodvarsson GS, Kwicklis EM, Fabryka-Martin J. Evolution of the conceptual model of unsaturated zone hydrology at Yucca Mountain, Nevada. Journal of Hydrology. 2001;247(1-2):1-30.

[175] Hockman JN, O’Neal WC. Thermal modeling of nuclear waste package designs for disposal in tuff. In: ANS/ASME Waste Management ’84 Meeting, Tucson, AZ, March 11-15, 1984. 1984, vol. vol. 1, p. 441-8.

[176] Pub. L. 98-616. The Hazardous and Solid Waste Amendments of 1984. (98 Stat. 3221). 1984.

[177] Mansure AJ, Ortiz TS. Preliminary evaluation of the subsurface area available for a potential nuclear waste repository at Yucca Mountain. SAND 84-0175. Albuquerque, NM: Sandia National Laboratories; 1984.

[178] Kerrisk JF. Solubility limits on radionuclide dissolution at a Yucca Mountain repository. LA-9995-MS. Los Alamos, NM: Los Alamos National Laboratory; 1984.

[179] Ogard AE, Kerrisk JF. Groundwater chemistry along flow paths between a proposed repository site and the accessible environment. LA-10188-MS. Los Alamos, NM: Los Alamos National Laboratory; 1984.

[180] Rothman AJ. Potential corrosion and degradation mechanisms of Zircaloy cladding on spent nuclear fuel in a tuff repository. UCID-20172. Livermore, CA: Lawrence Livermore National Laboratory; 1984.

[181] Jackson JL. Nevada nuclear waste storage investigations preliminary repository concepts report. SAND83-1877. Albuquerque, NM: Sandia National Laboratories; 1984.

[182] Ross B. Disruptive scenarios for high-level waste repository at Yucca Mountain, Nevada. Disposal Safety Incorporated; 1985.

[183] Carlos BA. Minerals in fractures of the unsaturated zone from drill core USW G-4, Yucca Mountain, Nye County, Nevada. LA-l 0415-MS. Los Alamos, NM: Los Alamos National Laboratory; 1985.

[184] MacDougall HR, Scully LW, Tillerson JR. Two-stage repository development at Yucca Mountain: An engineering feasibility study. SAND 85-1351 (Rev. 1). Albuquerque, NM: Sandia National Laboratories; 1985.

[185] WEC (Westinghouse Electric Corporation). Phase 1 study of metallic cask systems for spent fuel management from reactor to repository. WTSD-TME-085, Draft 2: Westinghouse Electric Corporation, Tennessee Valley Authority, Florida Power & Light; 1985.

[186] Ortiz TS, Williams RL, Nimick FB, Whitter BC, South DL. A three-dimensional model of reference thermal/mechanical and hydrological stratigraphy at Yucca Mountain, southern Nevada. SAND84-1076. Albuquerque, NM: Sandia National Laboratories; 1985.

[187] Pub. L. 99-240. Low-Level Radioactive Waste Policy Amendments Act of 1985. (99 Stat. 1842). 1986.

[188] NRC (US Nuclear Regulatory Commission). Disposal of high-level radioactive wastes in geologic repositories: Amendments to licensing procedures. Federal Register 1986;51(146):27158-17165.

[189] NRC (US Nuclear Regulatory Commission). 10 CFR Part 50: Safety goals for the operations of nuclear power plants; policy statement. Federal Register 1986;51(149):28044-9.

[190] DOE (US Department of Energy). Recommendation by the Secretary of Energy of candidate sites for site characterization for the first radioactive-waste repository. DOE/S-0048. Washington, DC: US Department of Energy; 1986.

[191] DOE (US Department of Energy). Civilian Radioactive Waste Management Program Plan, revision 3. Appendix B: History of the Civilian Radioactive Waste Management Program. Washington, DC: US Department of Energy; 2000.

[192] Carter LJ. Yucca Mountain and the nation’s high-level nuclear waste. The path to Yucca Mountain and beyond. In: Uncertainty underground. Macfarlane A.M., Ewing R.C., eds. Cambridge, MA: Massachusetts Institute of Technology Press; 2006.

[193] CRWMS (Civilian Radioactive Waste Management System). Probabilistic seismic hazard analyses for fault displacement and vibratory ground motion at Yucca Mountain, Nevada. Milestone SP321M3. Three volumes. Oakland, CA: Civilian Radioactive Waste Management System Management and Operating Contractor; 1998.

[194] Rulon J, Bodvarsson GS, Montazer P. Preliminary numerical simulations of groundwater flow in the unsaturated zone, Yucca Mountain, Nevada. LBL-20553. Berkeley, CA: Lawrence Berkeley Laboratory; 1986.

[195] Lin YT, Tierney MS, Sinnock S. Preliminary estimates of groundwater travel time and radionuclide transport at Yucca Mountain repository site. SAND85-2701. Albuquerque, NM: Sandia National Laboratories; 1986.

[196] Colglazier EW. Evidential, ethical, and policy disputes: Admissible evidence in radioactive waste management. In: Acceptable evidence: Science and values in hazard management. Mayo D.G., Hollander R.D., eds. New York, NY: Oxford University Press; 1991.

[197] SNL (Sandia National Laboratories). Particle tracking model and abstraction of transport process. MDL-NBS-HS-000020 REV 02 AD 02. Las Vegas, NV: Sandia National Laboratories 2008.

[198] DOE (US Department of Energy). Monitored retrievable storage submission to Congress. DOE/RW--0035/1-Rev.1, Volumes 1-2. Washington, DC: Office of Civilian Radioactive Waste Management, US Department of Energy; 1987.

[199] Huyakorn PS, White Jr. HO, Panday S. STAFF2D Version 3.1: A two-dimensional finite element code for simulating fluid flow and transport of radionuclides in fractured porous media with water table boundary conditions. Herndon, VA: HydroGeoLogic, Inc.; 1991.

[200] Barr GE, Miller WB. Simple models of the saturated zone at Yucca Mountain. SAND87-0112. Albuquerque, NM: Sandia National Laboratories; 1987.

[201] Norris AE, Wolfsberg K, Gifford SK, Bentley HW, Elmore D. Infiltration at Yucca Mountain, Nevada, traced by 36Cl. In: International Symposium on Accelerator Mass Spectrometry, Ontario, CA, April 27, 1987. 1987.

[202] Wilson CN, Oversby VM. Summary of results from the series 2 and series 3 NNWSI (Nevada nuclear waste storage investigations) bare fuel dissolution tests. In: Symposium on the Scientific Basis for Nuclear Waste Management XI, Boston, MA, November 30-December 3, 1987. Pittsburg, PA: Materials Research Society; 1987, vol. 112, p. 473.

[203] MacDougall HR, Scully LW, Tillerson JR. Site charaterization plan: Conceptual design report, Volumes 1-6. SAND84-2641/Vol. 1-6. Albuquerque, NM: Sandia National Laboratories; 1987.

[204] Rundberg RS. Assessment report on the kinetics of radionuclide adsorption on Yucca Mountain tuff. LA-11026-MS. Los Alamos, NM: Los Alamos National Laboratory; 1987.

[205] Fuentes HR, Polzer Wl, Gruber J, Lauctes B, Essington EH. Preliminary report on sorption modeling. LA-10952-MS. Los Alamos, NM: Los Alamos National Laboratory; 1987.

[206] Thomas KW. Summary of sorption measurements performed with Yucca Mountain, Nevada, tuff samples and water from Well J-13. LA-10960-MS. Los Alamos, NM: Los Alamos National Laboratory; 1987.

[207] Weinberg A. Statement in U.S. Congress, Nuclear Waste Program, hearings before the Committee on Energy and Natural Resources, U.S. Senate, first session, Part 2, pp. 2-3. Washington DC: US Government Printing Office; 1987.

[208] DOE (US Department of Energy). Site characterization plan: Yucca Mountain Site, Nevada research and development area, Nevada: Consultation draft, Nuclear Waste Policy Act. DOE/RW-0160-Vol.1 through Vol. 9. Washington, DC: Office of Civilian Radioactive Waste Management, US Department of Energy; 1988.

