Reliability Engineering and System Safety 122 (2014) 53–73

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

Evolution of repository and waste package designs for Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste

Rob P. Rechard [a,*], Michael D. Voegele [b]

[a] Nuclear Waste Disposal Research & Analysis, P.O. Box 5800, Sandia National Laboratories, Albuquerque, NM 87185-0747, USA
[b] 7404 Oak Grove Avenue, Las Vegas, NV 89117, USA

ARTICLE INFO

Available online 18 July 2013

Keywords:
Repository design
Container design
High-level radioactive waste
Radioactive waste repository
Performance assessment
Yucca Mountain

ABSTRACT

This paper summarizes the evolution of the engineered barrier design for the proposed Yucca Mountain disposal system. Initially, the underground facility used a fairly standard panel and drift layout excavated mostly by drilling and blasting. By 1993, the layout of the underground facility was changed to accommodate construction by a tunnel boring machine. Placement of the repository in unsaturated zone permitted an extended period without backfilling; placement of the waste package in an open drift permitted use of much larger, and thus hotter packages. Hence in 1994, the underground facility design switched from floor emplacement of waste in small, single walled stainless steel or nickel alloy containers to in-drift emplacement of waste in large, double-walled containers. By 2000, the outer layer was a high nickel alloy for corrosion resistance and the inner layer was stainless steel for structural strength. Use of large packages facilitated receipt and disposal of high volumes of spent nuclear fuel. In addition, in-drift package placement saved excavation costs. Options considered for in-drift emplacement included different heat loads and use of backfill. To avoid dripping on the package during the thermal period and the possibility of localized corrosion, titanium drip shields were added for the disposal drifts by 2000. In addition, a handling canister, sealed at the reactor to eliminate further handling of bare fuel assemblies, was evaluated and eventually adopted in 2006. Finally, staged development of the underground layout was adopted to more readily adjust to changes in waste forms and Congressional funding.

© 2013 Elsevier Ltd. All rights reserved.

1. Introduction

In 2008, the US Department of Energy (DOE) submitted the Safety Analysis Report for a License Application (SAR/LA) to the US Nuclear Regulatory Commission (NRC) in order to construct a repository at Yucca Mountain for high-level radioactive waste (HLW), commercial spent nuclear fuel (CSNF), and DOE-owned SNF (DSNF). Yucca Mountain (YM), located at the boundary between the Nellis Air Force Range and the Nevada National Security Site (formally known as the Nevada Test Site or NTS),[1] had been under consideration for a radioactive waste repository since 1978 (Fig. 1).

While many of the scientific characterization issues related to Yucca Mountain have been discussed in the literature over the years, much of the technological and engineering designs are in project reports. Hence, this paper presents the evolution of the repository and engineered barrier design in order to provide a historical perspective on the performance assessment (PA) underlying the SAR/LA described in this special issue of *Reliability Engineering and System Safety*. Companion papers describe the site selection, site characterization, and evolution of the modeling system for the PA [1–9]. Although part of the engineering strategy for the YM repository was recently summarized [10,11], this paper provides further background and historical context.

Seven PA iterations provide convenient points to discuss the status of Yucca Mountain Project (YMP) over the years. In 1982 and 1984, deterministic analyzes of volcanic eruptive doses and undisturbed groundwater releases, collectively designated herein as PA-EA [12,13], were conducted for the draft and final Environmental Assessments (EA) required by the *Nuclear Waste Policy Act of 1982* (NWPA) [14]. PA-EA provides the initial marker for the paper. The first stochastic PA, conducted in 1991 (PA-91) [15], serves as the second marker. PA-93 and PA-95, which serve as the third and fourth markers, respectively, provided preliminary guidance on site characterization and repository design [16, Fig. 1-1,17]. The Congressionally requested viability assessment (PA-VA), completed in 1998, serves as the fifth marker [18]. The conclusion of site characterization culminated with an analysis in late 2000 for the site recommendation (PA-SR) and serves as the sixth marker [19]. PA-LA, which forms the basis of the SAR/LA, serves as the final marker.

* Corresponding author. Tel.: +1 505 844 1761; fax: +1 505 844 2348.
E-mail address: rprecha@sandia.gov (R.P. Rechard).

[1] Because the area was known as the Nevada Test Site during most of the disposal system characterization of Yucca Mountain, this paper and companion papers use NTS rather than the current NNSS acronym.

0951-8320/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ress.2013.06.018

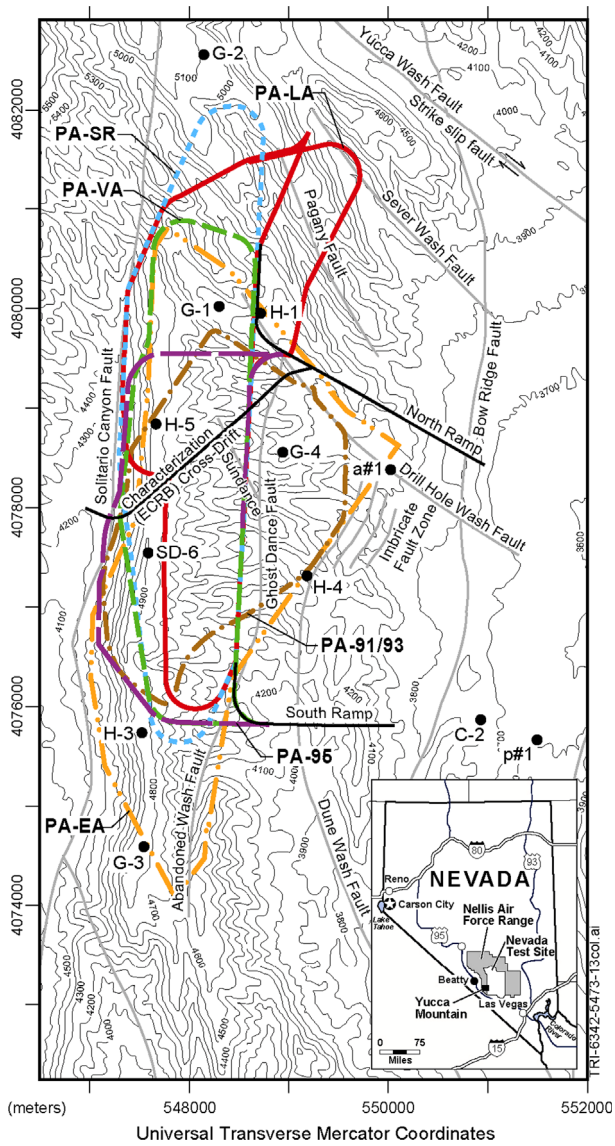


Fig. 1. Location and extent of various proposed layouts for Yucca Mountain repository.

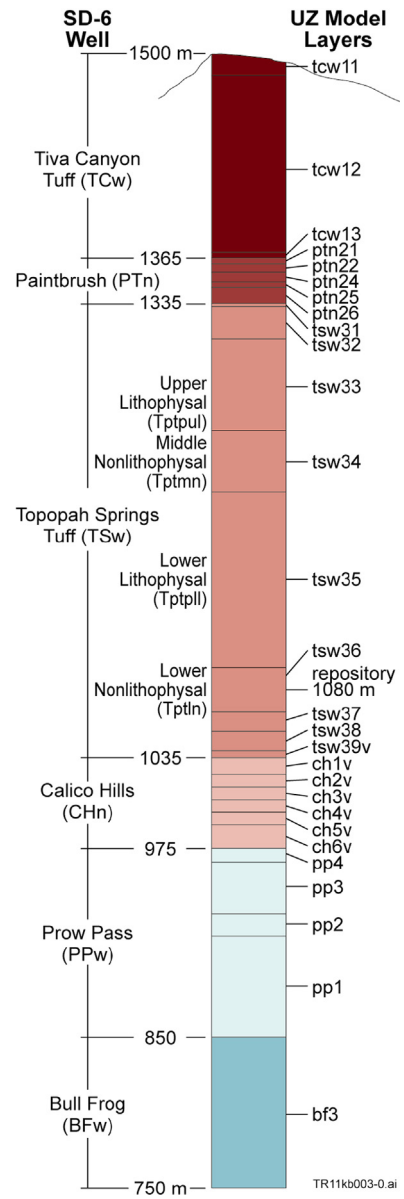


Fig. 2. General stratigraphy of Yucca Mountain at SD-6 borehole [16, Figs. 6 and 7, 25, Fig. 6.3.1-8].

