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Site selection and regulatory basis for the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste

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ABSTRACT

This paper summarizes the historical events from the identification of the Yucca Mountain site in southern Nevada in 1978 to its selection by the US Congress as the sole site to characterize for a repository for spent nuclear fuel and high-level radioactive waste in 1987. Coincident with this selection process and later site characterization, the US spent from 1977 to 2009 establishing long-term, radiation protection standards and a regulatory framework for demonstrating compliance. When first promulgated, the US Environmental Protection Agency's radiation protection standards limited cumulative release of radionuclides at a boundary ≤5 km from the edge of a generic repository over a 10^4-year regulatory period. But in 2001, site-specific standards for a repository at Yucca Mountain were promulgated to limit the dose to an individual at a point ≤~18 km from the repository edge in the predominant direction of groundwater flow over a 10^6-year period. Also during the 33-year effort, the regulatory framework of the US Nuclear Regulatory Commission, which implemented the radiation protection standards, changed from setting performance criteria on barrier subsystem components in 1983 to the identification and technical justification for barrier performance based on a performance assessment. Also, reasonable expectation as the standard of proof for evaluating compliance was clarified.

1. Introduction

In 2002, 15 years after selection by the US Congress for characterization, President Bush recommended and Congress authorized the US Department of Energy (DOE) to seek a license from the US Nuclear Regulatory Commission (NRC) to construct a repository at Yucca Mountain (YM). The repository, located on the western border of the Nevada National Security Site (formerly known as the Nevada Test Site or NTS), was intended for disposal of commercial spent nuclear fuel (CSNF),[1] high-level radioactive waste (HLW),[2] and DOE-owned spent nuclear fuel (DSNF) [4] (Fig. 1). In 2008, DOE submitted the License Application, including the Safety Analysis Report, for construction authorization (SAR/LA). The SAR/LA represented a significant milestone in the effort to implement nuclear waste policy in the US that had been in place since 1983 [5].

A major portion of the SAR/LA for Yucca Mountain depends upon a compliance analysis called a performance assessment (PA), which is described in this special issue of *Reliability Engineering and System Safety*. To present a historical perspective on the PA, this paper discusses selection of the site (Section 2) and the lengthy development of performance measures and corresponding limits for the YM repository specified by NRC and the US Environmental Protection Agency (EPA) (Section 3). The political forces and personalities that have influenced the Yucca Mountain Project (YMP) are of great interest and much has been written about them [6–11]. Yet, the corresponding scientific and engineering issues that YMP faced are also important if the US is to improve upon the technical implementation of nuclear waste policy in the future.[3] Although some of these scientific and engineering issues

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[1] Spent nuclear fuel (SNF) is "…fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated by reprocessing [1, Section 2(23)]".

[2] As used here, high level waste (HLW) 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…" [1, Section 3 (12)]. Although not used in this manner here, HLW also refers to a category of radioactive waste by the International Atomic Energy Agency (IAEA), which requires disposal in a deep, geologic repository to protect humans from exposure over the long-term and, thus, collectively includes SNF and material from reprocessing SNF. The NRC uses HLW similar to IAEA in its implementing regulations, 10 CFR 60 and 63 [2, Section 60.2; 3; Section 63.2].

[3] The names for the DOE Nevada office were Nevada Nuclear Waste Storage Investigations (NNWSI) Office in 1978, Yucca Mountain Site Characterization Office (YMSCO) after passage of *Nuclear Waste Policy Amendments Act* [1] and later office reorganization in 1991; and, finally, Yucca Mountain Project (YMP) Office after passage of the *Yucca Mountain Development Act* in 2002 [4].

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Fig. 1. View looking southeast at central portion of Yucca Mountain in southern Nevada.

have recently been summarized [11–13], this paper provides further background and historical context at the interface between site selection and the regulatory basis.

As the performance criteria solidified, the PAs evolved from using simple models for evaluating performance measures in 1984, to using numerous mathematical models for the SAR/LA in 2008. The PA iterations provide convenient points to discuss the status of YMP over the years. Although many iterations have occurred, seven PAs serve to demarcate the historical events presented herein.

In 1982, the dose of a volcanic eruption through the repository and in 1984, the consequence of an undisturbed scenario class were evaluated for the draft and final Environmental Assessments (EA) required by the *Nuclear Waste Policy Act of 1982* (NWPA) [1]. These deterministic analyses, collectively designated herein as PA–EA [14–16], provide the initial marker for the paper. The first stochastic PA, conducted by Sandia National Laboratories (SNL) in 1991 (PA-91) [17], serves as the second marker. PA-91 was followed by two assessments in 1993: one conducted by the recently awarded management and operator (M&O) contractor, TRW (PA-M&O-93) [18]; and one conducted by SNL (PA-93) [19, Fig. 1-1]. The latter PA-93 serves as the third marker. Another major PA was conducted in 1995 (PA-95) by the M&O contractor and serves as the fourth marker [20]. In 1997, Congress asked for a viability assessment of the proposed YM repository, which was completed the following year (PA–VA) and serves as the fifth marker [21]. An analysis in late 2000 for the site recommendation (PA–SR) serves as the sixth marker [22]. A licensing case (PA–LA), which became the basis for the 2008 SAR/LA, serves as the final marker.

Besides the task of developing performance measures (as discussed in this paper), six additional tasks are conducted in iterations of the PA [23, Fig. 1; 24]. Companion papers describe these remaining tasks such as characterization of disposal system, identification of hazards, evolution of the modeling system, and sensitivity analysis [23,25–32].

2. Site selection

2.1. Institutions and roles at YMP

The US legal framework is similar to other international programs in many aspects (e.g., the government defines the policy and approach), but differences are evident [12; 33, Section 3]. One difference is that regulatory responsibility for CSNF is divided among several agencies in the US.[4] EPA sets pre- and post-closure radiation protection standards for repositories for HLW and SNF and NRC implements those standards. NRC also sets and implements standards for storage of waste and transportation casks for radioactive waste. The US Department of Transportation (DOT) regulates the carriers and transportation routes for the radioactive waste. For the disposal of defense transuranic (TRU) waste at the Waste Isolation Pilot Plant (WIPP) in southern New Mexico, EPA sets and also implements the radiation protection standards (Table 1).

Another difference in the US is that a government agency, DOE, is responsible for siting, building, and operating repositories for SNF, HLW and TRU waste. Except for Germany, other countries have set up a public company (e.g., Belgium, France, Japan, Spain, and the United Kingdom), or electric utilities have set up a separate private entity (e.g., Canada, Finland, Sweden, and Switzerland) to site, build, and operate a SNF/HLW repository, somewhat similar to the situation for low-level waste (LLW) in the US [39].[5] This public or private entity in other countries may also be more closely integrated with the storage and transportation operations than in the US.

2.2. Site selection and national policy

2.2.1. Search for permanent disposal

The search for permanent disposal for radioactive waste began in 1955 when the Atomic Energy Commission (AEC), formed in 1946, asked the National Academy of Sciences (NAS) to examine the disposal issue.[6] In 1957, NAS reported that deep salt formations were promising for disposing of HLW [43]. With the technology available in the 1950s and 1960s, the AEC gave mined disposal in salt priority. However, AEC was slow to implement a solution [6,10].

Then in May 1969, the Rocky Flats Plant, built by AEC in 1951 to produce plutonium (Pu) components for nuclear weapons, caught fire. Located only 26 km from Denver, the fire attracted much public attention. The press reported that radioactive waste debris was to be sent to the Radioactive Waste Management Complex (RWMC), built in 1952 on the Idaho National Laboratory (INL) reservation near the Snake River and its associated aquifer. Because of its less than ideal location for long-term storage of radioactive waste, AEC promised Senator Church of Idaho that the waste would be moved to a more suitable site. In June 1970, AEC tentatively selected the abandoned Carey salt mine near Lyons, Kansas, the site of an underground research laboratory (URL) on heat dissipation managed by Oak Ridge National Laboratory (ORNL) between 1963 and 1968 [44, Chapter 4; 45, p. 10]. As part of the selection process, AEC funded cooperative studies with the Kansas Geologic Survey.

By 1971, a large number of boreholes for mineral exploration had been identified and loss of fluids from some solution mining had been reported near the mine. After much controversy, the AEC abandoned the Lyons Project and announced to Congress in May 1972 plans for what was later called a Retrievable Surface Storage Facility (RSSF), in which waste could be stored "a minimum of 100

[4] A similar situation once existed in Sweden where the Swedish Radiation Protection Institute (SSI) developed radiation protection standards and the Swedish Nuclear Power Inspectorate (SKI) handled implementation; however, in 2009 these two functions were merged into the Swedish Nuclear Power Authority (SSM) [34].

[5] In the US, the categories of radioactive waste were defined for the *management* of the waste. Using the source of the waste to designate SNF and HLW was a simple approach and related indirectly to some of the important radionuclide constituents. Waste that was not SNF, HLW, TRU waste, or byproduct material (as defined in the *Atomic Energy Act of 1954* [40]) was designated as LLW. For LLW, Congress assigned the disposal responsibility to the states in 1980, except for the NRC greater-than-class C category (GTCC). GTCC, which is similar to the EPA TRU waste category, remained the responsibility of the federal government [41,42].

[6] Many of the early events that preceded the selection of Yucca Mountain are associated with the handling of defense related radioactive waste, which was produced earlier than commercial SNF, and discussed when reviewing events related to the disposal of TRU waste at WIPP [38].

Table 1
Policy, regulatory, and operational framework for geologic disposal of SNF, HLW, and TRU radioactive waste and mixed radioactive waste in the US [35–38].

Entity	Function	Disposal system	Action
Congress	Set policy and set funding levels of agencies	YMP	NEPA—National Environmental Policy (1970) [47] NWPA—Nuclear Waste Policy (1984, 1987) [1,97] EnPA—Energy Policy (1992) [128] YMP Authorization (2002) [4]
		WIPP[a]	NEPA (1970) [47] RCRA—Hazardous Waste Policy (1976, 1984) WIPP Authorization (1979) Land Withdrawal Act (1992)
EPA (1970) [35]	Set standards	YMP	40 CFR 191—Generic protection standard issued (1985) (prior to 1992 EnPA) [112] 40 CFR 197—YM radiation protection standard issued (2001, 2008) [133,148]
		WIPP	40 CFR 261, 268 RCRA waste standards (1976) RCRA applied to mixed waste (1986) 40 CFR 191 promulgated and revised (1985, 1993) [112,120]
	Certify TRU disposal	WIPP	40 CFR 194—EPA implementation criteria promulgated (1996) Letter notice for formal review (1997) Compliance certification issued (1998)
State of Nevada	Issue operating permits	YMP	Water use, water discharge, sewage discharge, air quality, RCRA hazardous waste generation and storage, explosives permits issued
State of New Mexico[b]	Regulate RCRA constituent of TRU	WIPP	Judicial hearings issued (1999) RCRA Permit (1999)
	Issue operating permits		Water use, water discharge, storage tanks, right-of-way permits issued
NRC (1974) [36]	Regulate CSNF disposal via license	YMP	10 CFR 60—Generic technical criteria promulgated (1983) [2] 10 CFR 63—YM technical criteria promulgated (2001, 2008) [3] Docket notice for formal review issued (2008) [215]
	Certify transport cask	YMP/WIPP	10 CFR 71—Requirements for transport packaging of radioactive material (containment, shielding, criticality, heat)
DOT	Regulate transport routes, handling, and hazardous material	YMP/WIPP	49 CFR 172—Labeling requirements 49 CFR 173—Packaging and transport requirements 49 CFR 174, 49 CFR 200–299—Rail shipment requirements 40 CFR 177, 49 CFR 300–399—Highway shipment requirements 49 CFR 178—Packaging requirements
DOE (1974, 1977) [36,37]	Site repository	YMP	Generic EIS for mined, geologic disposal completed (1980) [70] 10 CFR 960—Generic site guidelines promulgated (1984) [86] EA required by NWPA completed (1986)[56] SCP required by NWPA completed (1988)[89] 10 CFR 963—PA site guidelines promulgated (2001) [104] EIS for site selection completed (2002) [102]
		WIPP	EIS for site selection completed (1980, 1990) Record of decision (1981)
	Build repository	YMP	Supplemental EIS for construction completed (2008) [177] SAR/PA–LA—Safety assessment for construction submitted (2008) [5]
		WIPP	Notice to construct (1983)
	Operate	WIPP	SAR—safety assessment for operation submitted (1990) RCRA Part B application submitted (1995) Compliance certification application submitted (1996) Supplemental EIS for operation completed (1997) Record of decision (1998)
Utility payers	Provide funding	YMP	Nuclear Waste Fund for civilian waste authorized by Congress
Taxpayers		YMP WIPP	Yearly budget for defense waste portion authorized by Congress Yearly DOE budget authorized by Congress

[a] For most WIPP references, refer to [38].
[b] Because EPA has granted some states, such as the State of New Mexico, the right to regulate hazardous waste (as defined in the *Resource, Conservation, and Recovery Act*—RCRA), New Mexico regulates waste with hazardous waste constituents (mixed waste) disposed at WIPP. NWPA does not discuss mixed waste, and YMP banned mixed waste to avoid dual regulation by NRC and the State of Nevada.

years" and, thereby, enable the AEC to "keep open all options" and to "move slowly" to permanent disposition [10, p. 80]. Nuclear proponents thought an RSSF would take pressure off finding a disposal site, a criticism that would be repeated often over the next 34 years [6, p. 76; 8; 10, p. 93–4; 46].

Earlier in the *National Environmental Policy Act* (NEPA) [47], Congress had set the policy that all federal agencies would consider environmental consequences of major actions and discuss alternatives in an environmental impact statement (EIS). The EIS process exerted its influence during the 1970s as the federal government formulated waste management plans through an administrative process. The new atmosphere created by NEPA engendered more detailed analysis of environmental hazards, which would be reflected later in regulations for Yucca Mountain. NEPA also added a venue for stakeholders to influence the process. For example, EPA, formed by Congress in 1970, and nuclear opponents, through comments on the EIS for the RSSF issued in 1974, claimed an RSSF (at possibly Hanford reservation, Idaho RWMC, or NTS) would be *de facto* permanent disposal. The criticisms prompted the newly formed Energy, Research, and Development Agency (ERDA), successor of AEC, to abandon consolidated surface storage, even as a near-term solution, and emphasize the search for other disposal sites, which had started again in 1972 with the help of the US Geological Survey (USGS).[7]

Besides salt, USGS and DOE considered other geologic media such as clay/shale with highly sorptive properties or igneous (i.e., crystalline, basaltic and later tuff) rocks less susceptible to exploratory drilling for economic resources [48,49]. Engineered barriers were proposed to complement the potentially less favorable hydrologic flow characteristics of igneous rocks in SZ while exploiting the stability of the geologic and geochemical environment. By 1978, multiple barriers were generally accepted for providing waste isolation in repositories to address geologic uncertainty [50, p. 13]. For example, Sweden incorporated the multiple barrier concept into their design for a crystalline rock repository for SNF by using a clay backfill and highly corrosion resistant container of titanium in 1978 (KBS I) or container of copper in the 1980s (KBS III) [6, p. 295; 45, p. 61].

2.2.2. Site identification

Use of the unsaturated zone (UZ) in desert environments for radioactive waste disposal was first mentioned by the NAS in 1966 [51], but others also encouraged use of the UZ and deserts. Winograd, a geologist at USGS, suggested disposal of HLW in boreholes, trenches, and pits in the UZ of the desert southwest in 1972 and 1974 [52,53]. By 1974, studies by ERDA mentioned possible waste disposal in the UZ in tuff and shale in arid and semi-arid regions [49, p. 50].