[209] DOE (US Department of Energy). Site characterization plan: Yucca Mountain Site, Nevada research and development area, Nevada. DOE/RW-0199-Vol.1 through Vol. 7. Washington, DC: Office of Civilian Radioactive Waste Management, US Department of Energy; 1988.

[210] Guzowski RV. Representative disruptive scenarios for use in development and demonstration of a performance assessment methodology for unsaturated tuff. SAND86-7170, NUREG/CR-4770. Albuquerque, NM: Sandia National Laboratories; 1988.

[211] Abrajano TA, Bates JK, Gerding TJ, Ebert WL. The reaction of glass during Gamma irradiation in a saturated tuff environment: Part 3, Long-term experiments at 1 x 10 to the 4th rad/hour. ANL-88-14. Chicago, IL: Argonne National Laboratory; 1988.

[212] Viniman DT, Bish DL, Cipera S. A preliminary comparison of mineral deposits in faults Near Yucca Mountain, Nevada with possible analogs. LA-11289-MS. Los Alamos, NM: Los Alamos National Laboratory; 1988.

[213] DOE (US Department of Energy). Site characterization plan overview: Yucca Mountain Site, Nevada research and development area, Nevada. DOE/RW-0198. Washington, DC: Office of Civilian Radioactive Waste Management, US Department of Energy; 1988.

[214] Szymanski JS. Conceptual considerations of the Death Valley groundwater system with special emphasis on the adequacy of this system to accommodate the high-level nuclear waste repository. Draft DOE internal report. Las Vegas, NV: Yucca Mountain Project Office, US Department of Energy; 1989.

[215] Anonymous. Feasibility of disposal of high-level radioactive wastes into the seabed, Vol. 1: Overview of research and conclusions. Paris, France: Organisation for Economic Co-operation and Development, Nuclear Energy Agency; 1988.

[216] NRC (US Nuclear Regulatory Commission). 10 CFR Part 2: Submission and management of records and documents related to the licensing of a geologic repository for the disposal of high-level radioactive waste. Federal Register 1989;54:14925-44.

[217] NRC (US Nuclear Regulatory Commission). Disposal of high-level radioactive wastes in geologic repositories; final rule. Federal Register 1989;54(126):27871- 2.

[218] NRC (US Nuclear Regulatory Commission). NRC staff site characterization analysis of the Department of Energy's Site Characterization Plan, Yucca Mountain site, Nevada. Washington, DC: US Nuclear Regulatory Commission; 1989.

[219] SNL (Sandia National Laboratories). General corrosion and localized corrosion of waste package outer barrier. ANL-EBS-MD-000003 REV 03. Las Vegas, NV: Sandia National Laboratories; 2007.

[220] Hobart DE, Morris DE, Palmer PD, Newton TW. Formation, characterization, and stability of plutonium (IV) colloid: A progress report. In: Nuclear Waste Isolation in the Unsaturated Zone: FOCUS ’89, Las Vegas, NV, September 18-19, 1989. Las Vegas, NV: US Department of Energy; 1989.

[221] NWTRB (Nuclear Waste Technical Review Board). Report to the US Congress and the US Secretary of Energy, January to December 1993. Arlington, VA: Nuclear Waste Technical Review Board; 1994.

[222] Crowe B, Harrington C, Turrin B, Champion D, Wells S, Perry F, McFadden L, Renault C. Volcanic hazard studies of the Yucca Mountain Project. Proceedings of Waste Management ’89: 15th International Waste Management Symposium and Conference, Tucson, AZ, 26 February – 2 March 1989. Tucson, AZ: Arizona Board of Regents; 1989.

[223] NWTRB (Nuclear Waste Technical Review Board). Third report to the US Congress and the US Secretary of Energy. Arlington, VA: Nuclear Waste Technical Review Board; 1991.

[224] Bates JK, Tani BW, Veleckis E. Identification of secondary phases formed during unsaturated reaction of UO2 with EJ-13 water. In: Meeting, Boston, MA, November 27-December 2, 1989. Materials Research Society; 1989.

[225] Eslinger PW, Doctor PG, Elwood DM, Engel DW, Freshley MD, Liebetrau AM, Reimus PW, Strange DL, Tanner JE, Van Luik AE. Preliminary postclosure risk assessment, Yucca Mountain, Nevada, candidate repository site. In: Proceedings of the Symposium on Safety Assessment of Radioactive Waste Repositories, 9-13 October 1989, Paris, France. OECD/Nuclear Energy Agency, the Commission of the European Communities (CEC, Brussels), and the International Atomic Energy Agency (IAEA) in cooperation with the French Atomic Energy Commission (CEA); 1990, p. 221-8.

[226] Bonano EJ, Davis PA, Shipers LR, Brinster KF, Beyeler WE, Updegraff CD, Shepherd ER, Tilton LM, Wahi KK. Demonstration of a performance assessment methodology for high-level radioactive waste disposal in basalt formations. NUREG/CR-4759, SAND86-2325. Albuquerque, NM: Sandia National Laboratories; 1989.

[227] Daling PM, Van Luik AE, Rhoads RE. Preliminary characterization of waste management system risks: Literature-based analysis. In: High-Level Radioactive Waste Management, Proceedings of the International Topical Meeting, April 8-12, 1990, Las Vegas, NV. New York, NY: American Society of Civil Engineers; 1990., vol. 2, p. 1328-33.

[228] Marietta MG, Bertram-Howery SG, Anderson DR, Brinster KF, Guzowski RV, Iuzzolino H, Rechard RP. Performance assessment methodology demonstration: Methodology development for evaluating compliance with EPA 40 CFR 191, Subpart B, for the Waste Isolation Pilot Plant. SAND89-2027. Albuquerque, NM: Sandia National Laboratories; 1989.

[229] NRC (US Nuclear Regulatory Commission). NRC high-level radioactive waste program annual progress report: Fiscal year 1996. NUREG/CR-6513, No. 1. Washington, DC: US Nuclear Regulatory Commission; 1997.

[230] NRC (US Nuclear Regulatory Commission). Waste confidence decision review. Federal Register 1990;55(187):38474- 514.

[231] NA/NRC (National Academies/National Research Council). Ground water at Yucca Mountain—how high can it rise? Washington, DC: National Academy Press; 1992.

[232] Meijer A. Yucca Mountain Project far-field sorption studies and data needs. LA-11671-MS. Los Alamos, NM: Los Alamos National Laboratory; 1990.

[233] Pruess K, Wang JSY, Tsang YW. On thermohydrologic conditions near high-level nuclear wastes emplaced in partially saturated fractured tuff: 2. Effective continuum approximation. Water Resources Research 1990;26(6):1249-61.

[234] Norris AE, Wolfsberg K, Gifford SK, Bentley HW, Elmore D. The use of chlorine isotope measurements to trace water movements at Yucca Mountain. In: Topical Meeting on Nuclear Waste Isolation in the Unsaturated Zone, Focus '89. La Grange Park, IL: American Nuclear Society; 1990.

[235] Whitfield J, M.W., Thordarson W, Hammermeister DP. Drilling and geohydrologic data for test hole USW UZ-1, Yucca Mountain, Nye County, Nevada. Open-File Report 90-354. Denver, CO: US Geological Survey; 1990.

[236] Wells SG, McFadden LD, Renault CE, Crowe BM. Geomorphic assessment of the late quaternary volcanism in the Yucca Mountain area, southern Nevada: Implications for the proposed high-level radioactive waste repository. Geology. 1990;18(6):549-53.

[237] EPRI (Electric Power Research Institute). Demonstration of a risk-based approach to high-level waste repository evaluation. NP-7057. Palo Alto, CA: Electric Power Research Institute; 1990.

[238] NWTRB (Nuclear Waste Technical Review Board). First report to the US Congress and the US Secretary of Energy. Arlington, VA: Nuclear Waste Technical Review Board; 1990.