2. Design of engineered system

The design of the repository has varied considerably over the life of YMP as the understanding of the geologic barrier has increased, the techniques for excavation have advanced, and desires for large containers for high throughput have been expressed (Fig. 1). Initially, the favored horizon for a repository at NTS was in the saturated zone (SZ), but the US Geological Survey (USGS) had suggested disposal of HLW in the UZ and alluvium in the 1970s. The USGS tentatively suggested the Topopah Spring welded tuff unit (TSw) in the unsaturated zone (UZ) in 1982 [1] (Fig. 2). That same year, Sandia National Laboratories (SNL) described a preliminary repository design [20]. However, a full evaluation of potential tuff units was not completed until 1983 and the report published a year later [21,22, p. 152]. Four units were formally evaluated: 2 units in the UZ (TSw and Calico Hills non-welded tuff or CHn) and 2 units in the SZ (Bullfrog and Tram welded tuff units or BFw and TRw, respectively) (Fig. 2). The report supported the selection of TSw for the repository.[2]

2.1. Engineered system in 1984 PA-EA

2.1.1. Repository design in 1984 PA-EA

In 1979, Congress decided to dispose only transuranic (TRU) radioactive waste generated from weapon production at the Waste Isolation Pilot Plant (WIPP) in bedded salt in southern New Mexico [26]. Congress stated in NWPA that remaining defense related DSNF should be disposed (presumably as defense HLW.[3]) with CSNF and the small amount of commercial HLW from the West Valley reprocessing plant closed in 1972 (Fig. A1), subject to

[2] A reference stratigraphy for thermal-mechanical modeling, published in 1985 [23], has been used by the project up through PA-LA and will frequently be used herein since it generally corresponds to the major hydrologic modeling units. However, the formal stratigraphy and informal extensions developed by USGS in 1984 and revised in 1996 [24] are frequently necessary when discussing units of the repository horizon.

[3] President Ford delayed commercial reprocessing of CSNF in October 1976, and President Carter indefinitely delayed reprocessing in 1977. An important reason for the decisions was concern about proliferation of weapon material, based on the detonation of the Pu weapon by India in 1974 [1]; however, reprocessing of DSNF within the weapons complex continued until 1992 [27].

Presidential approval [1]. Hence, for PA-EA, both CSNF and HLW were envisioned to be disposed. Furthermore, the design anticipated CSNF, HLW, and some commercial TRU[4] waste produced from reprocessing CSNF and fabrication of mixed-oxide (MOX) fuel [28, Tables 1-1] (Fig. 3).

A rough concept for a repository was used for evaluating the consequences of igneous intrusion in 1982 [16–18,29–32] (Table 1). However, a complete conceptualization for the repository was developed for the PA-EA with a stair-step design to remain horizontal and in the welded tuff (TSw) of the Topopah Spring Formation. Although the TSw unit had been selected in 1983 as noted above, the particular subunit had not; however, the lower non-lithophysal tuff unit (Tptpln) was favored [25, Fig. 6.3.1–8; 28] (Fig. 2). The ground support proposed was traditional rock bolts and wire mesh. The extraction ratio was 25%. The exploration area for the repository was set >200 m below the surface and >100 m above the water table [33]. These distance criteria would control the vertical location for the next 25 yr. Also by 1984, SNL had reported on borehole sealing methods [34,35] and construction methods for exploratory shafts [36].

The area required for 70,000 metric tons of heavy metal (MTHM) for the first repository specified in NWPA (until a second repository was constructed) was 6 km^2, based on an initial areal power loading of 12 W/m^2 (Table 1). The 12 W/m^2 areal power loading with 3.4 W/pkg (Table 1) was sufficient to keep rock temperatures <100 °C on the floor a few meters to tens of meters away from the waste packages, if one assumed a rock thermal conductivity of 2 W/m K [12,37]. The design criteria at the time was to limit the temperature rise at the surface to <6 °C and keep the tuff temperature in the repository <200 °C and, thereby, avoid altering zeolitic tuff in layers under the repository [28].[5] The latter criterion, expressed as a drift wall temperature <200 °C, remained a design goal throughout the life of YMP.

Both vertical and horizontal emplacements were under consideration during the mid-1980s [28, Figs. 2-12 and 2-14] (Fig. 3). Vertical emplacement was in the floor of a 6.1 m wide by 6.7 m tall disposal drift with one container placed in a 0.7-m diameter borehole spaced every 9 m for 10-yr old CSNF. Horizontal emplacement was in the pillars of a 6.1 m wide by 3.7 m tall disposal drift with $\sim$35 containers per borehole spaced every 14 m (Table 1). Although pillar emplacement involved between 3.3 and 9 times less excavation, floor emplacement was the baseline option (in the draft EA, the estimates were 2 mega tonnes—Mt—of excavated tuff for pillar emplacement versus 18 Mt for flow emplacement; in the final EA, the estimates were 6 Mt versus 20 Mt) [39, Table 5-1].

The 1984 draft EA required by NWPA used the initial SNL designs for floor or pillar emplacement [39, Table 5–1;40] (Fig. A1), but the 1986 final EA used a modified design that anticipated two stages of repository development as follows [39, Fig. 5-3]. For 4 yr between 1993 and 1998, the repository would be constructed to dispose of 400 MTHM/yr beginning in 1998. For an addition 3 yr between 1998 and 2000, facility operations would be tested and more surface and underground facilities built (e.g., second waste handling building) such that, in 2001, the repository could dispose 3000 MTHM/yr, a rate $\sim$50% higher than the annual rate of generation of CSNF in the US [41, p. 5]. This rate would guide repository designs for the next 25 yr to ensure that CSNF storage at reactors would decrease once the repository was operating. At this rate, operations were envisioned to continue for 28 yr. Mining of disposal drifts would occur for the first 22 yr for vertical emplacement, and the first 14 yr for horizontal emplacement. Monitoring was envisioned to occur for an additional 22 yr to accommodate the NRC requirement for retrieval up to 50 yr after initial waste emplacement (Sections 60.111(b) and 63.111(e)), and decommissioning was envisioned to take 3 yr.

2.1.2. Package design for 1984 PA-EA

At the same time SNL was developing preliminary layout designs for the repository in 1982, Lawrence Livermore National Laboratory (LLNL) was developing preliminary designs for HLW and CSNF containers based on drafts of proposed technical criteria in 10 CFR 60 [42]. By 1983, candidate materials for a container in the salt, basalt, and tuff repositories included stainless steel and high-nickel alloys [43,44]. The hole plug and liner [45, p. 5.35] was to be carbon steel [43]. Copper alloys were also evaluated for waste containers but were not as effective in the oxidizing, unsaturated zone (UZ) for the tuff repository as in the anoxic, saturated zone (SZ) proposed for the Swedish repository [46].[6] However, only 10-mm thick containers of 304 stainless steel containing CSNF were modeled in the 1984 PA-EA (i.e., no engineered barrier was modeled that would delay release of radionuclides, such as a corrosion resistant overpack, borehole liner, or adsorptive backfill). PA-EA assumed either an exponential failure rate with a mean of 10^4 yr or catastrophic failure after either 300 yr or 1000 yr, based on subsystem performance objectives in the NRC regulation, 10 CFR 60 [47, Section 60.113].

The containers for CSNF from either pressurized water reactors (PWRs) or boiling water reactors (BWRs) were assumed to be 0.65 m in diameter and between 4.0 and 4.75 m long [16,30,31,48] (Fig. 4; Table 1). About 33,000 containers were anticipated if the CSNF was not consolidated or $\sim$18,000 if CSNF was consolidated at the repository by removing hardware surrounding the fuel rods [28, Tables 1-1; 30].

HLW was not modeled in the 1984 undisturbed analysis in PA-EA; however, the earlier 1982 volcanic eruptive analysis had included HLW. The pour canisters for defense HLW were assumed to be 0.61 m in diameter and 3 m long (the standard canister used in the vitrification plant at the Savannah River Site); the pour canisters for commercial HLW were assumed to be 0.32 m in diameter and 3 m long.