Then in 1976, California enacted a moratorium on new nuclear reactors until the federal government approved a method of permanent storage of radioactive waste. The California moratorium was upheld by the Supreme Court because of the economic rather than safety regulatory emphasis [6, p. 86]. The moratorium along with earlier events (e.g., the Rocky Flats Plant fire), clearly placed nuclear waste isolation on the national agenda. In response, President Ford requested that ERDA accelerate the demonstration of waste isolation [54]. That same year, ERDA formed the National Waste Terminal Storage (NWTS) program (from the AEC Geologic Disposal Evaluation Program) to develop technology and facilities for storage of HLW and SNF [6, p. 135; 8; 55; 56, p. 2–11]. The goal was at least one repository operating in a pilot phase as early as 1985. [8]

Also in 1976, USGS Director McKelvey suggested that ERDA emplace nuclear waste at the NTS because of its (a) closed hydrologic groundwater basin [58], (b) long groundwater flow paths to potential outflow points [59], (c) many different types of rock suitable for waste isolation, (d) remoteness, (e) past nuclear testing, (f) arid climate (~150 mm/yr precipitation), and (g) thick UZ [6, p. 131; 53, 56; 60, p. 4; 61; 62]. The first rock investigated was clay/shale/argillite, but quickly expanded to crystalline rocks at Twinridge and Climax the next year. USGS had already suggested the alluvium in 1972 and would soon suggest tuff associated with zeolites (Table 2) [52,53,63].

In 1978, DOE (formed from ERDA as a cabinet department the year before) decided that a repository could only be built in the southwestern portion of NTS so as to not disrupt the weapons test mission. An important aspect was not only physical separation but also easy operational access so that an administrative separation could be maintained whereby the oversight roles of NRC and the State of Nevada for radioactive waste would not require their oversight of weapons tests. Site investigations then focused on the Calico Hills area to look at argillite and granite, Wahmonie to look at granite, and Yucca Mountain to look at volcanic tuff. The investigations found only small, highly fractured granite masses and structurally complex argillite; however, borehole UE25 a#1, cored to ~760 m, confirmed the presence of thick volcanic tuff deposits (Fig. 2) [64]. In 1979, USGS recommended that investigations focus on welded tuff underlying Yucca Mountain. Investigations to find suitable argillite and granite sites in the southern portion of NTS were stopped; however, work at Climax granite as a URL continued until 1985 to determine the general suitability of crystalline rocks [56,65].

Because tuff was not considered previously, DOE asked NAS to consider the suitability of tuff for waste disposal in 1978. Concerns were igneous and seismic disruption. However as argued by SNL and LANL, advantages of welded tuff, besides the obvious necessary thickness, depth, and hydrology in a desert location, included (1) good thermal characteristics to conduct heat from the waste, (2) good structural stability to allow waste to be retrieved during the pilot phase, (3) the ability of zeolitic, nonwelded tuff below the repository to adsorb radionuclides [66], and (4) absence of economic resource deposition concurrent with tuff deposition [56]. Supporting studies by SNL and LANL were published a year later [67–69].

In March 1979, the Interagency Review Group (IRG) for Nuclear Waste Management, formed the year before by President Carter with representatives from 14 federal agencies, completed its report and concluded that [9, p. 53; 10, p. 120; 44, Appendix A; 45, p. 30; 55, Appendix A; 70, p. 3–3] (1) responsibility for managing radioactive waste resides with the current generation, and in particular, the federal government; (2) mined, geologic disposal was a promising method for isolating SNF, HLW, and TRU; (3) the national program should assume that the first disposal facility would be a mined repository; (4) multiple barriers (specifically, the waste package) were a means of compensating for geologic uncertainty; (5) the federal government should consider a number of sites in a variety of geologic media and build one or more repositories, preferably in different regions of the US; (6) repository development should proceed cautiously, in a stepwise manner, and (7) safe storage should not be used as a reason to delay opening the first repository.[9] A year later in a generic EIS, DOE concluded that a mined geologic repository was the best option for disposal of commercial SNF and HLW [70,71].

By 1982, the Site Evaluation Working Group, organized by SNL in 1980, had formally screened 15 locations in the southwestern area of NTS and reported that Yucca Mountain remained the preferred site for a repository [56,72,73]. Also in 1982, USGS identified several advantages for using the UZ at Yucca Mountain and on their recommendation, DOE moved the repository to the UZ [6, p. 175; 56; 74–76]. Advantages mentioned included [75] (1) highly porous, low permeable, vitric layer (PTn) above the host

[7] The Rocky Flats Plant fire in 1969, the storage of the debris in Idaho in 1970, the Lyons controversy in 1971, the Arab oil embargo in 1972, and the leakage of HLW from a single-shelled storage tank at Hanford in 1973 prompted Congress to split the independent AEC in 1974 into [36] (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.

[8] In the 1970s, a mined, geologic repository was categorized as a storage option. Furthermore, a repository was called a terminal storage facility; hence, YMP was initially the Nevada Nuclear Waste Storage Investigations (NNWSI) Project in 1978. Closure after backfilling and sealing a terminal storage facility was described as permanent storage. 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 [48; 57, vol. 4, p. 1].

[9] IRG solicited the views of Congress, public interest groups, and the general public through written reviews, small group meetings, and public meetings. IRG distributed 15,000 copies of its October 1978 draft report for public review and considered more than 3000 written comments in preparing its recommendations to President Carter.

Table 2
Rock types and sites examined in Basin and Range region at Nevada Test Site area suggested by Nevada Senator Cannon in 1972, State of Nevada Legislature in 1975, and USGS in 1976 (Appendix A) [25].

Rock	Site suggested	Related URL/Tests
Argillite/clay/shale	Syncline Ridge (1976)	Syncline Ridge, Eleana Fm (1977–1979) Heater tests (February 1978–January 1979)
	Calico Hills (1978)	Borehole (April 1978)
Crystalline	Climax Stock (1976)	Heater tests and SNF placement/removal (1980–1985)
	Timber Mountain (1977)	
	Twinridge Hill (1977)	
	Wahmonie Stock (1978)	
	Calico Hills (1978)	Borehole (April 1978)
Alluvium		Greater Confinement Test (December 1983) Greater Confinement Disposal (May 1984–August 1989)
Tuff	Yucca Mountain (1978)	Borehole UE25a#1 (April 1978) Rainer Mesa, G-tunnel (May 1978–1989) Heater tests and fluid flow (February 1979–1983) Radionuclide migration tests (proposed May 1978) Surface trenches (January 1981–1982) Exploratory Studies Facility (1994–2005) Fran Ridge, Large-Block heater test (1996–1997) Busted Butte, Tracer migration tests (1998–2003)

layer (and high capillarity was later shown to diminish episodic percolation) [29]; (2) most waste would not contact much water in the UZ since openings typically block flow (where the evolution of the necessary seepage research is described in a companion paper [29]); (3) mineable but fractured tuff host unit (Topopah Spring welded tuff, TSw) to rapidly move percolation through the repository [77],[10]; (4) known source and direction of water flow; (5) water flux was likely small because of the very thick UZ and could be estimated through direct observation (where the evolution of infiltration research is described in a companion paper [29]); (6) many exploratory holes could be drilled without compromising the repository [78]; (7) zeolitics in nonwelded Calico Hills unit (CHn) layer below the host layer to adsorb radionuclides [66] (where the historical evaluation of the UZ pathway through zeolites, tuff and engineered material is mentioned in a companion paper [32]); (8) the saturated zone (SZ) adds additional travel time as a barrier [59] (where the characterization of the SZ tuff and alluvium pathway is described in a companion paper [32]); (9) passive ventilation of repository possible to keep waste cool versus active ventilation of the 1070-m deep Tram welded tuff unit in the SZ (where the evolution of thermal studies in the UZ is described in a companion paper [30]); (10) backfilling of drifts unnecessary; (11) sealing of shafts unnecessary; and (12) a long period with easy retrieval because the repository does not flood where the evolution of the repository design to take advantage of the UZ is described in a companion paper [26]. Other reasons already cited were federal land ownership, previous contamination through nuclear testing that had used ~3.4 t of Pu [79], remoteness/sparse population in the region, and a closed groundwater basin [22].

[10] Similarly, NRC designs for LLW sites promote rapid movement of percolating water through the waste disposal horizon by using coarse backfill, in addition to using a cap to divert percolation away from the waste.

2.2.3. Nuclear Waste Policy Act

Although developing a repository for TRU waste at WIPP was not easy, it did progress mostly administratively [38]. The US had more difficulty implementing a repository program for commercial SNF and HLW administratively. The Congressional Office of Technology Assessment (OTA) noted [80]

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

After nearly four years of debate over the findings of IRG, studies of OTA, hearings, and false starts at legislation, Congress set national policy and procedures in the *Nuclear Waste Policy Act of 1982* (NWPA) [1; 6, Chapter 6; 8]. NWPA endorsed the policy, voiced earlier in studies such as the IRG report and generic EIS [55,70], that the current generation should bear the costs of developing a permanent disposal option and selected geologic disposal.[11] In addition, NWPA addressed each of the three credibility issues noted above as follows [80].

Concerning the first issue, NWPA required the federal government to enter into contracts with the utilities for acceptance of waste as an incentive for future administrations to abide by the waste policy commitment to avoid penalties for breach of contract [1, Section 117c]. NWPA also required the federal government to site and seek licenses for two repositories for CSNF/HLW; however, NWPA only authorized construction and operation of the first repository. Furthermore, the first repository was statutorily limited to 70,000 MTHM (metric tons heavy metal initially placed in reactor) until a second repository was operating, as an important social-political compromise.

Also concerning the first issue, NWPA established steps to meet the goals and a timetable for opening the first repository. Although others suggested a conservative timetable [44], Congress insisted on an aggressive schedule that was agreed to by DOE in congressional testimony, but with significant program risks [44, Appendix B] (Table 3).

Although a repository was the primary component of the radioactive waste management system, NWPA required DOE evaluate the need for and to submit to Congress a proposal for 3 alternative sites for a Monitored Retrievable Storage (MRS) facility and cooperate with the private sector to conduct NRC-licensed demonstrations of alternatives to wet SNF storage at reactor sites [1, Section 218(a)]. The cooperative program, which licensed its first demonstration in Virginia in 1986, and various additional studies provided a foundation for utilities to build dry cask storage to alleviate the limited wet storage space available at reactors. It is the success of this program that allows time for the US to consider revising the current nuclear

[11] Furthermore, NWPA defined disposal as "emplacement in a repository… whether or not such emplacement permits the recovery of such waste" where a 'repository' means any system licensed by the Commission that is intended to be used for, or may be used for, the permanent deep geologic disposal of high-level waste and spent nuclear fuel…" and 'storage' means retention of high-level radioactive waste, spent nuclear fuel, or transuranic waste with the intent to recover such waste or fuel for subsequent use, processing, or disposal" and, thus, changed the earlier distinctions used in the 1970s for storage and disposal.

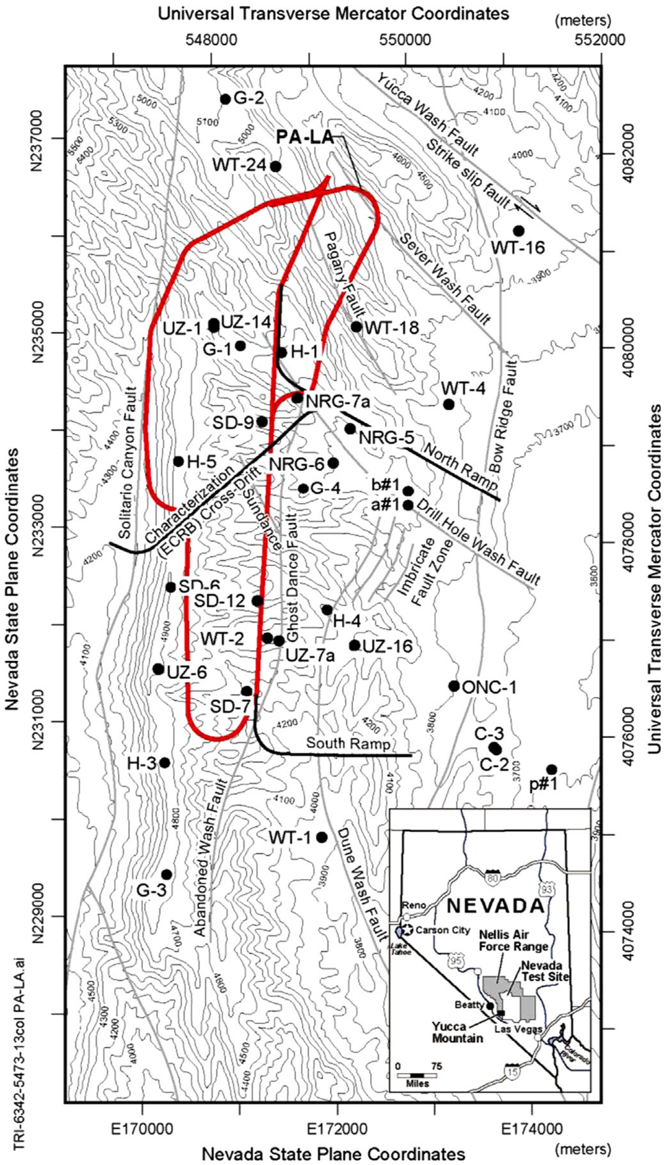


Fig. 2. Repository layout for PA–LA and pertinent wells at Yucca Mountain, Nevada.

waste management policy. Of the ~65,000 MTHM of CSNF currently stored in the US as of 2010, ~25% was in dry cask storage [26, Section 2.7; 39, Section 3.3].

Concerning the second credibility issue, NWPA assigned responsibility for the waste management functions to the single-purpose Office of Civilian Radioactive Waste Management (OCRWM), a new office within DOE that absorbed the functions of the NWTS Program [1, Section 304]. NWPA established the Nuclear Waste Fund (NWF), funded by a fee initially set at 0.1 ¢/kW-hr on power produced by nuclear reactors, to pay the full cost for repository selection, construction, and operation [1, Section 302]. Yet in 1985, Congress did not exempt expenditures for the waste program from NWF from the general budget sequestration process in the *Gramm-Rudman-Hollings Act*, even though the funds were derived from a fee for contracted disposal services rather than a tax [81,82].

The third issue dealt with the difficulty of waste management in a federal system of government: NWPA required an EIS, but limited the range of options that had to be considered since Congress had selected the geologic disposal option. NWPA also directed OCRWM to develop environmental assessments (EAs) of candidate sites with an additional venue for public involvement.[12] In addition, NWPA encouraged negotiation of consultation and cooperation agreements with the states, following the example of the WIPP legislation for the State of New Mexico [38,83]. Finally, NWPA established a procedure for a state or Native American Tribe to notify Congress of its disapproval of a site recommendation and the necessary procedure for Congress to override this disapproval (Table 3), should consultation and negotiation agreements fail.[13] The law bypassed several parliamentary procedures to ensure a timely vote on a motion to override state or tribal disapproval within 90 days.

Related to the third issue, NWPA established the regulatory environment for licensing the repository [1, Section 121]. NWPA directed EPA to set radiation protection standards for disposal and directed NRC to implement these standards by requiring licensing in three steps: approval to construct, approval to receive and possess waste, and approval to close and decommission. [14] NWPA also identified several site selection criteria for DOE to include in its siting guidelines.

2.2.4. *Siting guidelines and site selection under Nuclear Waste Policy Act*

DOE site selection guidelines were drafted in February 1983 and promulgated in December 1984 in 10 CFR 960 [85,86]. The site selection criteria were subjective, framed in terms of qualifying, favorable, potentially adverse, and disqualifying conditions to provide a relative ranking of several sites. The starting point for the criteria was the experience in searching for repository sites in salt. These were then expanded to incorporate more general criteria for other rock media developed by the NWTS Program and ideal criteria developed by NAS in 1978. To these were added the technical criteria mentioned in the Generic EIS on the management of CSNF and several disqualifying features specifically mentioned in NWPA. Finally, the criteria underwent extensive public review by state representatives and others as part of the formal rulemaking process.