[239] ICRP (International Commission on Radiological Protection). ICRP publication 60: 1990 recommendations of the International Commission on Radiological Protection. Annals of the ICRP 1991;21(1-3).

[240] Broad WJ. …Trouble. New York Times Magazine, November 18, 1990.

[241] Bertram-Howery SG, Marietta MG, Rechard RP, Swift PN, Anderson DR, Baker BL, Bean J, J.E., Beyeler W, Brinster KF, Guzowski RV, Helton JC, McCurley RD, Rudeen DK, Schreiber JD, Vaughn P. Preliminary comparison with 40 CFR 191, Subpart B, for the Waste Isolation Pilot Plant. SAND90-2347. Albuquerque, NM: Sandia National Laboratories; 1990.

[242] NWTRB (Nuclear Waste Technical Review Board). Fourth report to the US Congress and the US Secretary of Energy. Arlington, VA: Nuclear Waste Technical Review Board; 1991.

[243] US Courts. State of Idaho, Petitioner, Shoshone-Bannock Tribes, Intervenors, v. US Department of Energy, Respondent, Public Service Company of Colorado, Intervenor. United States Court of Appeals, Ninth Circuit. Decided September 20, 1991. Federal Reporter, 2nd Series 1991;945:295.

[244] Carrigan CR, King GCP, Barr GE, Bixler NE. Potential for water-table excursions induced by seismic events at Yucca Mountain. Geology 1991;19(12):1157-60.

[245] Stuckless JS, Peterman ZE, Muhs DR. U and Sr isotopes in ground water and calcite, Yucca Mountain, Nevada: Evidence against upwelling water. Science 1991;254:551-4.

[246] Turrin BD, Champion DE, Fleck RJ. $_{40}$Ar/$_{39}$Ar age of the Lathrop Wells Volcanic Center, Yucca Mountain, Nevada. Science 1991;253(5020):654-7.

[247] Barnard RW, Dockery HA. Nominal configuration, hydrogeologic parameters and calculational results. Volume 1 of technical summary of the performance assessment calculational exercises for 1990 (PACE-90). SAND90-2726. Albuquerque, NM: Sandia National Laboratories; 1991.

[248] Gallegos DP. A performance assessment methodology for high-level radioactive waste disposal in unsaturated, fracture tuff. NUREG/CR-5701, SAND91-0539. Albuquerque, NM: Sandia National Laboratories; 1991.

[249] Helton JC, Garner JW, Marietta MG, Rechard RP, Rudeen DK, Swift PN. Uncertainty and sensitivity analysis results obtained in a preliminary performance assessment for the Waste Isolation Pilot Plant. Nuclear Science and Engineering 1993;114(4):286-331.

[250] NRC (US Nuclear Regulatory Commission). Issue resolution status report, key technical issue: Evolution of the near-field environment. Revision 3. Washington, DC: Division of Waste Management, Office of Nuclear Material Safety and Safeguards, US Nuclear Regulatory Commission; 2000.

[251] Eisenberg NA, Lee MP, McCartin TJ, McConnell KI, Thaggard M, Campbell AC. Development of a performance assessment capability in the waste management programs of the US Nuclear Regulatory Commission. Risk Anal. 1999;19(5):847-76.

[252] Ahola M, Sagar B. Regional groundwater modeling of the saturated zone in the vicinity of Yucca Mountain, Nevada, Iterative performance assessment – Phase 2. NUREG/CR-5890. Washington, DC: US Nuclear Regulatory Commission; 1992.

[253] Pub. L. 102-486. Energy Policy Act of 1992. (106 Stat. 2776; 42 U.S.C. 13201 et seq.). 1992.

[254] Younker J, Andrews W, Fasano G, Herrington C, Mattson S, Murray R, Ballou L, Revelli M, DuCharme A, Shephard L, Dudley W, Hoxie D, Herbst R, Patera E, Judd B, Docka J, Rickertsen L. Report of early site suitability evaluation of the potential repository site at Yucca Mountain, Nevada. SAIC-91/8000. Las Vegas, NV: Technical and Management Support Services for DOE, Science Applications International Corporation; 1992.

[255] DOE (US Department of Energy). Notice of intent to prepare a programmatic EIS (PEIS) for the long-term storage and disposition of weapons-usable fissile materials. Federal Register 1994;59:31985-90.

[256] Gray W, Leider H, Steward S. Parametric study of LWR spent fuel dissolution kinetics. UCRL-JC-110160. Richland, WA: Pacific Northwest National Laboratory; 1992.

[257] Bates J, Bradley J, Teetsov A, Dradley C, Buchholtz ten Brink M. Colloid formation during waste form reaction: Implications for nuclear waste disposal. Science. 1992;256:649-51.

[258] Crowe BM, Valentine GA, Morley R, Perry FV. Recent progress in volcanism studies: Site characterization activities for the Yucca Mountain Site Characterization Project. Waste Management '92, International Waste Management Symposium and Conference, Tucson, Arizona, March 1-5, 1992. Tucson, AZ: Arizona Board of Regents; 1992.

[259] Gauthier JH, Wilson ML, Lauffer FC. Estimating the consequences of significant fracture flow at Yucca Mt high-level radioactive waste management. In: Proceedings of the Third Annual International Conference, Las Vegas, NV, April 12-16, 1992. La Grange Park, IL: American Nuclear Society; 1992 p. 891-8.

[260] EPRI (Electric Power Research Institute). Demonstration of a risk-based approach to high-level waste repository evaluation: Phase 2. TR-100384. Palo Alto, CA: Electric Power Research Institute; 1992.

[261] Applegate D. The mountain matters. In: Uncertainty underground, Yucca Mountain and the nation's high-level nuclear waste. Macfarlane A.M., Ewing R.C., eds. Cambridge, MA: Massachusetts Institute of Technology Press; 2006.

[262] Helton JC, Anderson DR, Baker BL, Bean JE, Berglund JW, Beyeler W, Economy K, Garner JW, Hora SC, Iuzzolino HJ, Knupp P, Marietta MG, Rath J, Rechard RP, Roache PJ, Rudeen DK, Salari K, Schreiber JD, Swift PN, Tierney MS, Vaughn P. Uncertainty and sensitivity analysis results obtained in the 1992 performance assessment for the Waste Isolation Pilot Plant. Reliability Engineering System Safety 1996;51(1):53-100.

[263] EPA (US Environmental Protection Agency). Criteria for the certification of compliance with environmental radiation protection standards for the management and disposal of spent nuclear fuel, high-level and transuranic radioactive wastes; advanced notice of proposed rulemaking. Federal Register 1993;58(27):8029-30.

[264] EPA (US Environmental Protection Agency). 40 CFR Part 191: Environmental radiation protection standards for the management and disposal of spent nuclear fuel, high-level and transuranic radioactive wastes, final rule. Federal Register. 1993;58(242):66398-416. US Environmental Protection Agency.

[265] Barr GE, Dunn E, Dockery H, Barnard R, Valentine G, Crowe B. Scenarios constructed for basaltic igneous activity at Yucca Mountain and vicinity. SAND91-1653. Albuquerque, NM: Sandia National Laboratories; 1993.

[266] Prudic DE, Harrill JR, Burbey TJ. Conceptual evaluation of regional ground-water flow in the Carbonate-Rock Province of the Great Basin, Nevada, Utah, and adjacent states. Open-File Report 93-170. Carson City, NV: US Geological Survey; 1993.

[267] Eslinger PW, Doremus LA, Engel DW, Miley TB, Murphy MT, Nichols WE, White MD, Langford DW, Ouderkirk SJ. Preliminary total-system analysis of a potential high-level nuclear waste repository at Yucca Mountain. PNL 8444. Richland, WA: Pacific Northwest National Laboratory; 1993.

[268] Wilder DG. Preliminary near-field environment report. UCRL-LR-107476. Two volumes. Livermore, CA: Lawrence Livermore National Laboratory; 1993.