2.2. Engineered system in PA-91

2.2.1. Repository design in PA-91

Alternative designs were understudy, but PA-91 basically used the repository design developed for the 1988 Site Characterization Plan (SCP) required by 10 CFR 60 [31,49–51]. Rather than stair step the repository as in 1984 PA-EA, the SCP repository followed the $\sim$6° dip of the lower non-lithophysal tuff unit (Tptpln) and remained >200 m below the surface and $\sim$183 m above the water table [16, 51,vol. 2 Figs. 4-30, 4-33, 4-37, 4-38] (Fig. 5a). The

[4] The commercial TRU waste mentioned in 1984, an EPA waste category, would possibly be classified as Greater Than Class C Low-Level Waste (GTCC LLW), an NRC waste category. GTCC and TRU waste is similar to the Intermediate-Level waste (ILW) category of the International Atomic Energy Agency (IAEA) and other countries, to be disposed in a geologic repository.

[5] In comparison, the proposed Swedish repository is designed for 12,000 metric tons (12 kt), for 6000 packages each containing 4 PWR assemblies to limit the thermal output to 1.7 kW/pkg and temperatures <100 °C to prevent excessive drying of the clay buffer next to the copper package [38]. The proposed Finish repository was initially designed for 6 kt and an expansion to 9 kt recently approved.

[6] In 1978 and through the KBS-1 design, the Swedish package scheme envisioned a 6 mm thick titanium overpack around a stainless steel handling canister. The annulus between the canister and overpack was to be filled with lead to diminish radiolysis of groundwater [45, p. 5.10]. By 1983, the Swedish package scheme envisioned a 50-mm thick copper alloy overpack over a cast nodular iron insert in the KBS-3 design [38]. The function of the iron insert was to scavenge oxygen in the mostly anoxic environment and form iron oxide rust, which, in turn, readily sorbed radionuclides as the SNF eventually degraded.

Table 1
Characteristics of repository designs in past PAs [16–18,29–32].

PA	Repository			Drift						Container		
	Place	Area (km^2)	Heat (W/m^2)	Back fill	Active count	Length (m)	Space (m)	Diameter (m)	Orient (°)	Count	Spacing (m)	CSNF[a] heat at t_0 (kW/pkg)
82	Floor	2.69[b]	22	Yes	Room 90	1008[c]	18.2	7.5w		89,559	1.35	0.6
EA[d]	Floor	6.00	12	Yes		460	30.5	$6.7 \times 6.1w$	35	33,000	9	3.4
	Pillar		12	Yes		490	430	$3.7 \times 6.1w$			14	3.4
91	Floor	5.61	14	Yes	Panel 17	91–122	38	$6.6 \times 4.6w$	35	33,000	SNF 4.6 HLW 2.3	2.0
	Pillar		14	Yes		430	230	$3.8 \times 6.7w$			SNF 21.0 HLW 10.5	2.0
93[e]	In-drift	4.63	14	Yes			25.4	7.6	55	8512[f]	23.2	8.0
	Floor	4.61	14	Yes			25.4	7.6		35,580	5.6	2.0
	In-drift	2.33	28	Yes			25.4	7.6		8512[f]	11.6	8.0
	Floor	3.14	28	Yes			25.4	7.6		35,580	2.8	2.0
95[g]	In-drift	3.80	20	Option	90	1400[c]	28	5.5		10,297		CSNF 9.9 HLW 1.8
VA[h]	In-drift	3.00	21	No	105	1019[c]	28	5.5	108	10,213	2.3–10.6	CSNF 10.7 [i] Co&DSNF 2.8
SR	In-drift	4.55	21	Option	51	1102[c]	81	5.5	72	11,770	0.1	11.8
LA	In-drift	4.98	18	No	99[l]	605[c]	81	5.5	72	11,629[j]	0.1	CSNF 10.5[k] Co-pkg 2.0

[a] Assumes ~0.98 kW/MTHM.
[b] Area for 47,000 MTHM repository.
[c] Total active drift length divided by active drifts.
[d] Source [28].
[e] Source [16, Table 4-5].
[f] Scaled from CSNF packages since HLW packages not explicitly modeled [16, Tables 4-5, 5-1 and 5-7].
[g] Source [17, Table 8.2].
[h] Source [31, vol. 2, Section 4.2.1.2].
[i] Average of 4 PWR and 2 BWR package heat loads used in thermal calculations [18, Vol. 3, Fig. 3-18].
[j] PA-LA modeled 11,629 packages to fill co-disposal packages and repository, but only 10,767 needed for 70,000 MTHM.
[k] Average of 3 PWR and 2 BWR package heat loads used in thermal calculations [32, Fig. 2.3.1.5].
[l] The active count of drifts depends upon the scenario for receiving various types of waste in addition to the total mass considered. For the receipt scenario reported in SAR/LA (which is based on limiting waste stream characteristics for a 70,000 MTHM repository with 10,767 packages) 91 emplacement drifts are needed [32, Table 1.3.1-3]. For the nominal PA-LA design, up to 108 emplacement drifts are planned in Fig. 12.

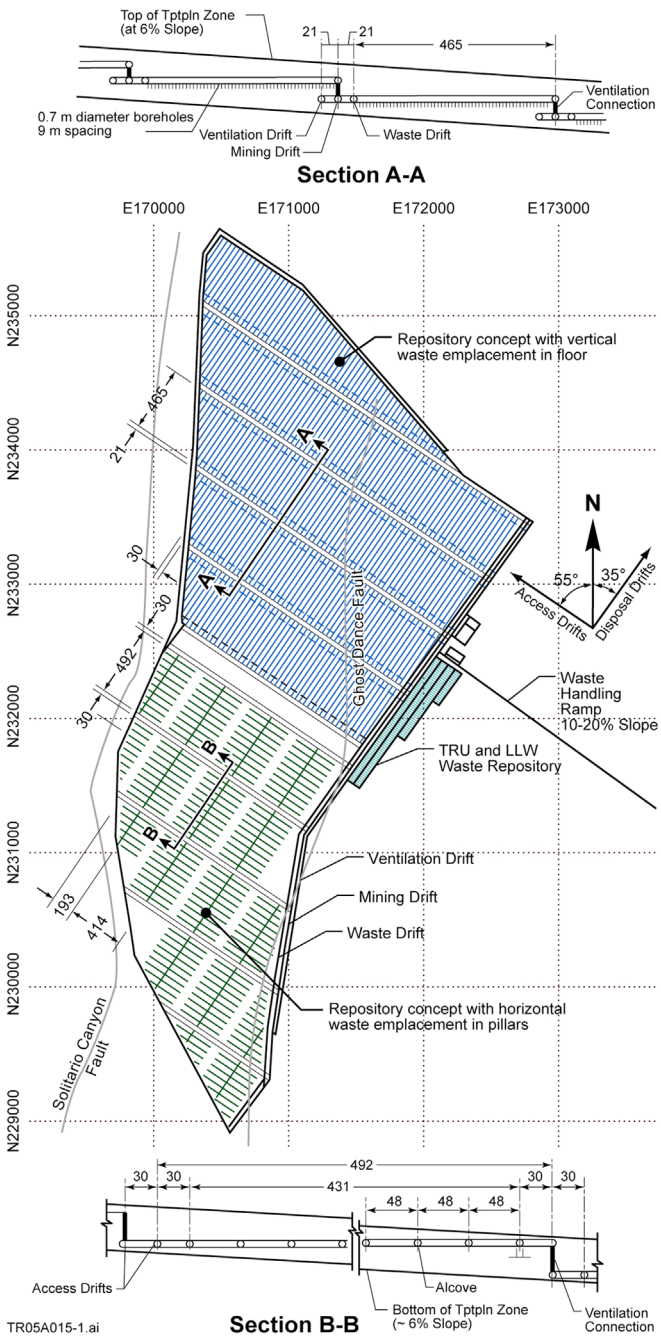


Fig. 3. Two repository concepts considered at time of PA-EA: waste disposal vertically in drift floor or waste disposal horizontally in drift pillar [28, Figs. 2-12 and 2-14].