Absence of economically attractive resources was a common theme in siting criteria. Exploration of salt sites in the Salina Group salt in Michigan in 1977 used criteria suggesting the absence of petroleum production and solution mining [45, p. 36]. The NAS suggested in 1978 [87, Section 4.1]: “No area with a present or past record of resource extraction, other than for bulk material won by surface quarrying, should be considered as a geological site for radioactive wastes”. The Generic EIS suggested [70, Section 5.1.1.2]: “The repository site shall be located in area that does not contain desirable or needed mineral resources, or to the extent presently determinable, resources that may become valuable in the future”. Hence, a disqualifying condition in 10 CFR 960 Subpart C, Section 960.4-2-8-1-was[15]

(1) Previous exploration, mining, or extraction activities for resources of commercial importance at the site have created significant pathways between the projected underground facility and the accessible environment; or

[12] The studies were called EAs in NWPA, which initially caused confusion since they were not related to EAs defined in 40 CFR 1501 regulations promulgated in 1979 to implement NEPA.

[13] Unitary forms of government with direct representation of local interests in the parliament, such as in Sweden and Finland, have had more success in siting HLW radioactive waste repositories [84, Section 2].

[14] The legislative history was clear that *mined* geologic disposal was intended; thus, EPA and NRC regulations only considered this disposal approach.

[15] Similarly, the formal site selection criteria for WIPP in 1975 required a minimum ~1.6 km (1 mile) distance to any boreholes from the perimeter of the waste, and resulted in the ~100 km^2 (16 $mile^2$) area withdrawn for public use at WIPP in 1992, based on the difficulty with exploratory boreholes and solution mining at Lyons, Kansas [38].

(2) Ongoing or likely future activities to recover presently valuable natural mineral resources outside the controlled area would be expected to lead to an inadvertent loss of waste isolation.

Because of the aggressive schedule, DOE conducted site selection while developing the guidelines, and the nine sites that had previously been selected for consideration using administrative procedures were identified for screening for the first repository under NWPA in February 1983 [56,88].[16] The next month, DOE held hearings to solicit comments from the State of Nevada and public regarding nomination of Yucca Mountain and solicit issues to discuss in the EA and the Site Characterization Plan (SCP) [89] required by NWPA and NRC [1, Section 113]. Although Nevada Senator Cannon had recommended NTS to AEC in 1972 [10, p. 92] and the Nevada Legislature had requested ERDA consider NTS in 1975 [90] (Appendix A), interest in hosting a storage or disposal facility had waned. At the 1983 hearings on the nomination of Yucca Mountain, Governor Bryan declared that, “It is unfair in my view for the rest of the nation to ask Nevada, in light of its past and present commitment in the nuclear field, to assume this new burden”, One concern was the compatibility with Las Vegas as a tourist attraction, 160 km to the southeast [6, p. 176; 91].

By December 1984, DOE had issued draft EAs of all nine sites (e.g., [92]). The draft EAs suggested five candidate sites to nominate for further site characterization (three salt sites: Davis Canyon, Utah; Deaf Smith, Texas; Richton Dome, Mississippi; one basalt site: Hanford, Washington; and one tuff site: Yucca Mountain). DOE also presented a ranking analysis in the draft EAs that suggested Yucca Mountain, Deaf Smith, and Hanford were the top three sites [88]. The deterministic PA–EA formed part of the basis of the EA for Yucca Mountain. As part of the EA, DOE also completed a preliminary evaluation of Yucca Mountain against the site selection guidelines in 10 CFR 960 and found no disqualifying conditions [56, p. 2–47].

DOE completed final EAs for the five sites by May 1986. Because of both technical and political criticism of the ranking analysis used to identify the five nominated sites, multi-attribute utility decision analysis was applied. The multi-attribute analysis ranked from 1st to 5th Yucca Mountain, Richton Dome, Deaf Smith, Davis Canyon, and Hanford [93]. However, the Secretary of Energy recommended and President Reagan concurred in further characterizing a portfolio of sites in three different media (tuff at Yucca Mountain, salt at Deaf Smith, and basalt at Hanford) [94]. The concept of lowering overall program risk by using a portfolio of sites had been indirectly suggested by the 1979 IRG [55], reflected in the NWPA requirement to consider sites in different geologic media [1, Section 112(a)] (Table 3), and codified in the siting guidelines, 10 CFR 960.

2.2.5. Nuclear Waste Policy Amendments Act

The April 1985 DOE announcement that located an MRS at one of three sites in Tennessee and the May 1986 DOE announcement (a) selecting the three finalists for the first repository, and (b) indefinitely deferring the search for a second repository in the east were followed by considerable turmoil.[17] Lawsuits were filed and over 40 bills were introduced in 1987 related to various aspects of SNF and HLW disposal [9, Chapter 5]. In hearings on the bills, technical concerns at Yucca Mountain were still the possibility of igneous and seismic activity. The decision to indefinitely defer the search for a second repository in the east upset western Congressional representatives [95], and the high cost of characterizing three sites (~$1 × 10^9$ per site by 1986) caused general Congressional concern [96].

In 1987 amendments to the *Gramm-Rudman-Hollings Act*, Congress placed appropriations from NWF under the domestic discretionary spending cap. In turn, the Office of Management and Budget (OMB) established a single budget for DOE, rather than two separate budgets as in the past [81]. Hence, YMP had to compete with other DOE programs such as the MRS storage program, which exacerbated historical concerns that a storage facility would displace a repository.

Also in December 1987, Congress decided to characterize solely Yucca Mountain as a deficit reduction measure in the *Nuclear Waste Policy Amendments Act of 1987* (NWPAA), which was included in the *Omnibus Budget Reconciliation Act* of that year. By this choice, Congress implied a sequential characterization process, which had been discussed in Senate hearings [96]. The perceived unfairness of site selection by Congress (along with concern that it would be the only national repository because of the indefinite delay of siting the second repository [95]), led to unwavering opposition to Yucca Mountain by Nevada state officials thereafter.[18]

The NWPAA also affirmed the DOE decision to delay consideration of a second repository, and revoked the DOE recommendation for an MRS site in Tennessee [96, Section 5001; 97]. Instead, Congress authorized construction of an MRS, established a commission to report to Congress on the need for an MRS; [19] linked an MRS sited by DOE to the construction schedule for a repository, as suggested by the Tennessee citizen Clinch River Task Force; and established an Office of Nuclear Waste Negotiator to find a willing host for an MRS or alternative repository (however, the Negotiator focused on finding an MRS). Based on the anticipated savings from characterizing only one site, NWPAA also set up a compensation schedule for hosting a repository or an MRS facility.

Following the example set by the establishment of the NAS Review Panel for WIPP, NWPAA established formal outside technical oversight by 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 to ensure scientific credibility.[20] Many of the changes made in site characterization and engineered barrier evaluations since their first report in 1990 were made in response to or supported by NWTRB comments (Appendix A).

2.2.6. Site recommendation and license application

In 2001, DOE completed the supplement to the draft EIS on Yucca Mountain [100], the Science & Engineering Report describing PA–SR [22], and the Preliminary Site Suitability Evaluation (SSE) report [101]. Final versions of the Science and Engineering report, SSE, and EIS were completed in February 2002 [102]. The SSE used the new

[16] The alternative of starting with a new national site screening process had been explicitly considered and rejected during the debates on NWPA [44].

[17] Although the aggressive NWPA schedule for the first repository had the effect of requiring DOE to adopt the sites that had already been under study using administrative procedures, the search for the second repository did follow the legislative procedures of NWPA as codified in 10 CFR 960 and still generated strong opposition [6–8; 9, p. 72; 95].

[18] Other attributes that have been cited for causing a general erosion of trust include lack of a consent-based process, setting unrealistic schedules, and the prescriptiveness of the siting process in NWPA [39, Section 3.4.3].

[19] An MRS facility can add important flexibility by decoupling reactor operations and the package designs for temporary storage from the repository operations and permanent disposal waste container designs; thus, several details on the difficulty in siting an MRS are presented in the timeline on designing the YM repository [26, Appendix A].

[20] Formed in 1978 along with but separate from the WIPP NAS review panel, DOE funded the Environmental Evaluation Group (EEG) to address technical concerns of New Mexico and state citizens. EEG was eventually place under the New Mexico Institute of Mining and Technology University in 1988 to prevent undue influence by either state politics or DOE [38,98]. Separate from the NWTRB, DOE also provided funds to the Nevada Nuclear Waste Project Office (NWPO), created by the state legislature but placed directly in the Governor's office [99].

Table 3
Aggressive siting schedule adopted in *Nuclear Waste Policy Act of 1982* [1], and effects of 1987 amendments [97].

Action	First repository	Second repository
Section 116(a): DOE identifies "potentially acceptable sites" and notifies state governors	• Within 90 days of enactment of Act (6 April 1983) • DOE identified 9 sites already under consideration using administrative process February 1983	Within 90 days of identification of any potentially acceptable site
Section 112(a): DOE issues siting guidelines	• Within 180 days of enactment (5 July 1983) • DOE completed draft of 10 CFR 960 February 1983; final completed December 1984; draft of 10 CFR 963 for YM completed November 1999; final completed November 2001	Same
Section 121(a): EPA issues radiation protection standards	• Within 1 year of enactment (7 January 1984) • EPA completed rule September 1985	Same
Section 121(b):NRC issues technical assurance requirements (e.g., multiple barriers)	• By 1 January 1984 • NRC completed rule June 1983; NRC added criteria for repository in UZ in July 1985	Same
Section 112(b)(2): DOE holds public hearing on issues to be addressed in EA and SCP	• Prior to nominating a site • DOE held hearing for YM in March 1983	
Section 112(b)(1)(A): DOE nominates at least 5 sites suitable to characterize and includes EA per Section 112(b)(1)(E)	• Following issuance of guidelines (December 1984) • DOE completed EAs and nominated 5 sites December 1984 (Yucca Mt, NV; Davis Canyon, UT; Deaf Smith, TX; Richton Dome, MS; Hanford, WA)	• No later than 1 July 1989 and must include at least 3 not nominated in first round • NWPAA deleted
Section 112(b)(1)(B): DOE recommends 3 sites to characterize	• By 1 January 1985 with at least 2 in different media • DOE selected YM, Deaf Smith, Hanford May 1986	1 July 89 NWPAA deleted
Section 112(c): President approves or disapproves sites	• <60 days of recommendation (6 month delay allowed) • President Reagan approved the 3 sites in May 1986	Same
Section 113(b)(1)(A): DOE submits site characterization plan (SCP) to state or tribe	• Prior to beginning site characterization • DOE completed SCP on YM December 1988	Same
Section 114(a): DOE holds public hearings on recommendation	• Prior to recommendation • DOE held hearings in August 2001	Same
Section 114(a)(2): DOE recommends 1 site for construction with EIS (Section 114(f)); President recommends to Congress	• By 31 March 1987 (may extend 1 year) • NWPAA deleted date • DOE Secretary recommended YM in February 2002 • President Bush recommended in February 2002	• 31 March 1990 (1-year extend) • NWPAA deleted and asked for assessment by January 2010 • DOE report sent January 2010
Section 116(a)(2) and Section 118(a): State or Tribe disapprove	• Within 60 days of presidential recommendation • Gov. Guinn, State of Nevada, disapproves April 2002	
Section 115: Review of recommendation	• Congress may override <90 days of disapproval • House overrode in May; Senate overrode in July	Same
DOE recommends another site if disapproved	• Within 1 year of disapproval • NWPAA deleted	Same
Section 114(b): DOE submits LA to NRC	• Within 90 days of when recommendation takes effect • DOE submits LA to NRC in June 2008 • NRC dockets LA in September 2008	Same
Section 114(d): NRC issues final decision	• Within 3 years of license submittal (may extend 1 year) • NRC closes review of LA end of September 2011	Within 3 years of submitting license (may extend 1 year)
Section 302(a)(5)(B): DOE, by utility contract, shall dispose	• Beginning 31 January 1998 • DOE issues contract in 10 CFR 961 in April 1983	

selection guidelines (10 CFR 963) for Yucca Mountain promulgated in 2001, which replaced the generic 10 CFR 960 guidelines [103,104]. Disqualifying conditions in 10 CFR 963 relied directly upon the results of a PA, rather than use separate disqualifying conditions or specific requirements for characteristics of the geology. This approach followed the lead established by NRC and EPA.

After a 9-month personal review of the Science & Engineering Report, SSE, and EIS [101], Energy Secretary Abraham recommended the site to President Bush in February 2002 [105]; and President Bush recommended the site to Congress. In April 2002, Nevada Governor Guinn disapproved the Site Recommendation because [106] (a) Nevada already hosted the NTS, (b) Nevada had the largest LLW site in the country at Beatty, west of Yucca Mountain, that had operated between 1962 and 1992 [6, p. 176], and (c) the proposed repository design did not depend on the geologic characteristics of the site. Congress overrode Nevada's disapproval by July [106] followed by President Bush signing the *Yucca Mountain Development Resolution* [4]. 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 (Appendix A) [107]. The court did, however, vacate the portion of the EPA radiation protection standards, 10 CFR 97, related to the 10^4-years 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 [108]. President Obama and Congress 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 Administration eliminated all funding and filed a motion to withdraw the SAR/LA from the NRC Atomic Safety Licensing Board (ASLB), which was to conduct formal hearings, because the YM repository was an "unworkable" approach. The ASLB denied DOE's motion and an appeal to the NRC Commissioners eventually upheld the ASLB decision. However, the NRC Commissioners also suspended pretrial depositions of the ASLB and the license review by the NRC staff in 2011 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 [218], but the programmatic uncertainty and lack of funding has brought a *de facto* stop to YMP.

3. Performance goals

3.1. Regulatory performance criteria for PA–EA, PA-91 and PA-93

3.1.1. EPA radiation protection standards for generic repository, 40 CFR 191

The selection of performance criteria for geologic disposal took many years in the US. In response to the 1976 directive by President Ford to accelerate the demonstration of waste isolation mentioned earlier [54], EPA conducted several public meetings in 1977 to develop a consensus of society's concept of acceptable risk (i.e., safety) [109; 110, Section 1.2] (Appendix B). In response to NWPA, EPA promulgated the draft 40 CFR 191 radiation protection standards for SNF, HLW, and TRU disposal in 1982, which had undergone more than 20 revisions [111, Section 4.5]. The final version, promulgated in 1985 [112], required a PA analysis to show compliance of a disposal system where PA was defined as an "analysis that (1) identifies the processes and events that might affect the disposal system; (2) examines the effects of these processes and events on the performance of the disposal system; and (3) estimates the cumulative release of radionuclides, considering the associated uncertainties by all the significant processes and events.[21]" Analysis often involves teasing a system apart into simpler components to gain understanding, as when characterizing a system. However, analysis may also involve the synthesis of diverse facts about components to comprehend the system as a whole, as done in a PA analysis.

As originally promulgated, 40 CFR 191 consisted of two subparts. Subpart A described criteria for management and storage during repository operations. Subpart B described Containment Requirements (Section 191.13) related to the post-closure PA, Individual Protection Requirements (Section 191.15), and Groundwater Protection Requirements (Section 191.16).

3.1.2. Containment Requirements in 40 CFR 191

The Containment Requirements selected the cumulative release of radionuclides as the primary indicator of potential health impacts (Table 4). The measure of this indicator (R) was the cumulative release 10^4 years after disposal of long-lived radionuclides (r) that reached the surface or crossed a vertical boundary 5 km in any direction from the perimeter of the emplaced waste [28, Eq. (B.1)].

The EPA radiation protection standards was a new concept for a government regulation in that it required a quantitative treatment of uncertainty in the measure and thus numerical simulation using mathematical models in order to assess compliance [111, Fig. 8; 113].[22] Specifically, the Containment Requirements required R to be expressed as a complementary cumulative distribution function to display uncertainty (CCDF or 1-$\mathcal{G}(R)$ where $\mathcal{G}$(R) is the summed distribution of cumulative release [28, Eq. (B.2)]. This CCDF was compared to a piecewise-uniform, limiting CCDF (Table 4). Hence, 40 CFR 191 did not simply limit the expected value (first moment of the distribution of uncertain results), nor the variance (second moment of the result distribution), but rather the whole distribution of results [111].