[269] Buscheck TA, Nitao JJ. Repository-heat-driven hydrothermal flow at Yucca Mountain: Part 1. Modeling and analysis. Nuclear Technology 1993;104(3):418-48.

[270] NWTRB (Nuclear Waste Technical Review Board). Special report to the US Congress and the US Secretary of Energy. Arlington, VA: Nuclear Waste Technical Review Board; 1993.

[271] Price LL, Conrad SH, Zimmerman DA, Olague NE, Gaither KC, Cox WB, McCord JT, Harlan CP. Preliminary performance assessment of the greater confinement disposal facility at the Nevada Test Site, Volume 1: Executive summary, Volume 2: Technical discussion, Volume 3: Supporting details. SAND91-0047. Albuquerque, NM: Sandia National Laboratories 1993.

[272] NWTRB (Nuclear Waste Technical Review Board). Underground exploration and testing at Yucca Mountain—a report to Congress and the Secretary of Energy. Arlington, VA: Nuclear Waste Technical Review Board; 1993.

[273] NWTRB (Nuclear Waste Technical Review Board). Report to the US Congress and the Secretary of Energy, January to December 1996. Arlington, VA: Nuclear Waste Technical Review Board; 1997.

[274] DOE (US Department of Energy). Multi-purpose canister system evaluation. DOE/RW-0445. Washington, DC: US Department of Energy; 1994.

[275] DOE (US Department of Energy). Civilian radioactive waste management program plan. DOE/RW-0458, Vols.1-3. Washington, DC: Office of Civilian Radioactive Waste Management, US Department of Energy; 1994.

[276] Finn PA, Buck EC, Gong M, Hoh JC, Emery JW, Hafenrichter LD, Bates JK. Colloidal products and actinide species in leachate from spent nuclear fuel. Radiochimica Acta. 1994;66/67:197-203.

[277] Andrews RW, Dale TR, McNeish JA. Total system performance assessment - 1993: An evaluation of the potential Yucca Mountain Repository. B00000000-01717-2200-00099 REV 01. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor. INTERA, Inc.; 1994.

[278] Golder. RIP integrated probabilistic simulator for environmental systems, theory manual and user's guide. Redmond, WA: Golder Associates; 1998.

[279] Flint LE, Flint AL. Spatial distribution of potential near surface moisture flux at Yucca Mountain. In: Fifth Annual International Conference on High-Level Radioactive Waste Management, Las Vegas, NV, May 22-26, 1994. La Grange Park, IL: American Nuclear Society; 1994, p. 23522-2358.

[280] CRWMS (Civilian Radioactive Waste Management System). Controlled design assumption document (CDA). B00000000-01717-4600-00032 REV 00A. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 1994.

[281] Liu HH. Calibrated unsaturated zone properties. ANL-NBS-HS-000058, REV 00. Las Vegas, NV: Sandia National Laboratories; 2007.

[282] Baer TA, Price LL, Emery JN, Olague NE. Second performance assessment Iteration of the greater confinement disposal facility at the Nevada Test Site. SAND93-0089. Albuquerque, NM: Sandia National Laboratories 1994.

[283] Bowman CD, Venneri F. Underground supercriticality from plutonium and other fissile material. Science and Global Security. 1996;5(3):279-302.

[284] NWTRB (Nuclear Waste Technical Review Board). Report to the US Congress and the US Secretary of Energy, 1994 findings and recommendations. Arlington, VA: Nuclear Waste Technical Review Board; 1995.

[285] NRC (US Nuclear Regulatory Commission). Use of probabilistic risk assessment methods in nuclear regulatory activities; final policy statement. Federal Register 1995;60(158):42622-9.

[286] Conner CB, Hill BE. Three nonhomogeneous Poisson models for the probability of basaltic volcanism: Application to the Yucca Mountain region, Nevada. Journal of Geophysical Research 1995;100(B6):10 107–10 25.

[287] Ho C-H. Sensitivity in volcanic hazard assessment for the Yucca Mountain high-level nuclear waste repository site: The model and the data. Mathematical Geology. 1995;27(2):239-58.

[288] Pub. L. 104-46. Energy and Water Development Appropriations Act of 1996. 1996.

[289] DOE (US Department of Energy). Department of Energy final interpretation of nuclear waste acceptance issues. Federal Register 1995;60(85):21793-8.

[290] Wittwer C, Chen G, Bodvarsson GS, Chornack M, Flint A, Flint L, Kwicklis E, Spengler RW. Preliminary development of the LBL/USGS three-dimensional site-scale model of Yucca Mt., Nevada. LBL-37356. Berkeley, CA: Lawrence Berkeley Laboratory; 1995.

[291] NWTRB (Nuclear Waste Technical Review Board). Report to the US Congress and the US Secretary of Energy, 1995 findings and recommendations. Arlington, VA: Nuclear Waste Technical Review Board; 1996.

[292] Geldon AL, Umari AM, Earle JD, Fahy MF, Gemmell JM, Darnell J. Analysis of a multiple-well interference test in miocene tuffaceous rocks at the C-Hole Complex, May-June 1995, Yucca Mountain, Nye County, Nevada. Water-Resources Investigation Report 97-4166. Denver, CO: US Geological Survey; 1998.

[293] Flint LE, Flint AL. Shallow infiltration processes at Yucca Mountain, Nevada – neutron logging data 1984-93. Water-Resources Investigations Report 95-4035. Denver, Co: US Geological Survey; 1995.

[294] NA/NRC (National Academies/National Research Council). Technical bases for Yucca Mountain standards. Washington, DC: National Academy Press; 1995.

[295] Taubes G. News & comment: Blowup at Yucca Mountain. Science 1995;268(5219):1826-39.

[296] Coppersmith KJ, Perman RC, Nesbit J. Assessing volcanic hazard at Yucca Mountain using expert judgment. In: Proceedings of International High-Level Radioactive Waste Management Conference, Las Vegas, NV, April 30-May 5, 1995. La Grange Park, IL: American Nuclear Society and New York, NY: American Society of Civil Engineers; 1995.

[297] PCLP (Peterson Consulting Limited Partnership). Independent management and financial review: Yucca Mountain Project, Nevada. Final report. Denver, CO: Peterson Consulting Limited Partnership; 1995.

[298] US Courts. Indiana Michigan Power Co. v. Department of Energy. United States Court of Appeals for the District of Columbia Circuit. Federal Reporter, 3rd Series 88:1272.

[299] NRC (US Nuclear Regulatory Commission). Disposal of high-level radioactive wastes in geologic repositories; final rule. Federal Register 1996;61(234):64257-70.

[300] Barr GE, Hunter RL, Dunn E, Flint A. Scenarios constructed for nominal flow in the presence of a repository at Yucca Mountain and vicinity. SAND92-2186. Albuquerque, NM: Sandia National Laboratories; 1995.

[301] Robinson BA, Wolfsberg AV, Viswanathan HS, Gable CW, Zycoloski GA, Turin HJ. Site scale unsaturated zone flow and transport model, modeling of flow, radionuclide migration, and environmental isotope distributions at Yucca Mountain. Milestone 3672. Draft. Los Alamos, NM: Los Alamos National Laboratory; 1996.

[302] Buesch DC, Spengler RW, Moyer TC, Geslin JK. Proposed stratigraphic nomenclature and macroscopic identification of lithostratigraphic units of the Paintbrush Group exposed at Yucca Mountain, Nevada. Open-File Report 94-469. Denver, CO: US Department of Interior, Geological Survey; 1996.

[303] NWTRB (Nuclear Waste Technical Review Board). 1997 findings and recommendations, report to the US Congress and the Secretary of Energy. Arlington, VA: Nuclear Waste Technical Review Board; 1998.

[304] CRWMS (Civilian Radioactive Waste Management System). Single heater test final report. BAB000000-01717-5700-00005 REV 00 ICN 1. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 1999.