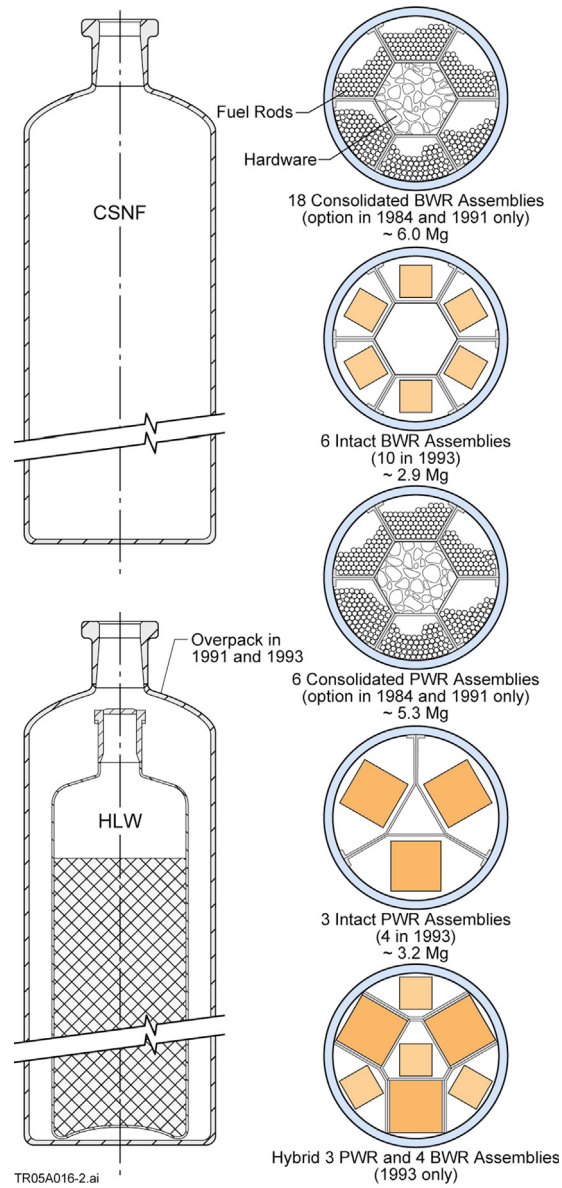


Fig. 4. Small, thin-walled, stainless steel package designs considered at time of PA-EA, PA-91 (SCP design), and PA-93, which maintained flexibility for disposal in various saturated and unsaturated geologic media [16, Figs. 4-1; 30; 31; 49, Figs. 3-9 and 3-10].

repository consisted of an access drift around the perimeter and three main drifts down the center of the repository to move miners and service equipment, radioactive waste, and tuff, all bored by a tunneling machine [51, vol. 1, Table 3-12]. Miners were to enter the repository through a shaft, but radioactive waste entered and tuff was removed via mildly sloping ramps bored respectively 7-m and 7.6-m to the surface. Except for limited use of a tunnel boring machine (TBM), the general configuration of the disposal panels, excavated by conventional drilling and blasting, was the same as envisioned in 1984; yet, the repository area for PA-91 (5.6 km^2) was somewhat smaller than in PA-EA (6 km^2) and SCP (5.75 km^2).

Both vertical waste emplacement in boreholes in drift floor and horizontal waste emplacement in the drift pillars were still under consideration (Table 1). The PA-91 design also envisioned commingling CSNF and HLW in drifts to allow a more consistent spacing down the drift and closer spacing of the drifts to slightly increase the thermal power loading to 14.1 W/m^2. Interspersing the lower heat output of HLW packages (and eventually DSNF in PA-VA and thereafter) with the higher heat output of the CSNF packages to maintain a more uniform thermal load within the repository would remain a part of the thermal strategy thereafter.

For floor emplacement, the spacing was 4.6 m for CSNF bore holes with an occasional HLW drill hole spaced in between (2.3 m). The boreholes were 7.6 m deep with a steel shield plug in the 3 m length above the container. For pillar emplacement, the CSNF borehole spacing was 21 m and long enough for 14 CSNF packages with an occasional drill hole spaced in between (10.5 m) for 18 HLW packages (Table 1). With this configuration, temperatures were above boiling around the package for ~300 yr.

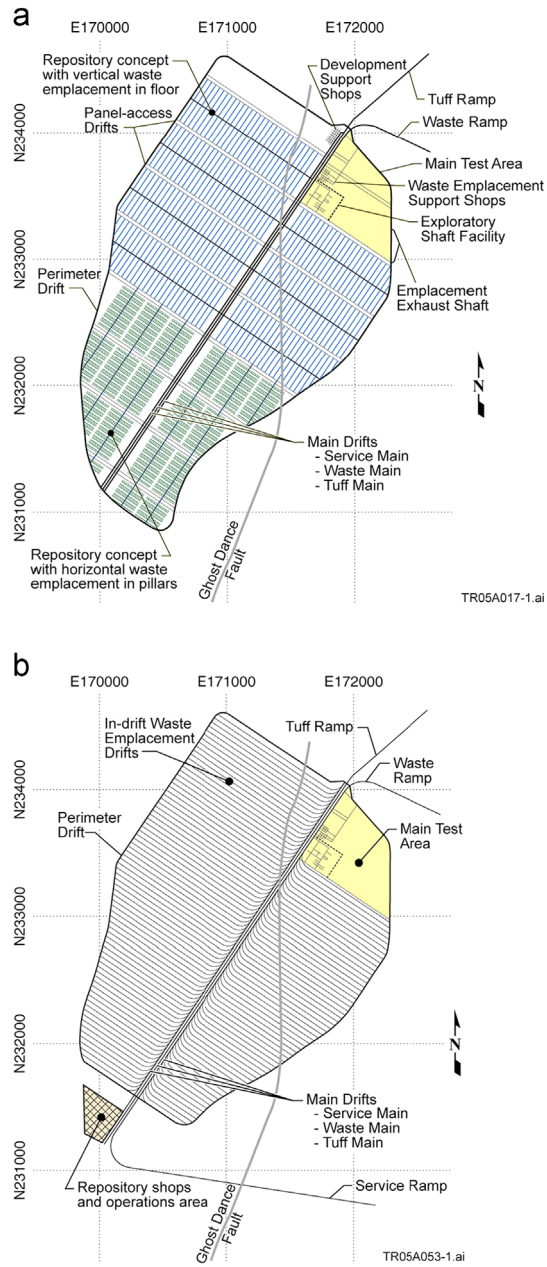


Fig. 5. Repository concepts (a) PA-91, which considered vertical and horizontal disposal, mostly used drill/blast construction [51, Figs. 4-30, 4-33, 4-37, and 4-38], and (b) PA-93 with waste disposal in drifts was bored entirely by tunneling machine [16, Fig. 4-6].

2.2.2. Package design in PA-91

PA-91 used the waste package (WP) design specified in the 1988 SCP (which was somewhat similar to PA-EA). The SCP specified a 9.5-mm thick, 304 stainless steel container either 0.61 or 0.66 m in diameter and either 3 or 4.8 m long. The SCP assumed that the handling facility at Yucca Mountain would consolidate most assemblies by removing hardware such that either 6 PWR assemblies or 18 BWR assemblies could fit into a container along with the hardware [31,51,52]. For those assemblies that could not be disassembled, the containers could accommodate either 3 PWR or 6 BWR intact assemblies (Fig. 4, Table 2).

Table 2
Changes in waste container design for floor and pillar emplacement [16; 30; 31].

PA	Type	Count As-is	Apart	Length (m)	Dia. (m)	Thick (m)	Mat.
84[a]	CSNF	33,000	18,000	4.0/4.8	0.65	10	304 SS
	CHLW			3.0	0.32		
	DHLW			3.0	0.61		
91[b]	CSNF	33,333	18,000	3.0/4.8	0.66	9.5	304 SS
	HLW overpack			3.3	0.66		
93	3-PWR/ 4-BWR	35,580[c]		4.8	0.71	9.5	A 825
	HLW overpack			3.2	0.66		

[a] Source [30], which conflicts somewhat with [28, Table 1-1].
[b] Source [31, Figs. 3-9 and 3-10].
[c] Scaled from 32,022 CSNF packages for 62,996 MTHM since HLW packages not modeled [16, Fig. 4-1, Tables 5-1 and 5-7].