The cumulative release was normalized by dividing by (a) EPA derived limits (L_r) for n_r radionuclides r and (b) mass placed in the repository expressed as a waste unit factor ($f^{mass} = M_0/10^3$ MT where M_0 was the MTHM mass with burnup between 25,000 MWd and 40,000 MWd, with adjustment factors for burnup outside this range) [28, Eq. (B.1)]. As discussed in background documents and the preambles to the draft and final promulgation, the limits L_r were set, based on technological achievability, to allow no more than 1000 deaths over the chosen 10^4 years period for 100,000 MTHM repository from aqueous releases of all radionuclides except ^{14}C from the repository to all the rivers of the world (3×10^{13} m^3/year) at a 5 km boundary and ingestion by the entire world population of 10^{10} [110, Section 7.8; 112, 114–116].[23]

By normalizing the cumulative release by M_0, the Containment Requirements did not penalize use of large repositories (which inherently creates a large source-term) [110,111,114]. Although the situation is changing, at the time of the promulgation of 40 CFR 191, the US had twice as many operating reactors as either France or the then Soviet Union and almost three times as many as the UK and

[21] 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 entire disposal system, the adjective is omitted here since the acronym must be repeated frequently.

[22] However, it was not the first regulation to use a probabilistic limit. The British in 1938 had established a reliability requirement for commercial aircraft: the probability of success for 1 h of flight was to be 0.99999 [111, Fig. 5].

[23] In a 1999 special issue of *Risk Analysis*, Rechard provides historical context for the development of the PA methodology and the generic EPA 40 CFR 191 radiation protection standards [111], and Okrent compiles reviews and philosophical discussions held during the development of 40 CFR 191 that gives the reader more background on the regulatory spirit of 40 CFR 191 [116].

Japan, so the US had to have either more repositories or larger repositories than other countries [70, Table 1.3.1].

The use of cumulative release (i.e., the integration over the specified time period) did not penalize the location of the repository away from large volumes of water (which promotes dilution and thus lowers the dose rate) [110,114]. Also, the use of cumulative release was less sensitive to the release rate of radionuclides from the engineered barrier and dispersion coefficients in the geologic barrier; thus, the fidelity of the source-term model could be less and, hence, the regulation did not promote use of expensive engineered barriers [110; 112, p. 38073; 114; 116].

Cumulative release was less easily manipulated than the time of peak dose by the use of parameters with overly broad uncertainty ranges. Committees of the Nuclear Energy Agency (NEA) have coined the term "risk dilution" where "dilution" refers to the use of overly broad ranges for parameters distributions. The usual example given is where the performance measure is mean peak dose. The concern cited is where the parameters that influence the time of peak dose are assigned overly broad ranges such that the time of the peak dose varies greatly, and, thus, the mean peak dose averaged over numerous simulations is greatly reduced from that calculated with narrow distributions [24,117].

The cumulative release was to include features, events, and processes (FEPs) associated with both undisturbed (i.e., normal evolution) and disturbed behavior (such as human intrusion). To deal with the uncertainty of the human intrusion event, EPA provided guidance in an appendix (Appendix B in the 1985 promulgation; Appendix C in the 1993 repromulgation) that "inadvertent and intermittent intrusion by exploratory drilling for resources…can be the most severe intrusion scenario assumed…" and provided guidance on the frequency of drilling to define the probability of the human intrusion event. EPA guidance generally suggested a frequency (and, thereby, a probability) of intrusion into repositories located in sedimentary rock, such as salt to be 30 boreholes/(km^2-10^4 yr), and suggested a factor of 10 less for other rocks, such as granite or tuff, with their lower likelihood of economic resources such as hydrocarbons. Later requirements, specific to WIPP, stated the frequency to be determined from the record of drilling in the sedimentary Delaware basin over the past 100 years [118].

The 40 CFR 197 invoked "reasonable expectation" as the standard of proof for compliance with the limits. Reasonable expectation connoted a more flexible standard of proof and use of central estimates when encountering unknowns. The concept of reasonable expectation had been challenged in a lawsuit after promulgation and found reasonable by the Court of Appeals, DC Circuit [119]: "Given that absolute proof of compliance is impossible to predict because of the inherent uncertainties, we find the Agency's decision to require 'reasonable expectation' of compliance is a rational one". The concept is discussed further with the promulgation of the site-specific reuglation.

3.1.3. *Individual and Groundwater Protection Requirements in 40 CFR 191*

In response to comments received on the proposed regulation, EPA also required an evaluation of individual dose (i.e., potential *rate* of exposure by an individual) as a secondary indicator of risk in the Individual Protection Requirements (Section 191.15). The measures were individual whole-body dose and critical organ dose in the first 10^3 years (rather than 10^4 years) as estimated using mean parameter values (i.e., not a stochastic calculation) [112]. The whole-body dose limit was 0.25 mSv/yr. The dose measures were to include only pathways from undisturbed FEPs. The rule also included Groundwater Protection Requirements (Section 191.16), designed to protect groundwater as a resource. As in the case of the Individual Protection Requirements, compliance with the groundwater standard considered only undisturbed performance of the repository system.

Because of a lawsuit concerning the 10^3 years time limit and the form of the Individual and Groundwater Protection Requirements, the court remanded 40 CFR 191 in 1987 [119]. In response, the EPA standards were revised in 1993 to increase the regulatory period for the Individual and Groundwater Requirements to 10^4 years, identical to the Containment Requirements, which were unchanged. For the Individual Requirements, the limit for the mean dose (d_{limit}) was lowered to 0.15 mSv/yr and the method of calculating dose measure was updated. The dose measure was changed to the annual committed effective dose equivalent (CEDE), defined as the dose received over a 50 years from 1 year of external exposure and ingestion of radionuclides by an individual, using methods and weighting factors for organ radiosensitivity of the International Commission on Radiation Protection (ICRP) applicable at the time [120, Appendix B; 121]. The new calculation method adopted protected the whole body and individual organs at the same level of risk with a single limit value rather than two separate limits as promulgated in 1985 [3, p. 55752]. Although not typically limiting releases in 40 CFR 191 (since disruptive FEPs were not considered), the Individual Protection Requirements laid the groundwork for the dose measure and limits later required for Yucca Mountain in 40 CFR 197.

Also in response to the court remand [119], a new Subpart C was added making the Groundwater Protection Requirements (Section 191.16) similar to those promulgated for the *Clean Water Act* in 40 CFR 141. The Groundwater Protection Requirements, as expressed in 40 CFR 191 (or as expressed later in 40 CFR 197), did not limit releases at Yucca Mountain or require substantial differences in modeling (e.g., [28]) and so are not discussed further.

3.1.4. *NRC implementing regulation for generic disposal system, 10 CFR 60*

In 1981, NRC promulgated the procedures for licensing a repository that adapted procedures developed for licensing an engineered reactor, such as formal hearings in front of the ASLB prior to authorizing construction of the repository, and included a requirement for developing an SCP [89]. In 1983, prior to final promulgation of 40 CFR 191 but cognizant of its likely contents, NRC added technical criteria to 10 CFR 60 [2,122] that set deterministic performance objectives on subsystems of the waste disposal system.[24] The quantitative performance objectives were (Section 60.113) (a) "containment of HLW in waste packages will be substantially complete for a period…not less than 300 years nor more than 1000 years after permanent closure of the geologic repository" (i.e., while short-lived fission products are present); (b) a maximum fractional release rate of 10^{-5} from the engineered barrier system (EBS) for radionuclide *r* with inventory after 1000 years of decay provided this rate limit was not less than 0.1% of a similarly calculated total release limit; and (c) a "pre-waste-emplacement groundwater travel time along the fastest path of likely radionuclide travel from the disturbed zone to the accessible environment shall be at least 1000 years or such other travel time as may be approved or specified by the Commission". Although comments received on the draft objected, NRC thought requiring quantitative performance objectives on subsystems would help to promote a multiple barrier disposal system and defense in depth [2; 3, p. 55737; 115]. For PA–EA and PA-91, the NRC container

[24] NRC promulgated amendments to 10 CFR 60 (Appendix B) (a) in 1985 to include criteria for siting in the UZ [123]; (b) in 1986 to revise the licensing procedures to agree with NWPA; (c) in 1989 to clarify the need to update the YMP EIS when filing for construction authorization, operation, and closure [124]; and (d) in 1996 to clarify terms [125]. Although these amendments demonstrate the lengthy, iterative effort expended by NRC to develop the regulations, they are not germane to the performance measures.

Table 4
Changes in regulatory basis for Yucca Mountain repository.

Regulation	Health indicator	Measure of indicator	Limit
40 CFR 191 Generic Repository 1985	1. Cumulative release including human intrusion scenario	Distribution of expected cumulative release R (i.e., $1-\overline{\mathcal{G}}(R)$) from retained scenario classes beyond 10^4 years at surface or 5 km boundary from perimeter of waste, normalized by mass fraction ($\sum M_r/10^3$ MT) of long-lived radionuclides (r) disposed in repository and EPA derived limits (L_r), based on population exposure	Limiting distribution defined by $R \le 1$ for probability ($\wp$) ≥ 0.1; $R \le 10$ for $0.1 > \wp \ge 0.001$
	2. Individual dose	Individual whole-body dose ($D_U(t, x^{ae}; \bar{\mathbf{e}})$) and critical organ doses for undisturbed scenario class ($\mathcal{A}_U$) over 10^3 yr at surface or 5 km boundary (x^{ae}) using mean model parameters ($\bar{\mathbf{e}}$)	<0.25 mSv/yr whole body
	3. Groundwater concentration	Concentration $C_U(t, x^{ae}; \bar{\mathbf{e}})$ in groundwater for $\mathcal{A}_U$ at 5 km boundary over 10^3years using $\bar{\mathbf{e}}$ for $^{226}Ra/^{228}Ra$, α-emitters (including $^{226}Ra/^{228}Ra$ but not Rn), and whole body dose from beta and gamma emitters	$^{226}Ra/^{228}Ra < 5$ pCi/L; α-emitters < 15 pCi/L; dose < 0.04 mSv/yr
40 CFR 191 Generic Repository 1993	2. Individual Dose	Committed effective dose equivalent (CEDE—dose received over 50 years from 1 year exposure) using methods of ICRP for $\mathcal{A}_U$ over 10^4 yr with $\bar{\mathbf{e}}$ (i.e., $D_U(t;\bar{\mathbf{e}})$)	<0.15 mSv/yr for $t < 10^4$ yr
	3. Groundwater concentration	$C_U(t; \bar{\mathbf{e}})$ for $\mathcal{A}_U$ at 5 km boundary over 10^4 yr	Radioactivity limits in 40 CFR 141 (Clean Water Act)
10 CFR 60 Generic Repository 1983	4. Performance of barriers[a]	Reasonable assurance standard of proof, and performance standards for multiple barriers: natural system barrier (groundwater travel time, τ^{gw}) and EBS (minimum container life, ${}^{min}\tau^{WPfail}$, and EBS release rates, $\overline{m}_r^{EBS}$, for each radionuclide r, based on total inventory of each radionuclide M_r. Retrieval period for 50 years after placement of first waste package.	$\overline{\tau}^{gw} < 1000$ yr; $300 \text{ yr} < {}^{min}\tau^{WPfail} < 1000$ yr; $\overline{m}_r^{EBS} < \max\{m_r^{\text{limit}}, m_{total}^{\text{limit}}\}$; $\dot{m}_r^{\text{limit}} = M_r(t=10^3 \text{ yr})/10^5\text{yr}$; $\dot{m}_{total}^{\text{limit}} = \sum_r^{n_r} M_r(t=10^3 \text{ yr})/10^8\text{yr}$
40 CFR 197 YM Repository 2001	1. Individual dose	Expected CEDE to reasonably maximally exposed individual (RMEI) using methods of ICRP for all retained scenario classes over 10^4 yr at NTS boundary (~18 km) (20 km in draft) along flow path and 5 km boundary elsewhere in 3.7×10^6 m^3 representative volume of groundwater $\overline{D}(t;\mathbf{e})$)	<0.15 mSv/yr for $t \le 10^4$ yr
	2. Human-intrusion dose	Unconditioned, expected CEDE for stylized case (i.e., borehole into degraded package that is not well sealed such that radionuclides migrate to underlying aquifer)	<0.15 mSv/yr for $t \le 10^4$ yr
	3. Groundwater concentration	Expected concentration ($\overline{C}(t)$) in 3.7×10^6 m^3 for all scenarios at ~18 km boundary for $^{226}Ra/^{228}Ra$, α-emitters (including ^{226}Ra but not U or Rn); and whole body dose from beta and photon emitters	$^{226}Ra/^{228}Ra < 5$ pCi/L; α-emitters < 15 pCi/L; dose < 0.04 mSv/yr
40 CFR 197 YM Repository 2008	1. Individual dose	Expected dose, $\overline{D}(t;\mathbf{e})$, over 10^6 yr (median dose, ${}^{50\%}D(t;\mathbf{e})$, in 2005 draft)	$<$ 0.15 mSv/yr for $t \le 10^4$ yr; <1 mSv/yr for $10^4 < t \le 10^6$ yr (3.5 mSv/yr in 2005 draft)
	2. Human-intrusion dose	Unconditioned, expected CEDE (i.e., dose not weighted by aleatoric probability of event, but epistemic expectation estimated from sampled $\mathbf{e}$)	<0.15 mSv/yr for $t \le 10^4$ yr; <1 mSv/yr for $10^4 < t \le 10^6$ yr
10 CFR 63 YM, 2001	4. Performance of barriers	Reasonable expectation standard of proof; required to describe basis of multiple barriers; also, 50-yr retrieval required	

[a] 40 CFR 191 also has multiple barrier assurance requirements but they are not applicable to a repository for commercial spent nuclear fuel.

lifetime performance objective was used as the postulated life of a waste container in place of a detailed waste container model. YMP evaluated the YM site against the groundwater travel time requirements in studies separate from PA–EA, PA-91, and PA-93 (e.g., [126]), although not discussed herein.

3.2. Policy and regulatory performance criteria for PA-95, PA–VA, PA–SR and PA–LA

The primary cumulative release indicator in the EPA standards 40 CFR 191 and the subsystem requirements on container failure rates and groundwater travel time in the NRC regulation 10 CFR 60 influenced the calculation techniques for PA–EA, PA-91 and preparation for PA-93. Then in 1992, Congress required a change to the regulatory environment for the YM repository.

3.2.1. Energy Policy Act of 1992

Because of concerns voiced in Senate debates about the (a) potential impacts of human intrusion and (b) inappropriate use of the derived limits in 40 CFR 191 when applied to gaseous release of ^{14}C from a repository in the UZ where extensive dilution could occur [19; 23, Fig. 2b; 127], the *Energy Policy Act of 1992* (EnPA), directed EPA to promulgate site-specific radiation protection standards for a repository at Yucca Mountain. EnPA further specified that "such standards shall prescribe the maximum annual effective dose equivalent to individual members of the public" as the risk indicator [107, 111; 128, Section 801].[25] The new EPA standards were to be "based upon and consistent with the findings and recommendations of the National Academy of Sciences" in a study required by EnPA. EnPA also required NRC to revise its implementing regulation, 10 CFR 60, to agree with the new EPA standards.

In response to EnPA, NAS made four recommendations in 1995 pertinent to this paper [111,131]: (1) use a maximum individual risk evaluated from an effective dose; (2) evaluate compliance at the time of peak risk from the repository (which was likely within 10^6 years at Yucca Mountain); (3) evaluate only the potential consequences (not probability) of a few selected situations of inadvertent human intrusion, and (4) avoid specifying criteria on subsystems of the disposal system, since these criteria could potentially result in suboptimal behavior of the overall disposal system.