[305] Reimus PW, Haga MJ, Adams AI, Callahan TJ, Turin HJ, Counce DA. Testing and parameterizing a conceptual solute transport model in saturated fractured tuff using sorbing and nonsorbing tracing in cross-hole tracer tests. Journal of Contaminant Hydrology. 2003;62-63:613-36.

[306] Eaton RR, Ho CK, Glass RJ, Nicholl MJ, Arnold BW. Three-dimensional modeling of flow through fractured tuff at Fran Ridge. SAND95-1896. Albuquerque, NM: Sandia National Laboratories; 1996.

[307] Flint AL, Hevesi JA, Flint LE. Conceptual and numerical model of infiltration for the Yucca Mountain area, Nevada. Milestone 3GUI623M. Denver, CO: US Geological Survey; 1996.

[308] Kerr RA. A new way to ask the experts: Rating radioactive waste risks. Science 1996;274:913-4.

[309] EPRI (Electric Power Research Institute). Yucca Mountain total system performance assessment, phase 3. TR-107191. Palo Alto, CA: Electric Power Research Institute; 1996.

[310] Van Konynenburg RA, ed.,. Comments on the draft paper "Underground supercriticality from plutonium and other fissile material". Science and Global Security. 1996;5(3):303-22.

[311] Kimpland RH. Dynamic analysis of nuclear excursions in underground repositories containing plutonium. Science and Global Security. 1996;5:323.

[312] Kastenberg WE, Peterson PF, Ahn J, Burch J, Casher G, Chambré P, Greenspan E, Olander DR, Vujic J, Bessinger B, Cook NGW, Doyle FM, Hilbert B. Considerations of autocatalytic criticality of fissile materials in geologic repositories. Nuclear Technology 1996;115:298-309.

[313] CRWMS (Civilian Radioactive Waste Management System). Unsaturated Zone Flow Model Expert Elicitation Project. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 1997.

[314] Pub. L. 104-206. Energy and Water Development Appropriations Act of 1997. (110 Stat. 2984). 1997.

[315] US Courts. Northern States Power Co. v. Department of Energy. United States Court of Appeals for the District of Columbia Circuit. Federal Reporter, 3rd Series 128:754.

[316] D'Agnese FA, Faunt CC, Turner AK, Hill MC. Hydrogeologic evaluation and numerical simulation of the Death Valley Regional Ground-Water Flow System, Nevada and California. Water-Resources Investigations Report 96-4300. Denver, CO: US Geological Survey; 1997.

[317] Czarnecki JB, Faunt CC, Gable CW, Zyvoloski GA. Hydrogeology and preliminary three-dimensional finite-element ground-water flow model of the site saturated zone, Yucca Mountain, Nevada. Milestone SP23NM3. Denver, CO: US Geological Survey; 1997.

[318] CRWMS (Civilian Radioactive Waste Management System). Criticality Abstraction/Testing Workshop results. B00000000-01717-2200-00187. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 1997.

[319] Tsang YW, Birkholzer JT. Predictions and observations of the thermal-hydrological conditions in the single heater test. J Contaminant Hydrology 1999;38(1-3):385-425.

[320] Francis ND, Itamura MT, Wilson ML. Total system performance assessment-viability assessment (TSPA-VA) analyses technical basis document, chapter 3, thermal hydrology. B00000000-01717-4301-00003 REV 01. Las Vegas, NV: Civilian Radioactive Waste Management System Management & Operating Contractor; 1998.

[321] Wang JSY, Bodvarsson GS. Evolution of the unsaturated zone testing at Yucca Mountain. J Contaminant Hydrology. 2003;62-63:337-90.

[322] CRWMS (Civilian Radioactive Waste Management System). Waste package probabilistic criticality analysis: Summary report of evaluations 1997. BBA000000-01717-5705-00015. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 1997.

[323] Kersting AB, Efurd DW, Finnegan DL, Rokop DJ, Smith DK, Thompson JL. Migration of plutonium in ground water at the Nevada Test Site. Nature 1999;397(6714):56-9.

[324] Fabryka-Martin JT, Flint AL, Sweetkind DS, Wolfsberg AV, Levy SS, Roemer GJC, Roach JL, Wolfsberg LE, Duff MC. Evaluation of flow and transport models of Yucca Mountain, based on chlorine-36 studies for FY97. LA-CSTTIP-97-010. Los Alamos, NM: Los Alamos National Laboratory; 1997.

[325] ICRP (International Commission on Radiological Protection). ICRP publication 77: Radiological protection policy for the disposal of radioactive waste. Annals of the ICRP 1997;27(Supplement 1997).

[326] Campbell K, Wolfsberg A, Fabryka-Martin J, Sweekind D. Chlorine-36 data at Yucca Mountain; statistical tests of conceptual models for unsaturated-zone flow. J Contaminant Hydrology 2003;62-63:43-61.

[327] Lee JH, Mon KG, Longsine DE, Bullard BE. Waste package degradation modeling and abstraction. Chapter 5 of total system performance assessment-viability assessment (TSPA-VA) analyses technical basis document. B00000000-01717-4301-00005 REV 01. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 1998.

[328] CRWMS (Civilian Radioactive Waste Management System). Waste package materials selection analysis. BBA000000-01717-0200-00020 REV 00. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 1996.

[329] Helton JC, Anderson DR, Basabilvazo G, Jow H-N, Marietta MG. Conceptual structure of the 1996 performance assessment for the Waste Isolation Pilot Plant. Reliability Engineering and System Safety 2000;69(1-3):151-65.

[330] Wernicke B, Davis JL, Bennett RA, Elosegui P, M.J. A, Brady RJ, House MA, Niemi NA, Snow JK. Anomalous strain accumulation in the Yucca Mountain area, Nevada. Science 1998;279:2096-100.

[331] NRC (US Nuclear Regulatory Commission). Issue resolution status report, key technical issue: Container life and source term. Revision 3. Washington, DC: Division of Waste Management, Office of Nuclear Material Safety and Safeguards, US Nuclear Regulatory Commission; 2000.

[332] NRC (US Nuclear Regulatory Commission). Issue resolution status report, key technical issue: Total system performance assessment and integration. Revision 3. Washington, DC: Division of Waste Management, Office of Nuclear Material Safety and Safeguards, US Nuclear Regulatory Commission; 2000.

[333] GAO (Government Accountability Office). Yucca Mountain: Quality assurance at DOE's planned nuclear waste repository needs increased management attention. GAO-06-313. Washington, DC: Government Accountability Office; 2006.

[334] CRWMS (Civilian Radioactive Waste Management System). Evaluation of flow and transport models of Yucca Mountain, based on chlorine-36 and chloride studies for FY98. BA0000000-01717-5700-00007, Rev. 00. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 1998.

[335] Day WC, Potter CJ, Sweetkind DS, Dickerson RP, San Juan CA. Bedrock geologic map of the Central Block Area, Yucca Mountain, Nye County, Nevada, Map I-2601. Denver, CO: US Geological Survey; 1998.

[336] Tseng P-H, Soll WE, Gable CW, Turin HJ, Bussod GY. Modeling unsaturated flow and transport processes at the busted Butte Field Test Site, Nevada. J Contaminant Hydrology 2003;62-63:303-18.

[337] NWTRB (Nuclear Waste Technical Review Board). Report to the US Congress and the Secretary of Energy, January to December 1999. Arlington, VA: Nuclear Waste Technical Review Board; 2000.

[338] Salve R, Oldenburg CM, Wang JSY. Fault-matrix interactions in nonwelded tuff of the Paintbrush Group at Yucca Mountain. J Contaminant Hydrology 2003;62-63:269-86.

[339] Barnard R. Disruptive events. Chapter 10 of total system performance assessment-viability assessment (TSPA-VA) analyses technical basis document. B00000000-01717-4301-00010 REV 00. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 1998.

[340] DOE (US Department of Energy). Disposal criticality analysis methodology topical report. YMP/TR-004Q Rev 00. Las Vegas, NV: Office of Civilian Radioactive Waste Management, US Department of Energy; 1998.