Although an HLW canister was not modeled in PA-91, SCP specified a stainless steel overpack 0.66 m in diameter (same diameter as CSNF) and 3.2 m long to encase the pour canister to make handling more consistent between HLW and CSNF and to ensure known behavior of the waste container (since pour canister behavior might be uncertain due to the thermal shock of pouring glass into the canister).

Although not considered in PA-91, YMP was evaluating longer-lived containers. As noted earlier for PA-EA, LLNL had examined high-nickel alloys [43]. Furthermore, Weinberg, former director of Oak Ridge National Laboratory (ORNL), proposed in hearings on *Nuclear Waste Policy Amendments Act of 1987* (NWPAA) that US adopt the Swedish approach of developing long-lived disposal containers (< 300,000 yr) [53]. Also, NRC had recently issued a staff position in response to a DOE request for clarification stating that the 300–1000 yr package performance objective in 10 CFR 60, Section 60.113 was a range on the minimum performance objective (not a 300 yr minimum lifetime and 1000 yr maximum credit allowance or a range on the maximum credit allowance that might also be reasonably inferred) [1,54]. Hence in 1991, YMP sponsored a workshop to explore package designs that lasted longer than 1000 yr. Ideas adopted and included for PA-93 were (a) multi-barrier materials to reduce uncertainty; (b) a multipurpose canister (MPC) for storage, transportation, and disposal to reduce handling; and (c) package simplification to ease fabrication [55].

2.3. Engineered system in PA-93

2.3.1. Repository design in PA-93

In November 1989, a study of alternatives to constructing the ESF was started in response to comments by the NRC on the SCP. Later critiques by Nuclear Waste Technical Review Board (NWTRB) formed by NWPAA, in its first report in 1990 also provided an impetus [56–58].[7] In September 1991, YMP completed the report. Expert panels ranked 34 alternatives that considered (1) means of access (shaft and/or ramp), (2) location of access (northeast and/or southeast), (3) number of access points to the repository, (4) location of main test area (northeast and/or southeast), and (4) excavation method (drill and blast and/or mechanical boring).. The top three options for number and means of access to the repository were (a) inclined ramp to TSw and lower CHn, (b) inclined ramp to TSw and internal shaft to CHn; or (c) one inclined ramp, one shaft to TSw and CHn, and one internal shaft to CHn [58]. Shortly

[7] The NWTRB reports to Congress and DOE provide an extensive list, and, when read in order, provide a chronology of issues raised about disposal of radioactive waste at Yucca Mountain after 1990 (www.nwtrb.gov).

afterwards the first option was chosen and a south ramp was added. The incline of the ramps was reduced (1.6% for the south ramp and a maximum 2.5% for the north ramp) to facilitate using a TBM and allow locomotive and rail transport during operations. By 1993, the construction technique was changed from drill-and-blast to a TBM for the entire repository to reduce costs and minimize disturbance, based on the ESF alternative study and further NWTRB recommendations. Consequently, the concept of modular panels was abandoned and long disposal drifts, spaced 25 m apart, which branched out from the main access drifts, were planned (Fig. 5b).

Two additional changes to the repository design were proposed to reduce costs and facilitate the desired waste disposal throughput of 3000 MTHM/yr. The first proposed change was to place radioactive waste in large disposal packages directly in the drifts.[8] With in-drift emplacement, the size of the disposal drifts could be reduced to 5.5-m in diameter (rather than 6.7 m high and 4.9 m wide in the SCP design) since drifts did not have to accommodate equipment to drill into the drift floor or pillars and rotate the packages (however, for PA-93, all drifts were 7.6 m in diameter for modeling convenience).

The second proposed design change, championed by LLNL [59,60], was to double the heat load (i.e., 28 W/m^2 rather than 14 W/m^2 as proposed in the SCP) to dry out the region around the repository for several thousand years rather than just several hundred years, based on modeling and heater tests conducted in G-tunnel at NTS between 1981 and 1983 [2,17,59–61]. Although the spacing between drifts was 25.4 m for both heat loads (consistent with a ~30% extraction ratio), the spacing between disposal containers was decreased for the higher heat loading. Doubling the heat loading halved the repository size such that disposal drifts fit west of main drift and the Ghost Dance Fault (i.e., 4.6 km^2 for 14 W/m^2 and 2.3 km^2 for 28 W/m^2) [16, Section 4.6] (Fig. 5a, Table 1), which, thereby, responded to another NWTRB suggestion to avoid straddling the Ghost Dance Fault even though inactive.[9] The drifts were assumed to be backfilled with tuff gravel 75 yr after waste emplacement.

2.3.2. Package design in PA-93

For PA-93, two package designs were under consideration that corresponded to the two emplacement schemes. The first WP design, used for vertical floor emplacement, was similar to the container proposed in SCP except constructed of high-nickel Alloy 825 (21% Cr, 3% Mo, 2% Cu, 1% Ti, 42% Ni), a highly corrosion resistant material (CRM). By 1993, YMP had decided not to consolidate PWR and BWR assemblies[10] and so the package was envisioned to hold 4 PWR fuel assemblies, 10 BWR fuel assemblies, a hybrid combination of 3 PWR and 4 BWR assemblies, or a HLW stainless steel pour canister (Fig. 4, Table 2). The 4 PWR/10 BWR package was about the maximum size that could be used in boreholes, whether in the UZ or SZ, and still maintain tuff temperatures below 200 °C, while assuming a short storage time at the surface (25 yr storage for PA-93 [6]).

The second WP design, used for in-drift horizontal emplacement, was much larger (1.75 m in diameter and 4.9 m long) for 21 PWR or between 40 and 44 BWR assemblies. The large size was possible because of the use of the UZ at Yucca Mountain with no backfill (at least for an extended period). An open drift in the UZ was more efficient in transmitting heat away from the package through thermal radiation and convection (either natural or forced); hence, a package could be larger and internal WP temperatures would not exceed 375 °C (the limit on CSNF cladding at the time[11]), and temperatures at the drift wall would not exceed 200 °C (the limit to avoid chemical changes is tuff, especially zeolitic tuff). In turn, a large package reduced the number of items handled and, thereby, facilitated a high disposal rate.[12]

The in-drift package was a multi-barrier design constructed of an inner layer of 9.5-mm thick Alloy 825 as a CRM, and an outer layer of 100-mm thick A516 mild steel for structural strength and as a corrosion allowance material (CAM). As proposed, the in-drift waste package held either 21 PWR assemblies, 40 BWR assemblies, or several HLW stainless steel pour canisters [16, Fig. 4-2] (Fig. 6, Table 3). The amount of expensive Alloy 825 was reduced somewhat by in-drift disposal.

2.3.3. PA-SNL-95 and PA-SNL-97

Separate from PA-93 (and PA-95), DOE funded PAs to explicitly examine the influence of direct disposal of DSNF and various processing options for defense HLW calcine stored at the Idaho National Laboratory (INL) reservation in 1993, 1995 (PA-SNL-95), and 1997 (PA-SNL-97) at Yucca Mountain (Fig. A1) [27; 72, Table 4–12; 73]. Because the DSNF is often cooler than CSNF (since the DSNF was experimental or used to produce Pu and, thus, not always left in the reactor to highly burn up the ^{235}U), two repository concepts were considered: (1) DSNF disposal in a separate cooler portion of the repository, which added disposal schedule flexibility without requiring storage buffer capacity, and (2) commingling DSNF with CSNF, which maintained more uniform temperatures throughout the repository, but required linking DSNF, CSNF and HLW delivery schedules unless sufficient storage buffer capacity existed at the repository or at a monitored retrievable storage facility (MRS) [72,73].