The Congressional requirement for EPA to consider dose, and the preference of the NAS for a dose indicator [130], prompted PA-93 to consider dose in addition to cumulative release. For

[25] The State of Nevada focused on the fact that ^{14}C as a gas exceeded the limits in 40 CFR 191 using one of two early conceptual UZ flow models in 1991 and 1993 [23, Fig. 2b] and characterized the Congressional guidance to EPA as changing the rules to fit the YM site [129, p. 10]. However, the nature of regulating a first of its kind facility required iteration. Furthermore, as early as 1983 NAS had encouraged adoption of dose as the health indicator when evaluating Yucca Mountain [130].

PA-95 and PA–VA, the NAS recommendations were available and confirmed their preference for a dose indicator and a very long regulatory period. The PA–SR used the dose measures in drafts of 40 CFR 197 and 10 CFR 63 proposed in 1999 as described below (Appendix B).

3.2.2. EPA radiation protection standards for YM disposal system, 40 CFR 197

In 1999, EPA proposed [132], and in 2001, promulgated [133] the site-specific radiation protection standards for a YM disposal system (40 CFR 197) (Appendix B), leaving the generic 40 CFR 191 applicable to other geologic repositories such as WIPP and the Greater Confinement Disposal (GCD) facility.[26] In 40 CFR 197, EPA selected individual dose as the primary risk indicator. As its measure, EPA selected the expected value of the CEDE to a reasonably maximally exposed individual (RMEI) located in the predominate direction of groundwater flow at the point of maximum concentration in the accessible environment beyond a post-closure controlled area. The post-closure controlled area could be no greater than 300 m^2 with a southern boundary no further south than the southern boundary of NTS (≤~18 km south) and ≤5 km in other directions from the perimeter of the emplaced waste (Section 197.12) [32, Fig. 1].[27] EPA set a limit (d_{limit}) of 0.15 mSv/year for the maximum mean of the expected peak CEDE dose (${}^{\max}\overline{D}(t)$) over a regulatory period of 10^4 years for both undisturbed and disturbed FEPs (Table 4).

EPA also elaborated upon the characteristics of reasonable expectation for the standard of proof (Section 197.14)

> Characteristics of reasonable expectation include that it: (a) Requires less than absolute proof because absolute proof is impossible to attain for disposal due to the uncertainty of projecting long-term performance; (b) Accounts for the inherently greater uncertainties in making long-term projections of the performance of the Yucca Mountain disposal system; (c) Does not exclude important parameters from assessments and analyses simply because they are difficult to precisely quantify to a high degree of confidence; and (d) focuses performance assessment and analyses upon the full range of defensible and reasonable parameter distributions rather than only upon extreme physical situations and parameter values.

Similar to 40 CFR 191, EPA required the inclusion of all uncertainty to provide as unbiased an estimate as practicable. Specifically, EPA noted (Section 197.36) “By specifying the mean as the performance measure and probability limits for the processes and events to be considered, and in concert with the intent of our ‘reasonable expectation’ approach in general, we have implied that probabilistic approaches for the disposal system performance assessments are expected.” However, the “mean value of the distribution of calculated doses” was compared to the 0.15 mSv/yr limit, not the entire distribution as in 40 CFR 191. [28]

With the Congressional discussion and eventual selection of dose as the measure of compliance [128], the amount of dilution and dispersion afforded by the natural barrier became important, which, in turn, reinforced plans for more extensive characterization of the lower UZ and SZ than had been necessary when using the cumulative release criterion in 40 CFR 191 [25].

The use of the release *rate* from the disposal system as the measure (not the cumulative release and the smoothing of the result provide by the time integral) made complying with the regulation potentially more difficult at Yucca Mountain because ambient oxygenated conditions in the UZ might promote, under some conditions, rapid degradation of the waste form and, thus, a more rapid release rate. Hence, the importance of more precisely modeling the release rate from the waste package increased (i.e., the importance of the fidelity of the exposure pathway/consequence model $\mathcal{R}_{,}(t)$ increased). In turn, the potential high release rate and need for precise modeling indirectly led to the usefulness of a robust waste package with well-defined characteristics.[29]

As shown in a companion paper [28, Appendix B], the underlying simulations are similar for evaluating a cumulative release measure or individual annual dose measure. Yet, an advantage of a dose standard is that development of the regulatory limit and its application is more flexible, and the burden of support shifts to the licensee in comparison to the development of derived population limits (L_r) for cumulative release [3, p. 55750]. Derived limits (L_r) require the regulator (rather than the licensee) to develop a model and defend several assumptions as to the manner in which the population is exposed. In comparison, dose ($D_r(t)$) is directly evaluated from $\mathcal{R}_{,r,}(t)$ [28, Eq. (B.10)] (i.e., $D_r(t)= \mathcal{R}_{,r}(t) f_r^{BDCF}/Q^{indv}$) using a biological dose conversion factor for radionuclide r (f_r^{BDCF}) calculated from a biosphere transport model. Granted, the biosphere transport model applies guidance by the regulator to assume (a) residents drink a fixed 2 L/day of contaminated water, (b) residents consume local food grown with contaminated water, and (c) the amount of dilution (Q^{indv}) afforded by the natural barrier (e.g., quantity of water withdrawn from the contaminated aquifer); yet, the uncertainties in food consumption and the pathways in the biosphere transport model are defended by the licensee (rather than the regulator) and pathways can readily be adapted to new information about the site.

Other aspects of the site can also be taken into account with a dose limit. A dose limit allows credit to be taken for dilution of radionuclides along the release pathway and a regulator need not specify a regulatory period. Also, in concept, an operator may select container designs that promote slow, extended release of radionuclides or the operator can size the repository inventory to site conditions.

Another advantage is that the regulatory dose limit is comparable to individual dose limits in other international radioactive waste programs (provided the FEPs and regulatory period considered are similar). For example, ICRP, NEA, and the International Atomic Energy Agency (IAEA) have recommended a maximum health risk of 10^{-5}/yr [135] or maximum public dose limit (d_{limit}) of 1 mSv/yr (average dose from natural sources at sea level) and average of 0.3 mSv/yr from a disposal facility [33,121,191]. For example, Germany set the exposure limit at 0.3 mSv/yr (for 10^6 years) and both France and Czech Republic set the exposure limit at 0.25 mSv/yr (for 10^4 years for France). Similar to the US, many radioactive waste programs have set design targets a factor of 2–3 lower than 0.3 mSv/yr for some specified period after disposal. For example, Finland sets the exposure limit at 0.1 mSv/yr for several thousand years, and at 5 mSv/yr for accident conditions; Switzerland sets the exposure limit at

[26] In addition to NTS and the LLW site at Beatty, Nevada hosted GCD on NTS, which operated between 1984 and 1989 and disposed of (a) 1.45 × 10^{16} Bq of ^{90}Sr from sealed radioactive sources and 2.62 × 10^{16} Bq of tritium (^{3}H) in a test borehole, (b) 6 kg (< 1.2 × 10^{13} Bq) of ^{239}Pu and 64 kg of ^{235}U in ~60,000 kg of classified TRU waste in 4 boreholes, and (2) 8.5 × 10^{16} Bq of LLW (mostly ^{3}H) in 5 boreholes. The waste was placed in the bottom 15 m of 36-m deep, 3-m diameter boreholes in an up to 900-m thick sequence of alluvial sandy tuff where the water table was 235 m below the surface [134, Section 2.1].

[27] The location of the RMEI at ~18 km, where inhabitants currently live rather than closer to the site, was one of many aspects of the 40 CFR 197 challenged by the State of Nevada, but upheld by the US Court of Appeals for DC Circuit [107].

[28] In concept, EPA could have chosen the distribution (i.e., CCDF) of peak doses as the dose measure and defined a limiting CCDF, as for releases, and, thereby, explicitly regulated the entire dose distribution. PA-93, PA-95, and PA–VA displayed such a CCDF [23].

[29] For example, one consideration of EPA when repromulgating 40 CFR 191 in 1993 was the potential cost should WIPP have to adopt more robust containers caused by extending the period of performance to 10^4 years and thereby elevating the importance of the dose standard [116, 120].

0.1 mSv/yr for 10^6 years [111, Fig. 13; 136]. Other countries setting an exposure limit at 0.1 mSv/yr are Hungary, Republic of Korea, Netherlands, Spain, and Slovak Republic [137, Section 1.3.2]. Alternatively, Sweden, Canada, the United Kingdom (UK) set the cancer fatality frequency a factor of 10 below the recommended maximum health risk at 10^{-6}/yr for 10^4 years (0.073 risk per Sv or 0.014 mSv/yr for Sweden and 0.06 risk per Sv or 0.017 mSv/yr for UK [121,66,68]).

3.2.3. Human intrusion scenario class in 40 CFR 197

Human intrusion had been (a) an important source of consequences in shallow land burial, (b) a basis for requiring *deep* geologic disposal, (c) the primary release pathway for disposal in salt when applying 40 CFR 191 [27, Section 3.3.2], and (d) an impetus to search for alternative geologic media with less frequent rates of exploratory drilling than sedimentary rock. Yet, treatment of the uncertainty associated with the inadvertent human intrusion event evolved for 40 CFR 197 in that the event was not included in probabilistic dose calculations, consistent with the NAS recommendation. Furthermore, EPA and NRC narrowed the focus of the anthropogenic disruption. First, exposure to the drillers was not included as noted by NRC [3, p. 55761]:

> NAS concluded, and the Commission agrees, that analysis of the risk to the public or the intruders (i.e., drilling crew) from radioactive drill cuttings left unattended at the surface for subsequent dispersal into the biosphere would not fulfill the purpose of the human intrusion calculation because it would not show how well a particular repository site and design would protect the public at large.

In other words, exposure to those inadvertently drilling into a repository and subsequent dispersal of drilling material was determined by the waste inventory, not characteristics of the designed disposal system.[30]

Second, human exposure that occurred much later in time from release via the abandoned borehole was evaluated in a stylized calculation. The circumstances of the human intrusion in the stylized calculation (which bypassed the UZ portion of the natural barrier, by providing a fast path to the aquifer underlying the YM repository, but retained the remainder of the natural barrier in the SZ) were specified as

> (a) There is a single human intrusion as a result of exploratory drilling for ground water; (b) The intruders drill a borehole directly through a degraded waste package into the uppermost aquifer underlying the Yucca Mountain repository; (c) The drillers use the common techniques and practices that are currently employed in exploratory drilling for ground water in the region surrounding Yucca Mountain; (d) Careful sealing of the borehole does not occur, instead natural degradation processes gradually modify the borehole; (e) Only releases of radionuclides that occur as a result of the intrusion and that are transported through the resulting borehole to the saturated zone are projected; and (f) No releases are included which are caused by unlikely natural processes and events.

The limit on dose from the stylized calculation (unweighted by the probability of the event) was 0.15 mSv/yr in the first 10^4 years and 1 mSv/yr beyond 10^4 years.

3.2.4. NRC implementing regulation for YM disposal system, 10 CFR 63

In 1995, NRC issued a Policy Statement calling for the expanded use of probabilistic risk assessments (PRAs) in setting regulations for all nuclear facilities.[31] The policy statement explicitly stated [138], "… (2) PRA and associated analyses (e.g., sensitivity studies, uncertainty analyses, and importance measures) should be used in regulatory matters, where practical within the bounds of the state-of-the-art, to reduce unnecessary conservatism associated with current regulatory requirements…and (3) PRA evaluations in support of regulatory decisions should be as realistic as practicable…".

In 1999, NRC proposed 10 CFR 63 implementing regulations specifically for Yucca Mountain and left 10 CFR 60 unchanged for the time being.[32] The proposed regulations adopted the 10^4 years regulatory period but (a) used a dose limit of 0.25 mSv/yr, (b) and called for a "reasonable assurance" concept for the standard of proof of compliance that had long been applied to nuclear reactors. However, by 2001, the promulgated [3] NRC regulations adopted (a) the EPA dose limit of 0.15 mSv/yr; and (b) EPA's characterization of "reasonable expectation" as the standard of proof for post-closure compliance. In the preamble to 10 CFR 63, NRC stated [3, p. 55740–47]

> EPA prefers "reasonable expectation" because it believes "reasonable assurance" has come to be associated with a level of confidence that is not appropriate for the very long term analytical projections that will be necessary for evaluating Yucca Mountain…To avoid any misunderstanding and to achieve consistency with final EPA standards, the Commission has decided to adopt EPA's preferred criterion of "reasonable expectation" for purposes of judging compliance with the postclosure performance objectives…For other determinations regarding compliance of the repository with preclosure objectives, the Commission will retain a standard of "reasonable assurance," consistent with its practice for other licensed operating facilities subject to active licensee oversight and control…However, the Commission wants to make clear that its proposed use of "reasonable assurance" as a basis for judging compliance was not intended to imply a requirement for more stringent analyses (e.g., use of extreme values for important parameters) or for comparison with a potential more stringent statistical criteria (e.g., use of the 95th percentile of the distribution of the estimate of dose).

The latter modification represented a subtle but important terminology change acknowledged by NRC Commissioner McGaffigan who commented, "This is an area [Reasonable Expectation versus Reasonable Assurance] where EPA made a contribution to the overall standard setting effort. Our proposed rule used the term 'reasonable assurance', partly because we had always used it, but the proposed Section 63.101 really was describing 'reasonable expectation'. The final rule is an improvement" [142]. This intent to equate reasonable assurance to reasonable expectation in the context of post-closure repository performance was reflected by the fact that the description for the standard of proof for post-closure compliance did not change substantially in the promulgated NRC regulation; rather, only the EPA terminology was substituted [107, p. 1301]. In other words, NRC had proposed to use the same terminology "reasonable assurance" for two subtly different concepts. The connotation depended upon context

[30] However, including human intrusion in 40 CFR 191 provided a convenient decision point for WIPP: When direct releases from drill cuttings dominated total releases (rather than slow migration along other pathways), the WIPP Project had conducted sufficient characterization of the disposal system [23; 38, p. 39].

[31] NRC explicitly equated PRA with PA in the US by noting in the preamble to the Policy Statement that "PRA is called performance assessment for waste management systems".

[32] NRC stated its intent to update its older 10 CFR 60 regulation [3, p. 55736; 139]. NRC later suggested that the update to 10 CFR 60 would look similar to 10 CFR 63 in relying on a risk-informed, performance-based approach [140,141].

(i.e., whether NRC was speaking about engineered pre-closure surface facilities or post-closure behavior of a geologic disposal system). [33] Although evidently not intended by NRC, YMP had indeed adopted a more conservative bounding approach when encountering unknowns, such as parameter and modeling uncertainty, for PA-SR, somewhat encouraged by the use of "reasonable assurance" terminology in the proposed 10 CFR 63 [23, Fig. 3]. As noted by the NWTRB, the use of conservative models and parameters complicated the understanding of the results from PA–SR; hence, NWTRB had requested a more realistic analysis of disposal system performance [143]. However, the standard of proof was clear for PA–LA with the use of reasonable expectation terminology in both regulations.

Although echoing the criteria for screening FEPs from 40 CFR 197, NRC elaborated upon the treatment of uncertainty. Using the generally accepted broad categories of sources for uncertainty in a PA (parameter uncertainty, model form uncertainty, and scenario/completeness uncertainty), NRC specified that

> Any performance assessment used to demonstrate compliance with §63.113 must: …(b) Account for uncertainties and variabilities in parameter values and provide for the technical basis for parameter ranges, probability distributions, or bounding values used in the performance assessment. (c) Consider alternative conceptual models of features and processes that are consistent with available data and current scientific understanding and evaluate the effects that alternative conceptual models have on the performance of the geologic repository. (d) Consider only events that have at least one chance in 10,000 of occurring over 10,000 years. (e) Provide the technical basis for either inclusion or exclusion of specific features, events, and processes in the performance assessment. Specific features, events, and processes must be evaluated in detail if the magnitude and time of the resulting radiological exposures to the reasonably maximally exposed individual, or radionuclide releases to the accessible environment, would be significantly changed by their omission…

Hence, the characterization of the uncertainty in the natural and engineered barriers was an important task of the PA. However, NRC did not establish an indicator and a corresponding measure for uncertainty in a performance assessment (e.g., a numerical limit on the "maximum" uncertainty permitted on the spread in the dose results) [3, p. 55748]. Rather, uncertainty was tied to reasonable expectation as the standard of proof where the characteristics of reasonable expectation are as cited in the previous section. Appropriately, there was no penalty for uncertainty; instead, it was to be fully addressed such that NRC could determine whether the agency had a reasonable expectation that DOE had "demonstrated the safety of the repository".