[341] AP (Associated Press). Court asked to force agency to accept civilian nuclear waste. Las Vegas Review-Journal, February 20, 1998, 1998.

[342] Ryan C. Hearings on Yucca water rights canceled. Las Vegas Sun, April 22, 1998.

[343] Vogel E. Waste haul hits bump in road. Las Vegas Review-Journal, Thursday, June 11, 1998.

[344] Manning M. New tests show water history in Yucca. Las Vegas, NV Las Vegas Sun, July 20, 1998.

[345] EPRI (Electric Power Research Institute). Alternative approaches to assessing the performance and suitability of Yucca Mountain for spent fuel disposal. TR-108732. Palo Alto, CA: Electric Power Research Institute; 1998.

[346] Rogers K. Bryan: New Yucca plan changes rules. Las Vegas Review-Journal, December 2, 1999.

[347] NRC (US Nuclear Regulatory Commission). Disposal of high-level radioactive wastes in a proposed geological repository at Yucca Mountain, Nevada; proposed rule. Federal Register 1999;64:8640-79.

[348] EPA (US Environmental Protection Agency). 40 CFR Part 197: Environmental radiation protection standards for Yucca Mountain, Nevada; proposed rule. Federal Register. 1999;64(166):46976-7016.

[349] DOE (US Department of Energy). Draft environmental impact statement for a geologic repository for the disposal of spent nuclear fuel and high-level radioactive waste at Yucca Mountain, Nye County, Nevada. DOE/EIS-250D. Las Vegas, NV: Office of Civilian Radioactive Waste Management, US Department of Energy; 1999.

[350] DOE (US Department of Energy). 10 CFR Parts 960 and 963: General guidelines for the recommendations of sites for waste repositories; Yucca Mountain site suitability guidelines: Supplemental notice of proposed rulemaking. Federal Register 1999;64(229):67053-89.

[351] D'Agnese FA, O'Brien GM, Faunt CC, San Juan CA. Simulated effects of climate change on the Death Valley regional ground-water flow system, Nevada and California. Water-Resources Investigations Report 98-4041. Denver, CO: US Geological Survey; 1999.

[352] Savage JC, Svarc JL, Prescott WH. Strain accumulation at Yucca Mountain, Nevada, 1983-1998. Journal of Geophysical Research 1999;104(B8):17627-31.

[353] Rogers K. Federal scientist to seek volcanoes near Yucca site. Las Vegas Review-Journal, Friday, November 21, 2003.

[354] Heizler MT, Perry FV, Crowe BM, Peters L, Appelt R. The age of Lathrop Wells volcanic center: An $^{40}Ar/^{39}Ar$ dating investigation. Journal of Geophysical Research. 1999;104(B1):767-804.

[355] Eckert T. Plan for stored nuclear waste gets cool reaction. San Diego, CA: San Diego Union Tribune, February 26, 1999, 1999.

[356] Brean H. DOE starts drilling program to monitor contamination. Pahrump Valley Times, March 5, 1999.

[357] Manning M. Report says DOE bungles big jobs. Las Vegas Sun, February 3, 1999.

[358] Budnitz B, Ewing RC, Moeller DW, Payer J, Whipple C, Witherspoon PA. Peer review of the total system performance assessment-viability assessment final report. Las Vegas, NV: Total System Performance Assessment Peer Review Panel; 1999.

[359] Claiborne W. Utah resisting tribe's nuclear dump. Washington Post, Tuesday, March 2, 1999.

[360] Taugher M, Smallwood S. WIPP opening ushers in new nuclear era. Albuquerque Journal, March 27, 1999 Section A, pp 1,2. 1999.

[361] Wilson NSF, Cline JS. Hot upwelling water: Did it really invade Yucca Mountain. In: Uncertainty underground: Yucca Mountain and the nation's high-level nuclear waste. Macfarlane A.M., Ewing R.C., eds. Cambridge, MA: Massachusetts Institute of Technology Press; 2006.

[362] Hayes T. Denial of water rights could kill proposed nuclear dump. Las Vegas, NV: Associated Press in Las Vegas Sun, November 8, 1999, 1999.

[363] NWTRB (Nuclear Waste Technical Review Board). Report to the US Congress and the Secretary of Energy, January to December 1998. Arlington, VA: Nuclear Waste Technical Review Board; 1999.

[364] EPRI (Electric Power Research Institute). Integrated Yucca Mountain safety case and supporting analysis, EPRI's phase 7 performance assessment. TR-1003334. Palo Alto, CA: Electric Power Research Institute; 2002.

[365] Conner CB, Stamatakos JA, Ferril D, Hill BE, Ofeogbu GI, Conway FM, Sagar B, Trapp J. Geologic factors controlling patterns of small-volume Basaltic Volcanism: Application to a volcanic hazards assessment at Yucca Mountain, Nevada. J Geophysical Research 2000;105(1):417–32.

[366] NRC (US Nuclear Regulatory Commission). Safety evaluation report for disposal criticality analysis methodology topical report, revision 0. Washington, DC: US Nuclear Regulatory Commission; 2000.

[367] CRWMS (Civilian Radioactive Waste Management System). Evaluation of codisposal viability for HEU oxide (Shippingport) PWR DOE-owned fuel. TDR-EDC-NU-000003. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 2000.

[368] Bodvarsson GS, Ahlers CF, Cushey M, Dove FH, Finsterle SA, Haukwa CB, Hinds J, Ho CK, Housworth J, Hu Q, Liu HH, Pendleton M, Sonnenthal EL, Unger AJ, Wang JSY, Wilson M, Wu Y-S. Unsaturated zone flow and transport model process model report. TDR-NBS-HS-000002, REV 00. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 2000.

[369] Stockman CT, Rechard RP. Waste form degradation process model report. TDR-WIS-MD-000001, REV 0, ICN 1. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 2000.

[370] Freeze G, Brodsky NS, Swift PN. The development of information catalogued in REV 00 of the YMP FEP database. TDR-WIS-MD-000003, REV 00 ICN 01. Las Vegas, NV: Bechtel SAIC Company; 2001.

[371] Eddebbarh A. Saturated zone site-scale flow model. MDL-NBS-HS-000011. Las Vegas, NV: Bechtel SAIC Company; 2004

[372] Sonnenthal E, Spycher N. Drift-scale coupled processes (DST and THC seepage) models. MDL-NBS-HS-000001, REV 00. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 2000.

[373] Rogers K. Yucca feeling heat on humidity. Las Vegas Review-Journal, Thursday, February 23, 2006.

[374] Rechard RP, Sanchez LC, Trellue HR. Consideration of nuclear criticality when directly disposing highly enriched spent nuclear fuel in unsaturated tuff, Part 1: Nuclear criticality constraints. Nuclear Technology. 2003;144:201.

[375] Rechard RP, Sanchez LC, Trellue HR. Consideration of nuclear criticality when directly disposing highly enriched spent nuclear fuel in unsaturated tuff, Part 2: Geochemical constraints. Nuclear Technology. 2003;144:222.

[376] Rechard RP, Tierney MS. Improbability of igneous intrusion promoting criticality of spent nuclear fuel disposed in unsaturated tuff. Risk Analysis 2005;25(4):997-1028.

[377] Alsaed A, Gottlieb P. Probability of criticality before 10,000 years. CAL-EBS-NU-000014, REV 00. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 2000.

[378] Scaglione J. 21 PWR waste package loading curve evaluation. CAL-UDC-NU-000001 REV 00. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 2000.

[379] Johnson C. Area officials blast nuclear waste route. Daily Press, California, February 23, 2000.

[380] Rogers K, Whaley S. Yucca water permit denied. Las Vegas Review-Journal, February 3, 2000.

[381] NWTRB (Nuclear Waste Technical Review Board). Report to the US Congress and the US Secretary of Energy, 1995 findings and recommendations. Arlington, VA: Nuclear Waste Technical Review Board; 1997.

[382] Manning M. DOE warned of predicted volcanic activity at Yucca Mountain. Las Vegas Sun, August 3, 2000.