2.4. Engineered system in PA-95

In 1992, Congress ratified the *Strategic Arms Reduction Treaty* (START I), which reduced strategic offensive arms by 30% [74]. Because of reduced demand for fissile material (^{235}U and ^{239}Pu) and because environmental regulations required extensive updating of facilities, DOE halted reprocessing of DSNF. Along with this decision and in response to the Presidential decision in 1985 to dispose DSNF with CSNF, DOE proposed direct disposal of DSNF in Yucca Mountain in addition to already existing defense HLW [75]. In 1995, DOE allocated 10% of the mass of the 70,000 MTHM repository to DSNF and HLW, with ~1/3rd (2333 MTHM) for DSNF and ~2/3rd (4667 MTHM) for HLW [76]. The 2333 MTHM DSNF

[8] DOE also proposed to take ownership of CSNF and store them at the nuclear reactor in the MPC as an approach to meet the contract obligation to accept waste by January 1998 [1, Table 3].

[9] Although the major temperature perturbation of the host rock only occurred in the first 1000 yr, NWTRB and USGS viewed the perturbation as a drawback by potentially causing changes in, for example, permeability by precipitation of salts, which might increase uncertainty in repository behavior [62–64, p. 228]. Hence, much experimental work, such as the drift scale test (DST) as reported in a companion paper [2], was conducted to evaluate the concern of coupled effects Also, performance assessments were run with several heal loads to examine the influence of temperature, as described in another companion paper [4].

[10] In a PNNL analysis of risks associated with various operations necessary for managing radioactive waste (i.e., storage, transportation, and disposal), consolidation noticeably increased exposure to workers using the techniques of the time [65; 66].

[11] For PA-VA through PA-LA, a temperature limit on CSNF of 350 °C would be used by YMP [32, Table 1.3.1-2;67]. In comparison, NRC eventually adopted a 400 °C temperature limit on cladding for transportation or while in dry storage at reactor sites [68]. HLW in borosilicate glass had a limit of 400 °C and, thus, did not control the repository design.

[12] Handling efficiency was an issue at the time because the US, with twice as many reactors as France or the then Soviet Union, and three times as many as the UK or Japan, would be handling many more assemblies and disposal containers than other countries [45, Table 1.3.1].

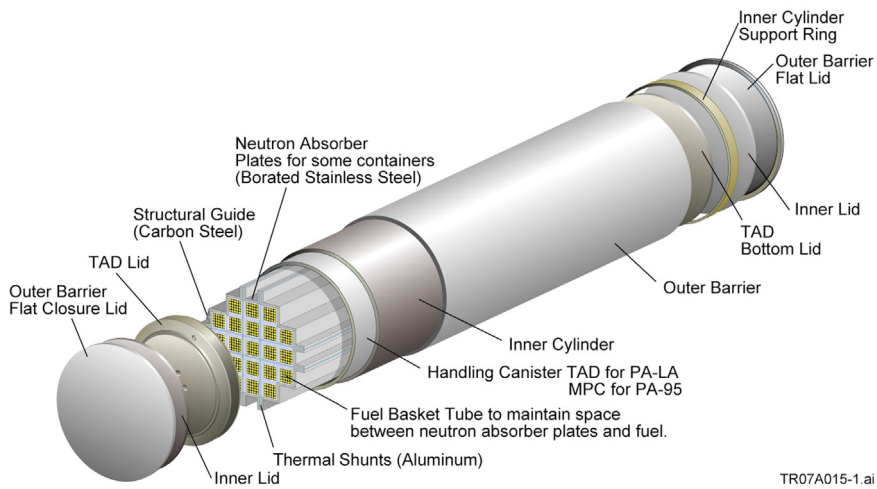


Fig. 6. In-drift waste package considered for PA-93 and thereafter. Use of a large container, which was permitted by the high heat dissipation that occurred in open drifts in the unsaturated zone, allowed YMP to directly link loading operations at nuclear reactor to disposal operations at Yucca Mountain, without using centralized storage [16, Fig. 4-2]. Inner handling canister considered for PA-95 (multipurpose canister or MPC) and for PA-LA (transportation, aging, and storage or TAD).

allocation included up to 65 MTHM of naval SNF. However, DSNF was not included in PA-95, but rather in separate analysis [27,72].

2.4.1. Repository design in PA-95

In 1994, DOE formally adopted the use of in-drift emplacement to help make a 3000 MTHM/yr receipt rate feasible[13] and a moderately high thermal loading strategy to save tunneling costs for ~200 km of drifts (160 drifts up to 1200 m long); however, this decision increased modeling complexity in the PA that took a number of years to fully resolve [4–6]. The general repository layout in PA-95 remained similar to PA-93 in that options such as disposal in parallel, perpendicular, or angled alcoves or cross drifts had been rejected [17, Section 3.6.2, Fig. 3.4-2; 18] (Fig. 7). The PA-95 design envisioned closely spacing the drifts 28 m apart such that decay heat would dry out the UZ for ~1000 yr. The moderately hot and more compact repository again fit west of the Ghost Dance Fault (~20 W/m^2 areal power density of initial heat for CSNF or 0.021 MTHM CSNF/m^2 areal mass loading assuming ~0.98 kW/MTHM for the PA-95 waste)[14] (Table 1) [17,Section 3.3;79–81]. Although DOE had decided otherwise in 1994 [79,80], the influence of a tuff gravel backfill in the drifts placed after 100 yr and a cool repository (6 W/m^2) was also evaluated in PA-95 [17, Section 3.3, pp. 4–8]. The invert of the drift was concrete [17, Fig. ES.4-3].

In September of 1994, YMP began excavating the 8-km long, 7.6-m-diameter ESF tunnel, with its custom-built $13-million TBM [64, p. 266]. Because the ESF was to be the main access to the repository, if authorized, it was constructed to the high standards required of a repository. Progress was initially slow but improved by September 1995 after YMP found enough money to modify the TBM and add a conveyer to remove excavated rock [80,82–85]. To avoid influencing future seepage experiments, little water was used to suppress silica dust in the tunnel; however, silica dust levels eventually exceeded health limits and in September 1996 DOE had to stop excavation while it implemented a dust suppression program [85].

2.4.2. Package design in PA-95

In PA-95, YMP envisioned using a 25-mm thick, 304 stainless steel handling canister. Stainless steel was chosen since the canister would usually be loaded and sealed at the nuclear reactor, and it would be necessary to avoid contaminating the reactor storage pool with degradation products from less corrosion resistant materials (Fig. 6). The multipurpose canister (MPC) would be overpacked for transportation (transportation cask), for storage (dry storage cask), and for disposal (waste container). Use of an MPC eliminated the need to directly handle CSNF assemblies or HLW canisters anywhere other than at the nuclear reactor [86], a concept encouraged by the NWTRB [57,87].[15] For PA-95, CSNF packages were represented by a large MPC with 21-PWR or 40-BWR assemblies. HLW packages were represented by an MPC with 4-HLW pour canisters. A smaller MPC was also envisioned to handle 12 PWR or 24 BWR assemblies for reactor sites with limited crane capacity, lack of rail access, or criticality control, but was not included in PA-95 (Section 3.6.2) [72, Appendix F; 86]. The 6468 MPCs with CSNF were projected to weigh ~60 t when loaded [17, pp. 3–5, Tables 3.5-1 and 8.2-1]. The 3829 MPCs with HLW were projected to weigh ~35.5 t [16; 17, pp. 3–5, Tables 3.5-1 and 8.2-1; 18; 25; 69–71] (Table 3). Along with container design and experiments of container corrosion, LLNL was responsible for experimental analysis of degradation rates for HLW and CSNF [88;89] (Fig. A1).

[13] From a system standpoint, the benefit of an MRS facility is to decouple reactor operation/storage requirements from repository operational requirements. As described in several reports (e.g.,[77,78]), an MRS coupled with a YM repository would have helped ensure waste management system flexibility in that disruptions to reactor operations could be minimized by setting precise schedules on timing and removal of CSNF (e.g., 3000-MTHM/yr rate) in transport and storage containers of various sizes while allowing schedule flexibility on acceptance rates and timing of the emplacement of CSNF in standard-sized disposal containers when starting operations and managing thermal loads through the life of a repository (e.g., implementing a cooler repository design [63]). However, Congress revoked siting the MRS in Tennessee in NWPAA. Congress also limited the role of the MRS by linking development of an MRS to the repository construction schedule and limited its storage capacity to entice states and the nuclear industry to more readily accept the storage facility concept, as suggested by the Tennessee Clinch River Task Force and adopted by DOE (Appendix A).