Concerning multiple barriers, NRC noted in the preamble [3, p. 55747].

> Part 63 not only requires DOE to account for uncertainty in its performance assessment but also contains a number of other requirements (e.g., use of multiple barriers, performance confirmation program) to compensate for residual uncertainties in estimating performance. The Commission will consider all these requirements in determining whether it has sufficient confidence (i.e., reasonable expectation) that DOE has demonstrated or has not demonstrated the safety of the repository.

Furthermore, NRC stated [3, p. 55758]:

> …Consistent with the Commission's risk-informed and performance-based regulatory philosophy, DOE is provided flexibility for deciding the extent and focus of site characterization. As the repository designer, DOE may place greater or lesser reliance on individual components of the repository system when deciding how best to achieve the overall safety objective.

NRC removed the quantitative requirements on the multiple barriers used in 10 CFR 60 (Table 4). By 1992, NRC staff had questioned their effectiveness [144, p. 857] and NAS had recommended their removal in 1995 as noted above [131]. Because the barrier criteria had been specified deterministically, they had been somewhat ambiguous within the probabilistic framework of the EPA radiation protection standards unless reasonably interpreted as limits on mean values. NRC replaced the quantitative requirements with a requirement in §63.115 to identify the barriers important to waste isolation, based on the PA, and describe the technical basis for their capability. Also, qualitative siting criteria, which had been in 10 CFR 60, were removed in 10 CFR 63, since they were, in concept, subsystem requirements.

In summary, NRC explicitly defined the important role of a PA in demonstrating compliance in 10 CFR 63. Following this change by NRC, DOE based disqualifying conditions in the 10 CFR 963 siting guidelines on PA results, as mentioned earlier.

3.2.5. Remand of 40 CFR 197

In addition to challenges on the site selection process mentioned earlier (which were over-ruled or not ripe for decision), environmental groups and the State of Nevada challenged the EPA on 40 CFR 197. In 2004, the US Court of Appeals for the DC Circuit vacated the portion of 40 CFR 197 specifying a regulatory period of 10^4 years. Although the period was consistent with other regulations (e.g., the 1985 40 CFR 191 and 1986 guidance on no-migration petitions for hazardous, non-radioactive waste in 40 CFR 268.6 [145]), the US Court of Appeals did not think consistency with other EPA regulations was pertinent [107]. The Appeals Court stated "In sum, we vacate 40 CFR Part 197 to the extent that it incorporates a 10,000-year compliance period because, contrary to the Energy Policy Act, Section 801(a), that compliance period is not 'based upon and consistent with the recommendations of the National Academy of Sciences', which recommended a regulatory period to the time of peak risk [131,146].

In response to the remand, EPA proposed in 2005 to set limits on dose for two periods: a limit on peak dose of 0.15 mSv/year for the *mean* of simulations before 10^4 years and 3.5 mSv/year for the *median* of simulations beyond 10^4 years through the period of geologic stability, which was ~10^6 years for Yucca Mountain (i.e., $d_{limit}(t < 10^4$ yr$)=0.15$ mSv/yr and $d_{limit}(10^4 < t < 10^6$ yr$)=3.5$ mSv/yr) [146] (Table 4). Furthermore, EPA again updated the CEDE dose calculation to be consistent with the smaller weighting factors on organs and dose coefficients for actinide ingestion currently recommended by the ICRP in Publication 60 and Publication 72 and reflected in the Federal Guidance Report 13 [121; 146, Appendix 1].

3.2.6. Repromulgation of 40 CFR 197 and 10 CFR 63

The regulatory framework for Yucca Mountain was completed shortly after the submission of the PA-LA (Appendix B). In June 2008, EPA repromulgated 40 CFR 197 in September 2008, that (1) lowered the maximum dose limit d_{limit} $(10^4 < t < 10^6)$yr to 1 mSv/yr, consistent with the IAEA model standard in 2006 and ICRP recommendation in 1997 [33; 147; 148, p. 61264]; (2) selected the mean as the measure of interest throughout the regulatory period rather than the proposed median beyond 10^4 years; (3) made a subtle change to the description

[33] NRC adopted the same terminology for two subtly different concepts on another topic in 10 CFR 63. Traditionally, NRC had used the term total effective dose equivalent (TEDE) to mean the sum of the external and internal doses. Yet, the NRC term TEDE differed from the similar EPA term annual CEDE in the manner in which the external dose was calculated. The NRC used a deep dose equivalent method for worker exposure, as measured with film badges. However in 10 CFR 63, NRC redefined TEDE to have the same meaning as the EPA effective dose equivalent approach but only when calculating external dose for the post-closure assessment [3, p. 55734 and Section 63.2].

of the probability criteria for screening FEPs from 10^{-4} over 10^4 years to 10^{-8} annually, and (4) required DOE to consider the effects of water table rise during seismic events, subject to requirements promulgated by NRC [148]. The first three changes had no impact on PA–LA, since both the mean and median doses had been presented ($\overline{D}(t)$ and $^{50\%}D(t)$) and were far below 1 mSv/yr and the FEP screening criteria was intended to be similar [23, Fig. 4]. The fourth change required a supplemental analysis that included water table rise in the seismic scenario class, similar to that evaluated in the Performance Margin Analysis (PMA) that accompanied the PA–LA [28, Fig. 4].

In March 2009, NRC promulgated 10 CFR 63 that adopted the EPA changes [149]. In addition, NRC, in guidance in the YM review plan [150], required a display of the 5th and 95th percentiles of dose about the expected value, which, thereby, retained the original intent of 40 CFR 191 to not focus on one measure of the distribution but to examine the entire distribution.

With the change to a compliance over the period of geologic stability for Yucca Mountain (i.e., 10^6 years), EPA also adopted a strategy to define what was of regulatory interest regarding the uncertainty for three natural disruptive events (similar to the approach adopted in 1985 for anthropogenic events). For a seismic event, the behavior of interest was damage to the disposal drifts, failure of waste packages, and changes in the elevation of the water table under Yucca Mountain (not, for example, a fault blocking a path to the SZ). For an igneous event, the behavior of interest was an igneous event directly intersecting the repository and causing damage to waste packages, which then allows releases to the groundwater or atmosphere and eventually the biosphere (not, for example, an igneous dike in the far field that changes flow patterns). For climate change beyond 10^4 years, the behavior of interest was the increased water flow through the repository, which could be represented by constant climate conditions through the period of geologic stability.

4. Summary

While the evaluation of a radioactive waste disposal system presented new technical challenges for modeling, it also presented a societal challenge in selecting a disposal site and developing a consensus of 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 geology of 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 these technical and social-political uncertainties, narrow differences, and adjust policy (similar to the solution of a complex mathematical model by an iterative process of trial and error). Consequently, the interplay between developing policy, selecting a site, developing safety criteria, and creating a corresponding assessment technique is an important aspect of the history of the YM repository program.

4.1. Site selection

In general, from 1955 through the 1960s, AEC undertook scientific and engineered studies for deep geologic disposal in salt of HLW and SNF. But the endorsed concept of using multiple barriers to build a robust disposal system permitted first ERDA and then DOE, the successors of AEC, to evaluate other media on land currently owned by the federal government in the 1970s. In 1976, USGS noted that the region around the 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, 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 (Appendix A). Furthermore, the ability to use large waste packages in the UZ facilitated direct linkage of the repository and nuclear reactor waste management practices and would eventually be appreciated as an additional advantage, as described in companion papers [26,30].

The concept of lowering overall program risk by using a portfolio of sites, preferably in different media, was first expressed by ERDA in 1976 when searching for up to 6 repository sites, recommended by IRG in 1979, required in NWPA in 1982, and codified by the siting guidelines in 1984 in 10 CFR 960. Thus, along with the first ranked YM tuff site and third ranked Deaf Smith bedded salt site, DOE added the fifth ranked Hanford basalt site to add diversity to the three site finalists. The diversity of sites being considered in the international community indicates that many different media can safely host a repository. In the future, several sites may need to be simultaneously under consideration to reduce program risk, but diversity of media should not be particularly necessary as noted as early as 1985 [44, Appendix B].

4.2. Legal and regulatory basis

4.2.1. Nuclear Waste Policy Act and amendments

In NWPA, Congress reaffirmed 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. 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 acting as a host; (2) provide funding for many decades though 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 site selection process and schedule for selecting the first repository site between 1983 and 1987, as noted above, did not soothe State fears: the search for a second repository heightened anxiety in the eastern US and was indefinitely delayed by the executive branch in 1986. Furthermore, Congress included the repository program under the budget balancing process in 1987, which introduced uncertainty in financial support. In 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 the State of Nevada, and eventually led the Obama Administration in 2010 to declare the YM repository as an unworkable solution, and bring a practical stop to the project by eliminating all funding for review by NRC and defense by DOE of the license application.

4.2.2. Radiation protection standards and implementing regulations for SNF and HLW

Between 1976, when President Ford directed EPA to develop radiation protection standards, and 2008 and 2009, when EPA and NRC finalized their regulations, the US regulatory agencies worked diligently to formulate a notion of safe disposal for SNF, HLW, and TRU (Appendix B). EPA initially selected cumulative release to a large population as the primary indicator of health impact in its 40 CFR 191 standards in 1985 [112], as measured at 5 km from the repository perimeter, after 10^4 years, and normalized by the mass disposed in the repository. As a new regulatory concept for the measure, EPA required inclusion of uncertainty (expressed as a CCDF), 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 and GCD).

In 1992, Congress mandated EPA to seek advice from NAS and to use individual dose as the indicator of health impact, consistent with the international community, in a site-specific regulation for Yucca Mountain. Hence, a dose measure was also calculated for PA-93 and PA-95, and solely for PA–VA. In 2001, EPA promulgated the site-specific radiation protection standards 40 CFR 197 that specified the mean peak dose calculated at a point no further south than the southern boundary of NTS, ~18 km from the repository, over 10^4 years as the performance measure with a limit of 0.15 mSv/yr. This measure was used for PA–SR, but prompted changes in site characterization (e.g., more of the SZ had to be characterized when changing from a 5-km to ~18-km compliance boundary). In response to a court ruling, EPA also extended the regulatory period to 10^6 years. The revised rule had a limit of 1 mSv/yr for the period beyond 10^4 year in 2008. 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 [119].

The treatment of uncertainty related to the disruptive inadvertent human intrusion scenario class 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) to avoid evaluating a wide spectrum of speculative futures and technology in 40 CFR 191. However, the treatment has evolved from the strategy promulgated in 40 CFR 91, in which releases from inadvertent human intrusion were included in the general performance assessment, conditioned by their probability based on frequency of drilling intrusion. Currently, the inadvertent human intrusion event is a stylized calculation that is not included in the probabilistic dose calculations for 40 CFR 197, consistent with the NAS recommendation.

The regulatory requirement to treat uncertainty quantitatively through the use of numerical models to evaluate the measure was successfully implemented for WIPP, GCD, and the SAR/LA for Yucca Mountain. Although the site-specific EPA and NRC regulations for Yucca Mountain will not directly apply to another repository, the 33-year experience will likely make selection of a hazard indicator, its measure, the evaluation of uncertainty, and the standard of proof less trying in the future such that the radiation protection standards and 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 new repository programs.

4.3. Insight

Collectively, the US spent over 30 years selecting a site, and then iteratively developing regulatory concepts of safe disposal over 10^4–10^6 years (hundreds to tens of thousands of generations), characterizing the natural barrier, and designing the engineered barrier of the YM disposal system. However, this effort did 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.

The Blue Ribbon Commission (BRC) on America's Nuclear Future, formed by Presidential direction in 2010 to review current waste management policy, recommended in January 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 the DOE endorsed in January 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 [39, p. viii; 151].[34] 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 several communities, might find that "their interests have been adequately protected and their well-being enhanced" [39, p. xv]. Scientists and engineers can then provide the necessary knowledge of the behavior of the natural barrier complemented with added features in the engineered barrier to evaluate whether a particular approach for a disposal system meets regulatory concepts of safe disposal for future generations.

Acknowledgments

Sandia National Laboratories (SNL) is a multi-program laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the DOE National Nuclear Security Administration under contract DE-AC04-94AL85000. The authors wish to thank L.A. Connolly, SNL, for help with references, and S.K. Best, Raytheon, for illustration support. The historical perspective and opinions presented are those of the authors and are not necessarily those held by reviewers, SNL, or DOE. As a historical perspective, the authors are reporting on the work of others; however, any interpretative errors of documentation are those of the authors alone. Each performance assessment discussed in this paper required numerous participants with expertise in many areas of science and technology. The most complete listing of these participants is made by examining the extensive reference list; however, many of references are corporate documents without authors. Therefore, some of the persons, who made an important contribution to the topic of this paper, are acknowledged here. Specifically, several geologists at USGS were prominent in background work and eventual siting of a geologic repository at NTS, including W.W. Dudley Jr. and W.E. Wilson [78]. Other USGS scientists cited herein include: I.J. Winograd (suggested disposal in the UZ [53] and volunteered for peer reviews but never part of the formal evaluation of YM [152]); F.E. Rush [58]; R.K. Waddell [59]; E.H. Roseboom (summary of siting in arid regions [75]); R.W. Spengler (analysis of first drill hole at Yucca Mountain [64]). In addition, geologists and other scientists at SNL, LLNL, and LANL become involved in the selection of a site and repository horizon: J.K. Johnstone, SNL (tuff unit evaluation for site selection [67,76]); R.R. Peters, SNL (tuff unit evaluation [76]); F. Bingham, SNL; J. Fernandez, SNL site selection [73]; S. Sinnock, SNL (site selection [72]); K. Wolfsberg, LANL (sorption studies of tuff [66]); B. Crowe, LANL (siting in tuff [69]); D. Bish, LANL; and DB Wilder, LLNL. Others who contributed include T. Cotton, JKA; M.D. Voegele,

[34] Many of the key elements endorsed by the 1979 consensus report of the IRG [55] and WIPP legislation [88] were endorsed in the consent-based siting process recommended by BRC in 2012. For example, BRC noted that "Transparency, flexibility, patience, responsiveness, and a heavy emphasis on consultation and cooperation will all be necessary..." for implementing siting and waste management [39, p. ix]. This collaboration is similar to the process of consultation and state concurrence encouraged by IRG in which conflicts between the state and the federal government were to be worked out through dialog and accommodation, as mentioned in Section 2.2.3 [55]. Similarly, consultation and cooperation of the federal government with the state was used successfully for WIPP, where the State of New Mexico came to cautiously welcome its presence and accept a federal agency as the facility owner [38;98].

SAIC/TRW/BSC; J. Younker, SAIC (early site suitability evaluations [153]); P. Gnirk, RE/SPEC (support to DOE for development of site guidelines in 10 CFR 960); and L Merkhoffer, ADA (decision analysis). Because so many were involved in site selection at YMP, the authors recognize that this list is unavoidably incomplete, and we apologize for omissions and oversights. Furthermore, geoscientists from USGS and elsewhere were also extensively involved in site characterization as mentioned in a companion paper [25].

Appendix A. Progression in the selection of Yucca Mountain

NTS Selected

1950 Dec: Nevada Proving Grounds (later Nevada Test Site or NTS and finally Nevada National Security Site) selected for nuclear weapons testing; first test (Able) in Jan following year.

1952 Idaho National Lab (INL) completes Radioactive Waste Management Complex (RWMC) for storage of nuclear waste [38].

1955 Sep: Atomic Energy Commission (AEC), formed in 1946, asks National Academy of Science (NAS) to examine disposal of high-level waste (HLW); NAS holds workshop with 65 scientists at Princeton [43].