[383] Dornan G. Scientists say metal in nuclear casks could corrode dangerously fast. Nevada Appeal, August 2, 2000.

[384] Manning M. Tons of plutonium taint NTS. Las Vegas Sun, October 23, 2000.

[385] EPRI (Electric Power Research Institute). Evaluation of the candidate high-level radioactive waste repository at Yucca Mountain using total system performance assessment, phase 5. TR-1000802. Palo Alto, CA: Electric Power Research Institute; 2000.

[386] NRC (US Nuclear Regulatory Commission). Changes to adjudicatory process. Federal Register 2001;66(73):19610-71.

[387] Rogers K. Errors in Yucca calculations found. Las Vegas Review-Journal, May 30, 2001.

[388] NRC (US Nuclear Regulatory Commission). 10 CFR Part 2: Licensing proceedings for the receipt of high-level radioactive waste at a geologic repository: Licensing support network, design standards for participating websites; final rule. Federal Register 2001;66(105):29453-9.

[389] NWTRB (Nuclear Waste Technical Review Board). Report to the US Congress and the Secretary of Energy, January 1, 2001, to January 31, 2002. Arlington, VA: Nuclear Waste Technical Review Board; 2002.

[390] BSC (Bechtel SAIC Company). CRWMS modular design/construction and operation options report. TDR-CRW-MD-000002 REV 03. Washington, DC: Bechtel SAIC Company 2001.

[391] Whelan JF, Roedder E, Paces JB. Evidence for an unsaturated-zone origin of secondary minerals in Yucca Mountain, Nevada. In: 9th International High-Level Radioactive Waste Management Conference (IHLRWM), Alexis Park Resort, Las Vegas, NV, April 29-May 3, 2001. La Grange Park, IL: American Nuclear Society; 2001.

[392] Paces JB, Whelan JF. Water-table fluctuations in the Amargosa Desert, Nye County, Nevada. In: 9th International High-Level Radioactive Waste Management Conference (IHLRWM), Alexis Park Resort, Las Vegas, NV, April 29-May 3, 2001. La Grange Park, IL: American Nuclear Society; 2001.

[393] DOE (US Department of Energy). Disposal criticality analysis methodology topical report. YMP/TR-004Q, REV 01. Las Vegas, NV: Office of Civilian Radioactive Waste Management, US Department of Energy; 2000.

[394] NA/NRC (National Academies/National Research Council). Disposition of high-level waste and spent nuclear fuel: The continuing societal and technical challenges. Washington, DC: National Academy Press; 2001.

[395] AP (Associated Press). Lab kicks off program to transform nuclear waste. Las Vegas Review-Journal, January 19, 2001, 2001.

[396] Dublyansky YV. Paleohydrogeology of Yucca Mountain by fluid inclusions and stable iIsotopes. In: 9th International High-Level Radioactive Waste Management Conference (IHLRWM), Alexis Park Resort, Las Vegas, NV, April 29-May 3, 2001. La Grange Park, IL: American Nuclear Society; 2001.

[397] IAEA (International Atomic Energy Agency) and NEA (Nuclear Energy Agency). Joint IAEA-NEA international peer review of the Yucca Mountain Project's total system performance assessment supporting the site recommendation process Washington, DC: US Department of Energy; 2001.

[398] IAEA (International Atomic Energy Agency). An international peer review of the biosphere modelling programme of the US Department of Energy's Yucca Mountain Site Characterization Project. Vienna, Austria: International Atomic Energy Agency; 2001.

[399] AP (Associated Press). Study OKs Utah nuke waste dump. Las Vegas Review-Journal, January 17, 2002, 2002.

[400] NRC (US Nuclear Regulatory Commission). Integrated issue resolution status report. NUREG-1762. Washington, DC: Office of Nuclear Material Safety and Safeguards, US Nuclear Regulatory Commission 2002.

[401] Woods AW, Sparks S, Boklhove O, LeJeune A-M, Conner CB, Hill BE. Modeling magma-drift interaction at the proposed high-level radioactive waste repository at Yucca Mountain, Nevada. Geophysical Research Letters 2002;29(13):19-1 to -4.

[402] DOE (US Department of Energy). Surplus Plutonium Disposition Program. Department of Energy. Federal Register 2002;67(76):19432-5.

[403] Williams NH. Contract No. DE-AC08-01RW12101—Total system performance assessment—analyses for disposal of commercial and DOE waste inventories at Yucca Mountain—input to final environmental impact statement and site suitability evaluation REV 00 ICN 02. Letter from N.H. Williams (BSC) to J.R. Summerson (DOE/YMSCO), December 11. RWA:cs-1204010670, with enclosure.2001.

[404] BSC (Bechtel SAIC Company). Total system performance assessment-license application methods and approach. TDR-WIS-PA-000006 REV 00, ICN 01. Las Vegas, NV: Bechtel SAIC Company; 2003.

[405] D'Agnese FA, O'Brien GM, Faunt CC, Belcher WR, San Juan CA. A three dimensional numercial model of predevelopment conditions in the Death Valley Regional Ground-Water Flow System, Nevada and California. Water-Resources Investigations Report 02-4102. Denver, CO: US Geological Survey; 2002.

[406] NWTRB (Nuclear Waste Technical Review Board). Letter report to Congress and Secretary of Energy, Evaluation of Department of Energy's Technical and Scientific Work. Arlington, VA: Nuclear Waste Technical Review Board; 2002.

[407] US Courts. United States of America vs. State of Nevada. Case 2:00-CF-0268-RLH-LRL: United States District Court, District of Nevada; 2007.

[408] EPRI (Electric Power Research Institute). Evaluation of the proposed high-level radioactive waste repository at Yucca Mountain using total system performance assessment, phase 6. TR-1003031. Palo Alto, CA: Electric Power Research Institute; 2002.

[409] Tetreault S. Yucca opposition expands litigation. Las Vegas Review-Journal, Friday, April 12, 2002.

[410] Tetreault S. Key official says DOE failing to make Yucca case. Las Vegas Review-Journal, Thursday, May 1, 2003.

[411] NRC (US Nuclear Regulatory Commission). Yucca Mountain review plan, final report. NUREG-1804, Rev. 2. Washington, DC: Office of Nuclear Material Safety and Safeguards, US Nuclear Regulatory Commission; 2003.

[412] Fick B. Radioactive waste rule rejected. Las Vegas, NV Associated Press in Las Vegas Review-Journal, Friday, July 4, 2003.

[413] AP (Associated Press). Chemists' new findings raise concern about Yucca. Las Vegas Review-Journal, November 18, 2003, 2003.

[414] Detournay E, Mastin LG, Person JRA, Rubin AM, Spera FJ. Final report of the igneous consequences peer review panel. Las Vegas, NV: Bechtel SAIC Company; 2003.

[415] NA/NRC (National Academies/National Research Council). One step at a time: The staged development of geologic repositories for high-level radioactive waste. Washington, DC: National Academy Press; 2003.

[416] NWTRB (Nuclear Waste Technical Review Board). An evaluation of key elements in the US Department of Energy's proposed system for isolating and containing radioactive waste. Arlington, VA: Nuclear Waste Technical Review Board; 2003.

[417] Heilprin J. NRC study says storage facility adequate. The Miami Herald, Thursday, February 12, 2004.

[418] NRC (US Nuclear Regulatory Commission). U.S. Nuclear Regulatory Commission staff evaluation of U.S. Department of Energy analysis model reports, process controls, and corrective action. Washington, DC: Division of Waste Management, Office of Nuclear Material Safety and Safeguards, US Nuclear Regulatory Commission; 2004.

[419] NEI (Nuclear Energy Institute). News: Yucca license delayed. Nuclear Engineering International, November 23. 2004.

[420] Johnson J. DOE releases flood of Yucca Mountain data. C&EN, July 8, 2004.

[421] Belcher WR. Death Valley regional ground-water flow system, Nevada and California—Hydrogologic framework and transient ground-water flow model. Scientific Investigations Report 2004-5205. Reston, VA: US Geological Survey; 2004.