[14] In 1995, YMP switched to an areal CSNF mass loading concept for designing the package and drift spacing in the repository because the heat output per package after ~200 yr would be similar for packages containing a similar CSNF mass loading whereas a design concept based on initial areal power density would have a more variable heat output after ~200 yr [17, Section 3.3]. However, herein we report the areal power density to provide comparison to past designs.

[15] If the MPC is large (as is possible for disposal in the UZ), then loading an MPC at the nuclear reactor would not unduly disrupt operations. On the other hand, if the MPC must be small to keep heat loads low for disposal in the SZ and other media such as crystalline rock, then loading an MPC might be better handled elsewhere to avoid extensively disrupting reactor operations.

Table 3
Changes in representative waste container dimensions for drift emplacement used in past PAs [16–18,25,69–71].

PA	Type	Count	Length (m)	Dia (m)	Thick (mm)	Lid (mm)	Material
93	21-PWR or 40-BWR	8512 [a]					
	Outer corrosion allowance		4.9	1.8	100	100	516 Steel
	Inner corrosion resistance				9.5	9.5	825 Alloy
95[b]	21-PWR or 40-BWR	6468					
	Outer corrosion allowance		5.7	1.8	100	100	516 Steel
	Inner corrosion resistance				20	20	825 Alloy
	MPC for handling			1.7	25	25	304 Stainless
	HLW (4 canisters)	3829					
	Outer corrosion allowance		3.7	1.7	100	100	516 Steel
	Inner corrosion resistance				50	50	825 Alloy
	HLW canister		3.0	0.61			304 Stainless
	Total	10,297					
VA[c]	PWR/BWR blend	7667	5.3	1.7			
	HLW/DSNF (HLW only: 1243)	1663	5.4	2.0			
	DSNF (1303)	883	5.4	2.0			
	Outer corrosion allowance				100	100	516 Steel
	Inner corrosion resistance				20	25	22 Alloy
	Total	10,213					
SR[d]	21-PWR(plates), 21-PWR(rods), 12 PWR	4770	5.2	1.6			
	44-BWR, 24 BWR	3090	5.2	1.7			
	Outer corrosion resistance				20	25	22 Alloy
	2nd Outer lid					10	22 Alloy
	Inner structural strength				50	100	316 Stainless
	5-HLW, 1-DSNF (short: 31%)	1100	3.6	2.1			
	5-HLW, 1-DSNF (long: 45%)	1630	5.2	2.1			
	5-HLW (long)	700	5.2	2.1			
	2-HLW, 2-MCO	160					
	Naval short	210					
	Naval long	110	5.85	1.88			
	Outer corrosion resistance				25	25	22 Alloy
	Inner structural strength				50	100	316 Stainless
	DSNF canister (long)		4.57	0.46	9.4		316 Stainless
	MCO (multi-canister overpack)		4.23	0.64			304 Stainless
	Total	11,770					
LA	21-PWR,[e] 12-PWR,[f] 44 BWR	7796	5.85	1.88			
	CSNF TAD handling canister			1.7	25	Top 51 plug 381 end 89	316 Stainless
	Naval short	323					
	Naval long	94	5.85	1.88			
	Outer corrosion resistance				25	25	22 Alloy
	Inner structural strength				51	51	316 Stainless
	5-HLW, 1-DSNF (short)	1257	3.68	2.03			
	5-HLW, 1-DSNF (long)	1940					
	2-HLW, 2-MCO	219	5.29	2.03			
	Outer corrosion resistance				25	25	22 Alloy
	Inner structural strength				51	Top 227 end 51	316 Stainless
	Total	11,629[g]					

[a] Scaled 7640 CSNF pkg for 62,826 MTHM (2791 pkg with 5 HLW/pkg for 7000 MTHM not modeled) [16, Tables 5-1 and 5-7].
[b] Source [17, Table 8.2-1] yet, estimate for 1995 was 6323 CSNF and 3259 HLW [17, Table 3.5-1].
[c] Table lists estimate for volcanic eruptive scenario [69, Table 10-9]; another estimate was 2957 DSNF/HLW without HLW [70, Table A6-11]; for PA-VA undisturbed scenario, CSNF, HLW, and DSNF were modeled separately as shown in parentheses [18, vol. 3, Section 3.2.2.1].
[d] Primary container dimensions listed for PA-SR; two other variants for 170 12-PWR and 90 24-BWR [71].
[e] Primary container listed for PA-LA; one other container variant for 173 12-PWR [25, Table 6.3.7-1].
[f] Prior to PA-LA, internal CSNF basket composed of carbon steel; for PA-LA, 316 stainless steel used.
[g] 11,629 modeled in PA-LA to fill repository and fill co-disposal packages, but only 10,767 packages needed for 70,000 MTHM.

2.5. Engineered system in PA-VA

2.5.1. Repository design in PA-VA

Construction of the ESF mostly in the middle non-lithophysal tuff (Tptpmn or TSw) was completed in 1997. In 1998, construction of the Enhanced Characterization of Repository Block (ECRB) cross drift, encouraged by NWTRB [57], was started and completed 15–27 m above the elevation of the future disposal drifts. As required by Congress [1], a more complete design was provided for PA-VA and an effort made for the PA analysis to be more consistent with the current repository design. By the time of VA, the aggressive schedule in NWPA provided an impetus to design large surface and underground facilities to achieve high waste disposal throughput from the start of operations, rather than the modest 8-yr staged development proposed in the 1986 EA [90].

For the PA-VA, the repository block was defined as that volume of tuff 100 m above the current water table, 200 m below the surface, 120 m west of Ghost Dance fault, and 60 m standoff distance from other major faults. The repository was extended farther north of the North Ramp than in PA-95. The repository was roughly horizontal and primarily in the lower lithophysal unit (Tptpll) with a small fraction in the middle non-lithophysal

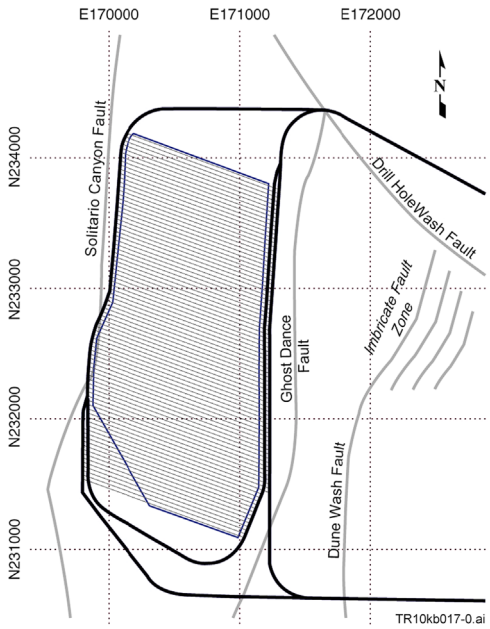


Fig. 7. PA-95 repository layout with in-drift disposal [17, Fig. 3.4-2].

unit (Tptpmn) and lower non-lithophysal unit (Tptpln) (the favored unit for the repository in PA-EA and SCP) (Fig. 8). A moderate temperature repository concept was used (i.e., 21 W/m^2 when considering only CSNF or 18.7 W/m^2 when also considering the 7000 MTHM of HLW). The heat loading for PA-VA was similar to the 20 W/m^2 used in PA-95 and halfway between the 14 and 28 W/m^2 considered for PA-93 [18, vol. 2, Section 7.1.1]. The drift spacing was 28 m (an extraction ratio $<20\%$) to maintain the drift wall temperature <200 °C (Fig. 8).