1957 Sep: NAS recommends 1st examining HLW disposal in salt [43]. NAS notes solidifying HLW would facilitate disposal. Oak Ridge National Lab (ORNL) begins research in salt below recently closed Naval Air Station in Hutchinson, KS [6] and US Geological Survey (USGS) begins survey of salt formations (Fm); draft available following year: final published in 1962 [38, Fig. 1]. **Dec:** 1st commercial nuclear reactor starts in Pennsylvania.

1961 Jul: Based on studies in 1958, ORNL examines salt beds at a Carey salt mine near Hutchinson, KS. ORNL concludes that disposal of liquid HLW in salt impractical [45, Ch 2].

1962: ORNL begins Project Salt Vault, an underground research lab (URL) at an abandoned Carey salt mine near Lyons, KS [45, Ch. 3].

1965 ORNL places 14 spent nuclear fuel (SNF) assemblies in floor and heaters in pillars at Carey mine [154]. SNF retrieved in 1967 [44, App. A].

1966 NAS suggests placing HLW in unsaturated zone (UZ) in desert [53].

1969 May: Rocky Flats Plant near Denver catches fire. Shipment of debris to Idaho increases attention on nuclear waste disposal [38].

1970 Jun: AEC tentatively selects Carey salt mine near Lyons as repository for transuranic (TRU) waste and HLW [6, p. 67; 155]. **Nov:** NAS reports bedded salt satisfactory for waste disposal [38].

1971 After drill holes and solution mining found at Lyons [6, p. 69], Congress directs AEC to stop project until safety certified.

1972 Winograd of USGS proposes use of thick alluvium in UZ for HLW disposal [52]. **Jan:** AEC develops 3 options: look for another salt site; examine other media such as granite and basalt; or build surface storage facility [10, p. 78]. **Feb:** AEC asks USGS to again look for salt sites [44]. **May:** AEC abandons Lyons project and announces plans for 100-yr storage (later called Retrievable Surface Storage Facility or RSSF) to allow time to develop a repository [6, p. 75]. Nevada Senator Cannon urges AEC to use NTS for reprocessing and waste disposal [10, p. 92].

1973 Nationwide search for suitable salt site resumed. USGS and ORNL recommend salt beds in southeastern NM [38].

1974 Winograd of USGS elaborates on use of thick alluvium in UZ for HLW disposal [53]. **May:** India detonates Pu bomb using material and technology supplied by US for peaceful purposes. Pacific Northwest National Lab (PNNL) completes 1½-yr review of alternatives for HLW/SNL including storage on surface or deep geologic facilities and disposal in seabed, ice sheets, space, injection wells, cavities (with or without transmutation) [49]. **Sep:** AEC issues draft environmental impact statement (EIS) emphasizing reprocessing and RSSF [156]. **Nov:** Environmental Protection Agency (EPA) and anti-nuclear groups claim RSSF de facto disposal in comments on EIS [6, p. 76].

1975 Because of unemployment in southern Nevada, state legislature passes resolution urging Energy Research and Development Administration (ERDA), successor to AEC, to choose NTS for storage and processing of nuclear material [90]. USGS develops conceptual model for regional groundwater flow at NTS [157]. **Apr:** ERDA abandons RSSF concept [44, App. A]. **May:** Sandia National Labs (SNL) as new project lead, recommends site in center of Delaware Basin of SE NM for Waste Isolation Pilot Plant (WIPP) for TRU waste [38].

1976 Feb: ERDA sets up National Waste Terminal Storage (NWTS) Program (successor to AEC Geologic Disposal Evaluation Program for salt started in 1974) to search for sites in variety of media and to develop technology and facilities primarily for commercial HLW/SNF. **May:** In change from 1974 draft EIS, ERDA issues 5-volume report on 2 options for radioactive waste storage (continue burial or deep geologic storage) and 6 options for disposal: deep boreholes, sub-seabed, cavities with rock melt, well injection, ice sheets, and space with and without transmutation) [57]. **Jun:** California enacts moratorium on building nuclear reactors until US demonstrates HLW disposal [6, p. 86]. **Jul:** USGS urges emplacing HLW at NTS [60, p. 4]. USGS and Sandia National Labs (SNL) 1st look at clay/shale/argillite in Eleana Fm at Syncline Ridge [158]. By 1977, granite at Twinridge Hill and Timber Mountain also examined [159]. **Oct:** President Ford orders demonstration of nuclear waste disposal; NWTS proposes up to 6 repositories with the 1st two in salt followed by 4 others in other rock types; the goal is a repository operating in a pilot phase as early as 1985 [45] and others between 1997 and 2006 [44, App. A]. Multiple repositories proposed to (a) spread burden of nuclear waste regionally; (b) allow direct storage or disposal of SNF in mines, which takes more area if not cooled on surface, (c) minimize impact should a site prove unacceptable. In response to Indian 1974 bomb test and prompted by position of Presidential Candidate Carter, President Ford defers reprocessing commercial SNF in favor of once-through fuel cycle [10, p. 108]. **Nov:** More geologic media feasible by using multiple barriers; thus, ERDA notifies 36 governors that it will look for repository sites in their states [6, p. 130].

USGS Suggests Disposal at NTS

1977 Apr: President Carter indefinitely defers reprocessing commercial SNF because of Pu proliferation concerns, opposes funding reprocessing at Barnwell, SC and opposes Fast Breeder Reactor at Clinch River, TN [6, p. 118]. These actions imply direct permanent storage/disposal of SNF. **Aug:** ERDA adds previous land use as criterion for identifying sites [56, p 2-11]. Discontent caused by letters to 36 governors, prompts ERDA to diligently explore Hanford and NTS for possible sites. **Oct:** Newly formed Department of Energy (DOE), successor of ERDA [37], establishes Nevada Nuclear Waste Site Investigations (NNWSI) Project to look at NTS [56]. Participants are SNL, Los Alamos National Lab (LANL), Lawrence Livermore National Lab (LLNL), and USGS [160]. President Carter proposes away-from-reactor (AFR) storage for SNF [10, p. 112].

Thick Tuff Found

1978 With cost increases and drop in orders for reactors, NWTS proposes 2 repositories sufficient [45, p. 61]. **Feb:** LLNL evaluates 30 granitic sites in southwestern portion of NTS [161]. **Mar:** President Carter forms Interagency Review Group (IRG), to study nuclear waste disposal [55, App. A]. **Apr:** DOE decides repository can be built in 100-km^2 area in southwestern portion of the NTS and not disrupt weapon tests [56, p. 2-14], which eliminates granite sites at Twinridge Hill and Timber Mountain and argillite site at Syncline Ridge. Also, borehole in Eleana Fm at Synclide Ridge finds argillite is structurally too complex [56, pp 1-13, 2-14]. SNL reports on effects of drying clay in heater experiments in Eleana Fm [162]. USGS identifies 5 sites in 100-km^2 area: Calico Hills, Wahmonie, Skull Mt, Jackass Flats, and Yucca Mt (YM). Borehole at Calico-Hills does not find granite within 900 m and finds argillite structurally too complex. Surface mapping and geophysical survey at Wahmonie finds granite mass is too small, faulted, and hydrothermally altered. Study of thick alluvium, such as at Jackass Flats, deferred because of its low thermal conductivity [163]. Also, Jackass Flats and Skull Mt not promising. Borehole UE25a#1, cored to ~750 m, finds thick tuff deposits at YM [64]. **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 [163]. **Jun:** USGS discusses issues related to characterizing a site, heat perturbation, groundwater movement, containment period, and supports using multiple barriers [50]. **Aug:** At request of Nuclear Regulatory Commission (NRC) (successor of AEC), NAS lists 7 characteristics of an ideal repository site and also recommends HLW disposal only (no high-value SNF) [87].

1979 Feb: SNL and LANL wrap-up adsorption/desorption experiments on argillite [164]. **Mar:** *The China Syndrome* movie released March 16; on March 28, Three Mile Island reactor accident occurs. IRG recommends mined geologic disposal, use of multiple barriers, looking for sites in variety of media in different regions of US, and not delaying disposal even though storage safe [55]. DOE identifies >200 granitic bodies in 17 eastern states. **Sept:** Because tuff not considered previously, DOE asks SNL and LANL to present suitability of tuff for HLW disposal to NAS [67]; NAS informally supports and 7 months later, NAS writes letter encouraging more study [45, p. 148]. **Oct:** USGS recommends thick layers of welded tuff at YM [163].

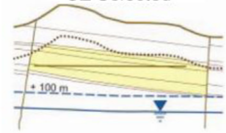
Mined Disposal Selected

1980 Feb: President Carter issues waste management policy proposing selecting 1-2 sites from 4-5 candidates with state participation [10, p. 122]. **Oct:** DOE issues EIS on options for commercial SNF management and selects mined geologic disposal with sub-seabed and deep boreholes as potential backup [70].

Fig. A1. Identification and selection of Yucca Mountain site [155–178]

1981 Mar: President Reagan withdraws AFR storage idea and lifts ban on reprocessing commercial SNF [44, App. A]. **Jun:** Winograd of USGS again proposes shallow burial in thick alluvium in desert (e.g., Sedan nuclear crater at NTS) for TRU waste [62]. His suggestion leads to use of UZ at YM the next year [75] and disposal of TRU and low-level waste (LLW) in 3-m diameter, 36-m deep boreholes at Greater Confinement Disposal (GCD) facility on NTS in 1984 [134, §1.2].

UZ Selected



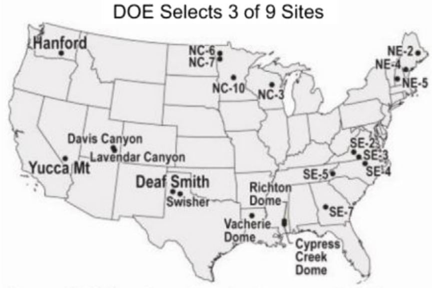
1982 Jul: After examining the Tram and Bullfrog units in SZ and Tuffaceous Beds of Calico Hills and Topopah Spring (TSw) units in UZ, USGS suggests ~350-m thick TSw unit [75]; **Aug:** Site Evaluation Working Group, organized in 1980, reports that YM remains preferred site out of 15 in southwest NTS [72].

NWPA Passed

1983 Jan: In *Nuclear Waste Policy Act* (NWPA) [1], Congress (a) selects geologic disposal option and exempts DOE from considering other alternatives in EIS; (b) requires DOE to identify 2 sites and operate one of them; (c) limits 1st repository to 70,000 MTHM until 2nd repository operating (for implied regional equity); (d) requires site selection guidelines; (e) sets timetable for nominating at least 5 sites, recommending 3 viable sites, and selecting and opening first repository by 1998; and (f) requires Environmental Assessment (EA) of viable sites. **Feb:** DOE identifies 9 sites already under consideration (7 salt sites: 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) [6, p. 229]. DOE publishes draft guidelines for selecting a site (10 CFR 960) [85]. **Mar:** DOE solicits comments from State of Nevada and public regarding nomination of YM and issues to discuss in EA and Site Characterization Plan (SCP) [163]. Gov Bryan declares nomination an unfair burden, already have NTS and waste might discourage growth of Las Vegas [91]. **Jun:** SNL formal unit evaluation supports 1982 USGS suggestion to use TSw [76]. **Dec:** ^{90}Sr, tritium, and other nuclear waste placed in GCD test borehole [134, §1.2].

1984 May: Disposal of 330 Ci of ^{239}Pu in 60 Mg of classified TRU waste from cleanup begins at GCD [134, §1.2]. **Dec:** DOE finalizes 10 CFR 960 site selection guidelines [86]. DOE issues draft EA on all 9 potential sites and nominates 5 sites for final EAs (YM; Davis Canyon, UT; Deaf Smith, TX; Richton Dome, MS; and Hanford, WA) [92]. Criticism of ranking prompts DOE to use multi-attribute utility analysis [93].

DOE Selects 3 of 9 Sites



1986 Apr: Chernobyl reactor accident. **May**: DOE recommends 3 sites (YM [56], Deaf Smith, and Hanford with ranking of 1,3 and 5 by multi-attribute study) to characterize for 1st repository [94]. 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 areas in 7 states for 2nd repository but postpones characterization because new reactors not being built [165], high characterization costs, and great concern in the east [7].

Congress Selects YM

1987 Dec: *Nuclear Waste Policy Amendment Act* (NWPAA) [97], (a) selects YM as sole site to characterize from 3 finalists; (b) affirms DOE decision to delay 2nd repository; and (c) sets up compensation schedule.

1989 Aug: Last of 2.3 MCi of LLW tritium disposed at GCD [134, §1.2]. **Nov:** Berlin Wall falls, signaling end of the Cold War and changing demands for nuclear material.

1991 Mar: Based on refusal of Supreme Court to review decision, US District Court orders Nevada to take action on 3 permits for characterizing YM [166]. **Sep:** 9th Court of Appeals rules ban on nuclear waste shipments imposed by Idaho Gov Andrus is illegal [167].

1992 Jan: For Congress, DOE completes Early Site Suitability Evaluation (ESSE) started in spring of 1991 using 10 CFR 960 criteria. ESSE finds no disqualifying conditions [153].

1994 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 [168].

1997 Congress calls for a viability assessment (VA) that includes a performance assessment (PA), a design of the repository and package, cost for completing the LA, and cost for constructing, operating, and closing the repository [169].

1998 Dec: VA shows YM remains a viable site [21].

1999 USGS [152], NWTRB [170], & NRC [171] agree YM viable site. **Jul:** Based on PA-VA, DOE publishes 1400-page draft EIS on either building YM or leaving waste at 77 sites around US [172]. **Nov:** DOE drafts guidelines (10 CFR 963) for evaluating YM suitability by using PA to examine whole system, following NRC precedent in 10 CFR 63 [103].

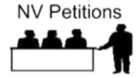
2000 Oct: DOE estimates ~3.4 tonnes of Pu used in 1054 detonations over 40 yr (tests stopped in 1992); of 1054 detonations, 100 atmospheric and 921 underground at NTS [79].

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" [173]. **Jul:** DOE releases Supplemental Science and Performance Analysis (SSPA) update to PA-SR [143]. **Aug:** DOE releases Preliminary Site Suitability Evaluation (PSSE) [22], which discusses site recommendation (SR) based on (1) proposed criteria in 10 CFR 963 [103] and (2) technical support in Science & Engineering Report (S&ER) describing PA-SR [22]. **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 transient becomes of concern relative to repository disposal. **Nov:** DOE finalizes site selection guidelines in 10 CFR 963 [104]. **Dec:** Supplement to draft EIS on YM completed, based on PA-SR [100].

Congress Approves YMP

2002 Feb: DOE completes final EIS on site selection (4904-pages including 2864-page response to comments in Vol. 3) [102], based on new PA-EIS [174], 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 review of draft, Energy Sec Abraham recommends YM to President Bush [105]. President Bush recommends YM to Congress. **Apr:** Nevada Gov Guinn disapproves the recommendation under special rules in NWPA. **May:** House overrides Nevada's disapproval 306 to 117 [175]. **Jul:** Senate overrides disapproval (60 to 39 to bring motion to floor, unrecorded voice vote for override). President Bush signs *Yucca Mountain Development Act*, authorizing DOE to apply to NRC for construction authorization [4]. **Aug:** US District Judge Campbell voids Utah laws passed to keep nuclear waste out of state by excessive fees and numerous permits [176].

Court Rejects NV Petitions



2004 Jul: DC Court of Appeals rejects all Nevada petitions on site selection process: NWPAA rendered moot challenges on site selection process [107].