[422] Perry FV, Cogbill AH, Kelley RE. Uncovering buried volcanoes at Yucca Mountain. EOS, Transactions of the American Geophysical Union 2005;86:485-8.

[423] Johnson J. DOE defends 'hot' repository design. C&EN, May 31, 2004.

[424] Rogers K, Tetreault S. Yucca Mountain: Test shows no dust hazard. Las Vegas Review-Journal, Friday, February 13, 2004.

[425] DOE (US Department of Energy). Title 40 CFR Part 191: Compliance recertification application for the Waste Isolation Pilot Plant. DOE/WIPP 2004-3231. Carlsbad, NM: Waste Isolation Pilot Plant, Carlsbad Field Office, US Department of Energy; 2004.

[426] Hebert J. Trial begins over government's nuclear waste costs. Associated Press, July 13, 2004.

[427] AP (Associated Press). State files suit over nuke railroad. Reno Gazette-Journal, September 8, 2004, 2004.

[428] NYT (New York Times). The nuclear waste site in Utah, editorial. New York Times, September 16, 2005.

[429] EPA (US Environmental Protection Agency). 40 CFR Part 197: Public health and environmental radiation protection standards for Yucca Mountain, Nevada; proposed rule. Federal Register. 2005;70(161):49014.

[430] NRC (US Nuclear Regulatory Commission). Implementation of a dose standard after 10,000 years; proposed rule. Federal Register 2005;70(173):53313-20.

[431] NWTRB (Nuclear Waste Technical Review Board). Technical evaluation of US Department of Energy Yucca Mountain infiltration estimates. Arlington, VA: Nuclear Waste Technical Review Board; 2007.

[432] NWTRB (Nuclear Waste Technical Review Board). Report to the US Congress and the Secretary of Energy; January 1, 2005 to February 28, 2006. Arlington, VA: Nuclear Waste Technical Review Board; 2006.

[433] Gross MB. Seismic consequence abstraction. MDL-WIS-PA-00003, REV 02. Las Vegas, NV: Bechtel SAIC Company; 2005.

[434] Freeze G. The development of the total system performance assessment-license application features, events, and processes. TDR-WIS-MD-000003, REV 02. Las Vegas, NV: Bechtel SAIC Company; 2005.

[435] Kim D, Cotton TA. Yucca Mountain and the Global Nuclear Energy Partnership. In: WM'07 Conference, Tucson, AZ, February 25-March 1, 2007. 2007.

[436] Smith EI, Keenan DL. Yucca Mountain could face greater volcanic threat. EOS. 2005;86(35):317-20.

[437] DOE (US Department of Energy). Evaluation of technical impact on the Yucca Mountain Project technical basis resulting from issues raised by emails of former project participants. DOE/RW-0583. Las Vegas, NV: Office of Civilian Radioactive Waste Management, US Department of Energy; 2006.

[438] IAEA. Geological disposal of radioactive waste. Safety Requirements No. WS-R-4. Vienna, Austria: International Atomic Energy Agency; 2006.

[439] ASLBP (Atomic Safety and Licensing Board). In the matter of US Department of Energy (high level waste repository pre-application matters). Before administrative judges of Atomic Safety and Licensing Board, United States Nuclear Regulatory Commission. Order denying motion to strike. December 12, 2007. Memorandum of analysis issued January 4, 2008. ASLBP 04-829-01-PAPO. 2008.

[440] Werner E. DOE releases design requirements for nuclear transport canisters. Associated Press in Las Vegas Sun, June 19, 2007.

[441] Tetreault S. Documents added to Yucca database. Las Vegas Review-Journal, May 1, 2007.

[442] Tetreault S. Agencies to spend $25 million retracing key Yucca research. Las Vegas Review-Journal, January 31, , 2007.

[443] Fitzpatrick CJ, Egan JR, Malsch MG. Motion to strike DOE's October 19, 2007 LSN recertification and to suspend certification obligations of others until DOE validly recertifies, motion to Atomic Safety and Licensing Board. US Nuclear Regulatory Commission; 2007.

[444] CNWRA (Center for Nuclear Waste Regulatory Analyses), NRC (US Nuclear Regulatory Commission). Risk insights derived from analyses of model updates in the total-system performance assessment version 5.1 code. San Antonio, TX: Center for Nuclear Waste Regulatory Analyses; 2008.

[445] NRC (US Nuclear Regulatory Commission). Department of Energy; notice of acceptance for docketing of a license application for authority to construct a geologic repository at a geologic repository operations area at Yucca Mountain, NV. Federal Register 2008;73(179):53284:5.

[446] DOE (US Department of Energy). Final supplemental environmental impact statement for a geologic repository for the disposal of spent nuclear fuel and high-level radioactive waste at Yucca Mountain, Nye County, Nevada. DOE/EIS-250F-S1F. Las Vegas, NV: Office of Civilian Radioactive Waste Management, US Department of Energy; 2008.

[447] Ehrhorn TF, Jarek R. Features, events, and processes for the total system performance assessment: Analysis. ANL-WIS.MD-000027, REV 0. Las Vegas, NV: Sandia National Laboratories; 2008.

[448] SNL (Sandia National Laboratories). Probabilistic volcanic hazard analysis update (PVHA-U) for Yucca Mountain, Nevada. TDR-MGR-PO-000001, REV 01. Las Vegas, NV: Sandia National Laboratories; 2008.

[449] DOE (US Department of Energy). Yucca Mountain repository license application, safety analysis report, update No. 1. DOE/RW-0573, Update No. 1: Office of Civilian Radioactive Waste Management, US Department of Energy; 2009.

[450] US Courts. In RE: Aiken County, petitioner; On petitions for declaratory and inunctive relief, petitions for extraordinary relief, and petitions for review No. 10-1050 (consolidated with 10-1052, 10-1069, 10-1082) US Court of Appeals for the District of Columbia Circuit; 2011.

[451] NRC (US Nuclear Regulatory Commission). Technical evaluation report on the content of the US Department of Energy's Yucca Mountain repository license application. Posclosure volume: Repository safety after permanent closure. NUEG-2107. Washington, DC: US Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards; 2011.

[452] NRC (US Nuclear Regulatory Commission). Technical evaluation report on the content of the U.S. Department of Energy's Yucca Mountain Repository license application. Preclosure volume: Repository safety before permanent closure. NUREG-2108. Washington, DC: US Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards; 2011.

[453] GAO (Government Accountability Office). Commercial nuclear waste: Effects of a termination of the Yucca Mountain Repository Program and lessons learned. GAO-11-229. Washington, DC: Government Accountability Office; 2011.

[454] US Courts. In RE: Aiken County, et al., petitioners; State of Nevada, intervenor; On petition for Writ of Mandamus. No. 11-1271: US Court of Appeals for the District of Columbia Circuit; 2013.

Distribution List

1	MS0721	Peter B. Davies, 6200
1	MS0736	Evaristo (Tito) J. Bonano, 6200
1	MS0736	Peter N. Swift, 6200
1	MS0736	Martha Pendleton, 6200
1	MS0747	Laura L. Price, 6224
50	MS0747	Rob P. Rechard, 6222
1	MS0747	Robert J. MacKinnon, 6224
1	MS0747	Geoff A. Freeze, 6224
1	MS0747	S. Dave Sevougian, 6224
1	MS0748	Jon C. Helton, 1341
1	MS0751	Frank D. Hansen, 6910
1	MS0754	Pat V. Brady, 6910
1	MS0779	Kevin McMahon, 6222
1	MS0779	David Sassani, 6222
1	MS0779	Sylvia J. Salzstein, 6225
1	MS0747	Christine T. Stockman, 6225
1	MS1104	S. Andrew Orrell, 6100
1	MS1138	Mike L. Wilson, 6921
1	MS1138	Stephanie P. Kuzio, 6926
1	MS0899	Technical Library, 9536 (electronic copy)

Sandia National Laboratories