2008 Jun: DOE submits Safety Analysis Report (SAR/LA) [5]. DOE submits final EIS on repository construction [177].

2009 Mar: Obama Administration funds only limited staff to respond to NRC requests for more information on SAR/LA [108]

Administration Halts YMP

2010 Feb: Administration zeros budget for YMP. **Mar:** DOE files motion with Atomic Safety Licensing Board (ASLB) to withdraw LA/SAR with prejudice because YMP "not a workable option" and "the Nation needs a different solution for nuclear waste disposal." South Carolina (SC) and Washington (WA) sue DOE. President directs DOE form Blue Ribbon Commission (BRC) to recommend a plan for nuclear waste management [39] (similar goal as IRG in 1978). **Jun:** ASLB denies DOE motion [108].

2011 Mar: After 9.0 earthquake in Japan (4th largest in world), 14-m tsunami causes electrical and pump failure. Without cooling, meltdown occurs at 3 of 6 units at Fukushima reactor, and SNF storage pool of 4th unit catches on fire. Safety of wet fuel storage becomes of concern. **Apr:** About $\$15\times10^9$ spent by DOE of which ~$\$11\times10^9$ spent for site selection, site characterization, and LA [178]. **Jul**: DC Appeals Court declines to intervene but suggests suing NRC. SC and WA sue NRC.

2012 Jan: BRC recommends a consent-based siting approach [39].

Fig. A1. (continued)

Appendix B. Legal and Regulatory Basis for Yucca Mountain Repository

1946 *Atomic Energy Act of 1946* [179] (a) establishes government monopoly on nuclear material, and (b) creates Atomic Energy Commission (AEC) with 5 commissioners to oversee monopoly.

1954 In *Atomic Energy Act of 1954* [40], Congress allows regulated, civilian atomic energy use; thereby, creating need to dispose larger quantities of nuclear waste [10, p. 18].

1970: Jan: President Nixon signs *National Environmental Policy Act* (NEPA) [47], which requires federal agencies to write an environmental impact statement (EIS) on any major action and present alternatives. **Jul:** Congress forms executive Environmental Protection Agency (EPA) and transfers to it research, monitoring, standard setting, and enforcement activities related to environment [35]. **Aug:** In 10 CFR 50, AEC requires commercial high-level waste (HLW) be solidified within 5 yr and delivered to repository 5 yr after solidified (1st nuclear waste regulation) [180].

1971 Appeals Court requires AEC to look at all environmental impacts in EIS for nuclear reactors.

1974 Oct: Congress splits independent AEC into [36] (1) independent Nuclear Regulatory Commission (NRC), to regulate civilian use of nuclear materials by defining what a licensee must demonstrate in a Safety Analysis Report (SAR) to show it meets EPA health limits and (2) Energy, Research, and Development Agency (ERDA) of executive branch, which is responsible for nuclear weapons, nuclear power research, and resulting radioactive waste, but with wider energy role.

1975 May: NRC promulgates guidance on how to provide "reasonable assurance" nuclear reactors meet "As Low As Reasonably Achievable (ALARA)" policy for limiting radiation exposure [181].

Ford Asks for EPA Standard

1976 Jul: DC Court of Appeals rules NRC reactor license must consider confidence of waste disposal; overturned by Supreme Court in 1978 [10, p. 100]. **Oct:** President Ford directs EPA to develop standards for spent nuclear fuel (SNF) and HLW disposal [112]. **Dec:** EPA announces intent to develop disposal standards [109].

1977 Jan: Congress forms Department of Energy (DOE) from ERDA [37]. **Feb:** EPA conducts public workshop to understand public concerns and technical issues of waste disposal [112]. NRC also begins work on waste disposal issues.

1978 Jan: EPA announces public forum to develop disposal criteria for radioactive wastes [182]. **Nov:** EPA publishes *Criteria for Radioactive Wastes* and seeks comments [183]. NRC publishes general policy for licensing steps and seeks comments [184].

1979 May: DC Court of Appeals Court rules NRC must assess degree of confidence that wastes from nuclear reactors can be safely stored until disposed [10, p. 169]. **Oct:** NRC begins deliberations on waste confidence rule [185]. **Dec:** NRC withdraws general policy and proposes licensing steps [186].

1980 Dec: *Low-Level Waste Policy Act* (LLWPA), defines low-level waste (LLW) by what it is not [41].

NRC Sets Licensing Steps

1981 Feb: In its implementing HLW regulation (10 CFR 60) NRC promulgates licensing steps, such as on-the-record, trial-like hearings for construction t licensing in front of Atomic Safety Licensing Board (ASLB), and requires steps such as a Site Characterization Plan (SCP) [122]. **Mar:** Developing generic disposal criteria is difficult; thus, EPA starts standards for each type of radioactive waste [112,§1.2]. NRC proposes technical criteria for 10 CFR 60.

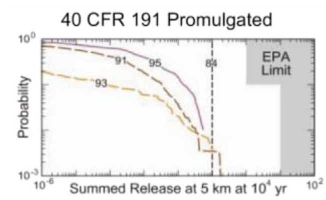
EPA Drafts 40 CFR 191

1982 Apr: Congressional Office of Technology Assessment (OTA) finds that national policy issues overshadow technological problems of nuclear waste disposal. **Dec:** EPA proposes disposal standard, 40 CFR 191, for HLW, SNF, and transuranic (TRU); draft defines performance assessment (PA), sets a population-based release limit for nuclides at 10 km boundary, and requires displaying a distribution of uncertain results (implying numerical modeling) [114].

NWPA Passed

1983 Jan: In *Nuclear Waste Policy Act* (NWPA) [1], Congress (a) selects geologic disposal option and exempts DOE from considering other alternatives in an EIS; (b) directs promulgation of EPA and NRC disposal regulations; (c) requires NRC to comment on sufficiency of site characterization analysis prior to SR; (d) defines State disapproval and override procedure, and (e) requires DOE to contract with utilities to dispose of waste to provide disincentive for administration policy changes. **Jan-Sep**: EPA Science Advisory Board (SAB) holds 9 public meetings on 40 CFR 191 [187]. **Apr:** In 10 CFR 961, DOE publishes contract between DOE, 68 utilities, and 7 other commercial waste owners for disposal of commercial SNF and HLW and payment of fees into the Nuclear Waste Fund [188]; contract gives utility with oldest fuel priority in queue but does not require utility to ship its oldest fuel. **Jun:** NRC promulgates technical criteria in 10 CFR 60 that sets 3 deterministic criteria on subsystems: 300-1000 yr container life, release rate limits on engineered barrier, and 1000 yr travel time in geologic barrier [2]. **Aug:** Procedures promulgated for exchanging data between NRC and DOE for independent evaluation [189].

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 a factor of 10 to 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 [187]. **Aug:** NRC promulgates waste confidence rule stating capacity will eventually be available; NRC will review in 5 yr [185].



1985 Jul: NRC adds criteria to 10 CFR 60 for repository in the UZ [123]. **Sep:** EPA promulgates 40 CFR 191 that sets 5 km boundary, clarifies inclusion of uncertainty to provide an estimate of "reasonable expectation," retains FEP screening criteria of 10^{-4} in 10^4, rounds limits (L_i) and often increases a factor of 10, and increases probability for 1st level of limiting distribution from 0.01 to 0.1 and second level from 10^{-4} to 10^{-3} [112].

1986 Jan: Congress assigns responsibility for greater-than-class-C (GTCC) LLW to federal government in *Low-Level Waste Policy Amendments Act of 1985* (LLWPAA) [42]. **Jul:** NRC revises licensing procedures in 10 CFR 60 to agree with steps in NWPA [190]. **Aug:** NRC promulgates probabilistic safety goals for nuclear reactors that continues trend started with EPA probabilistic 40 CFR 191 [191].

1987 Jul: In response to challenges to Individual and Groundwater Protection Requirements, 1st Court of Appeals remands 40 CFR 191 but affirms use of "reasonable expectation" as standard of proof [119].

1989 In response to LLWPAA, NRC amends 10 CFR 61, regulation for LLW, to require disposal of GTCC LLW in geologic repository unless NRC approves other method. **Apr:** Based on deliberations in July 1988 by representatives from NRC, DOE, Nevada governments, industry, Native Americans, and environmentalists, NRC promulgates in 10 CFR 2 (a) procedures for licensing hearings, and (b) process of submitting documents related to LA electronically in a Licensing Support System (later called Licensing Support Network or LSN) "to permit early submission of better focused contentions." [192] **Jul:** NRC clarifies need in 10 CFR 60 to update EIS when applying for authorization to construct, operate, or close [124].

1990 Sep: NRC reaffirms confidence in geologic disposal and adds by 2025; will review in 10 yr [193]. **Nov:** International Commission of Radiation Protection (ICRP) sets limit of 1 mSv/yr for public (average from natural sources at sea level except radon exposure) [121, ¶191].

Congress Asks for New EPA Standard

1992 NRC and DOE reach agreement on procedures for interactions during the pre-licensing period [194]. **Oct:** Congress, in the *Energy Policy Act of 1992 [128]*, requires (a) EPA to promulgate a site-specific standard using a dose criterion for a repository at Yucca Mt (YM), (b) EPA to seek advice from the NAS, and (c) NRC to revise 10 CFR 60, to agree with new EPA standard.

1993 Feb: EPA announces intent to draft 40 CFR 194 to implement 40 CFR 191 at WIPP [195]. **Dec:** In response to court remand [119] and *WIPP Land Withdrawal Act*, EPA revises 40 CFR 191 and sets the dose limit at 0.15 mSv/yr over 10^4 yr [120].

Fig. B1. Legal and regulatory basis for radioactive waste disposal at Yucca Mountain [179–217]

1993 Feb: EPA announces intent to draft 40 CFR 194 to implement 40 CFR 191 at WIPP [195]. **Dec:** In response to court remand [119] and *WIPP Land Withdrawal Act*, EPA revises 40 CFR 191 and sets the dose limit at 0.15 mSv/yr over 10^4 yr [120].

NAS Advises

1995 Mar: For site-specific regulation on YM, NAS advises (a) risk calculation to whenever dose is largest (likely within 10^6-yr period), (b) eliminating subsystem requirements, and (c) suggests reporting only consequence from human intrusion [131]. **May:** DOE notifies utilities that it does not have obligation to accept SNF by 1998 [196]. **Jun:** NRC policy statement calls for detailed modeling with unbiased parameters in analysis for NRC, including PAs [138].

1996 Jul: DC Court of Appeals vacates DOE interpretation and rules that DOE will be liable for missing 1998 contract deadline [197]. **Dec:** NRC clarifies terms in 10 CFR 60 [125].

ICRP Advises 1 mSv/yr

1997 Jan: To meet NWPA requirement to comment on site characterization sufficiency, NRC identifies 9 key technical issues (KTIs) important to repository performance (plus a 10^{th} issue related to promulgating 10 CFR 63). NRC decides to periodically write reports on the 9 KTI topics [198] and conduct technical exchanges with DOE to facilitate resolution. **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. ICRP makes no recommendations for use of a collective, population dose [147]. **Nov:** DC 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 [199].

1998 Feb: Utilities petition DC Court of Appeals to force DOE to accept waste [200]. NRC completes 1^{st} version and 1^{st} revision of 9 reports on KTIs. **Sep 97 & Aug:** Evolution of the Near-Field Environment (ENFE) technical exchange [194]. **Mar & Nov:** Container Life and Source Term (CLST) [201]. **Apr & Nov:** Total System Performance Assessment and Integration (TSPAI) [202].

EPA Drafts 40 CFR 197

1999 Feb: In draft 10 CFR 63 for YM, NRC proposes [203] (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. Energy Sec Richardson proposes to take title of commercial SNF and assume management of onsite storage; cost estimates for storage until 2010 are between \$2 and \$3 $\times 10^9$ to be paid by Nuclear Waste Fund. Nuclear opponents reject idea because they want to punish utilities by keeping them liable for waste problems; utilities reject idea because it removes pressure to open repository [204]. **Aug:** In draft 40 CFR 197 for YM, EPA proposes [132] (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) 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 [205, p. 5-1].

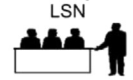
NRC Adopts Reasonable Expectation

2001 Apr: While encouraging more informal hearings, NRC retains formal hearings for construction, receipt, and closure licensing at repositories [206]. **May:** In change to 10 CFR 2, NRC adopts DOE suggestion to require electronic access to documents 6 months prior to submission of LA [207]. **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 [133]. Nevada petitions DC Court of Appeals to declare 40 CFR 197 invalid since it does not require geology as primary barrier. **Nov:** NRC promulgates 10 CFR 63, which adopts EPA concept of reasonable expectation, 0.15 mSv/yr dose limit, equates TEDE to annual CEDE, 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. [3]. NRC issues sufficiency review stating confidence that DOE will have sufficient information in LA to resolve issues [205, p. 5-4].

2002 Apr: Using arguments similar to June lawsuit, Nevada petitions DC Court of Appeals to declare 10 CFR 63 invalid since regulations do not require geologic criteria [208]. **Sep:** 11^{th} Court of Appeals rules settlement between Peco Energy, operator of 3 Peach Bottom reactors, and DOE to allow Peco to offset Nuclear Fund fee in lieu of charging a fee for storing waste is not proper. All taxpayers must pay for damages for contract breech, not a subset of taxpayers through utility fees [209].

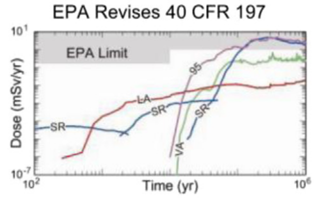
2003 Jul: NRC releases final version of LA review plan, which is developed to maintain consistency during review [150].

Court Vacates 40 CFR 197 & ASLB Rejects LSN



2004 Jun: DOE places ~1.2 million documents including ~700,000 e-mails (~5.6 million pages) in LSN [210]. **Jul:** DC Court of Appeals rejects Nevada lawsuits except Court vacates portion of 40 CFR 197; Court states EPA rejected, without sufficient basis, NAS advice [131] for a regulatory period to when dose is largest [107]. ASLB rejects initial certification of LSN. ASLB notes ~4 million e-mails from personnel no longer with YMP had not been reviewed for their relevancy [211].

EPA Revises 40 CFR 197



2005 Aug: In draft revision of 40 CFR 197, EPA extends period of compliance to 10^6 yr and proposes a peak dose limit of 0.15 mSv/yr for mean of simulations for 1^{st} 10^4 yr and 3.5 mSv/yr for *median* of simulations between 10^4 and 10^6 yr [146]. **Sep:** As requested by EPA, NRC defines model style for climate change beyond 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 [212].

IAEA selects 1 mSv/yr

2006 May: International Atomic Energy Agency (IAEA) publishes its 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 [33].

2007 May: DOE announces the LSN contains 3.4 million documents related to YMP [213]. **Dec:** ASLB rules that certification of LSN in October is valid and DOE may continue to add important documents to the LSN [214].

NRC Dockets LA

2008 Sep: NRC dockets the LA SAR seeking construction authorization [215]. EPA re-promulgates 40 CFR 197 with 3 changes from draft: dose limit beyond 10^4 yr lowered to 1 mSv/yr; FEP screening criterion restated as annual probability of 10^{-8}, and mean selected as the measure of interest throughout regulatory period [148].

2009 Mar: NRC re-promulgates 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 with mean of 41 mm/yr, based on more analysis [149].

2010 Aug: NRC staff releases Vol 1 of Safety Evaluation Report (SER) discussing general information submitted in LA SAR. **Dec:** NRC update waste confidence rule stating repository will be available and waste can be stored at reactor for 60 yr beyond licensed operation [216].

2011 Jul: As part of closing YM review, NRC staff release Vol 3 of SER on technical evaluation of post-closure aspects of LA SAR [217]. No conclusions, but document supports DOE technical claims on YM performance. **Sep:** NRC staff release portion of Vol 2 of SER on evaluation of pre-closure aspects of LA SAR. NRC Commissioners divided on whether to overturn ASLB decision to deny DOE motion to withdraw LA SAR but affirm Chairman's decision to close NRC activities related to YM because of a lack of funding from Congress.

2012 Sep: In response to court remand of waste confidence rule, NRC Commissioners request staff develop EIS on extended storage and waste confidence within 2 yr.

Fig. B1 (continued)

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