Spacing between hot CSNF packages was large and varied between 10.6 and 8.9 m. A cool co-disposal or DSNF package might be placed between two CSNF packages and in this case spacing between packages was reduced to 2.3 m [6, Fig. 8; 18, vol. 3, Fig. 3-18]. To accommodate 10,213 packages for 70,000 MTHM, 107 km of disposal drift length was anticipated, which translated into ~105 drifts [18, vol. 2, Section 4.2.1] (Table 1). The area of the repository was ~3 km^2. Backfill to create a capillary barrier (either backfill only or backfill plus a drip shield) was studied as an option but its use was not recommended. Backfill caused operational difficulties in filling the long drift. Also, any sand in the backfill would insulate the waste containers and promote internal temperatures above 350 °C for the large horizontal containers that could prematurely damage CSNF cladding during the first 1000 yr after emplacement.[16]

Congress also required a more complete description of the repository operations for PA-VA. Steps taken to maintain operational safety and ease retrievability of packages prior to closure included pre-cast concrete lining and invert for the 5.5 m diameter disposal drifts for PA-VA (Fig. 9), but more expensive steel supports and invert (as in the SCP design) were mentioned as an option if changes in pH caused by degradation of the concrete proved to be of sufficient concern.

[16] Cladding was not designated as a barrier important to isolation in PA-LA; none the less, YMP wanted to maintain its integrity, if possible. Also, in evaluating the insulating properties of rockfall for PA-LA, YMP found that a very coarse gravel might not unduly insulate the package because of convection in large gravel pores [41, p. 96; 91].

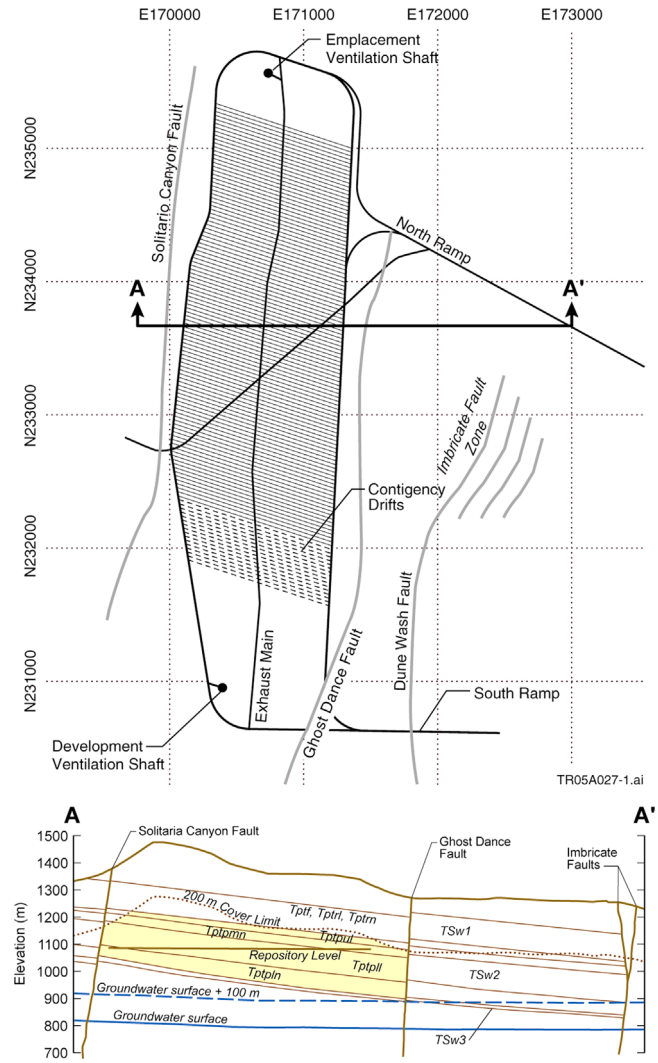


Fig. 8. PA-VA repository layout [18, vol. 3 Figs. 4-21 and 4-22].

2.5.2. Package design in PA-VA

Along with the repository design, a more complete design and description of the proposed manufacturing process for the waste container was provided for PA-VA. Congress had stopped development of the 25-mm thick stainless steel MPC handling canister [84,92] (Fig. A1), but its absence in PA-VA did not require a major modeling change since the MPC had not been considered as a barrier in PA-95.[17] The evaluation of corrosion resistance of nickel alloys was begun in 1996 with the completion of a corrosion facility at LLNL [93], and an important change in container design in regards to PA-VA modeling was replacing the inner 20-mm Alloy 825 layer with another high nickel Alloy 22 to increase life (22% Cr, 13% Mo, 3% W major alloys with 58% Ni and 3% Fe) (Table 3).

As alluded to in the previous section, DSNF was included in PA-VA and envisioned to be mostly co-disposed with HLW in 1663 containers with the remaining DSNF disposed in 883 containers [18, vol. 3, Section 3.2.2.1; 69, Table 10-9] (Table 3). Co-disposal of usually one DSNF canister with 5 HLW canisters offered the advantage of greatly reducing the need for criticality control inside the package since the fissile mass was limited (Fig. 10)

[17] However, the Navy chose to proceed with a similar multipurpose canister for the management of propulsion SNF in storage, transportation, and direct disposal.

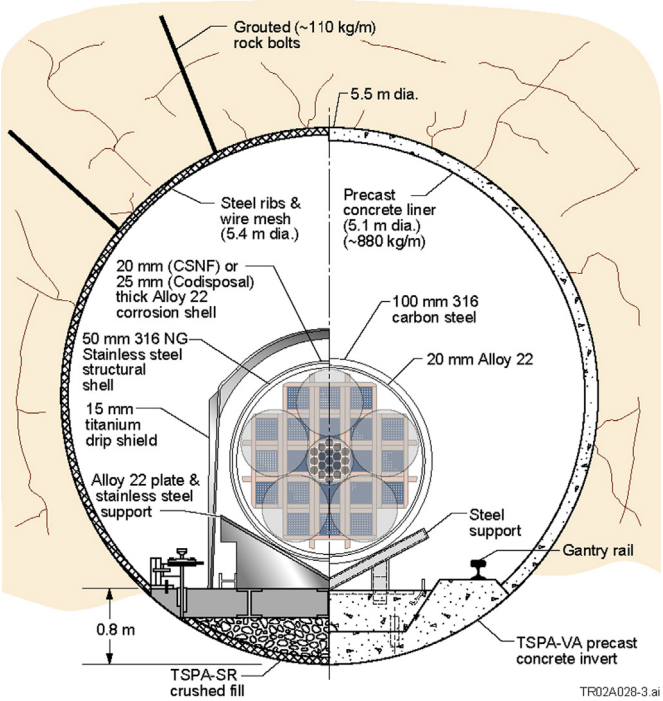


Fig. 9. Concrete ground support and invert used in PA-VA was switched back to steel in PA-SR and included titanium drip shield to limit influence of dripping water chemistry during thermal period.

[70, Table A6-10]. However, sufficient HLW and DSNF canisters of the correct length had to be available when packaged for disposal at the repository [18, vol. 3, Section 3.2.2.1; 69, Table 10-9], which when combined with the concept of commingling the cool DSNF/HLW packages with hot CSNF packages further linked all three waste types (i.e., the concept required linking CSNF, DSNF, and HLW delivery schedules, including proper canister lengths, sufficient storage area at the repository, or an MRS, as previously mentioned). Discrepancies existed between anticipated needs and availability of a sufficient number of HLW canisters [70, Table A6-11], and more operational details were provided for PA-LA, based on schedule models.

Similar to other aspects of the PA-VA, a Waste Package Degradation Expert Elicitation (WPDEE) panel of six experts (four from outside DOE) was assembled to evaluate corrosion rates that had been used for container materials in the PA-95 [18, vol. 3, Section 3.4.1.1; 94, Section 5.3]. The corrosion models used for wet and humid corrosion of carbon steel were found adequate. Six-month, short-term electrochemical polarization tests from the LLNL corrosion facility and some literature data were available to set the corrosion rate of the Alloy 22 layer [94, Table 5-7]. The experts thought that generalized corrosion of the underlying Alloy 22 CRM layer would be very slow and that localized corrosion would only occur in wet environments around drips with low pH and high Cl^- content [94, Section 5.3].

2.6. Engineered system in PA-SR

2.6.1. Repository design in PA-SR

Along with PA-VA, YMP conducted several sensitivity studies, by modifying parameter values, to determine the influence of several design options, including backfill, ceramic coating on the waste container, increased steel and Alloy 22 thicknesses, and drip shields. The sensitivity analysis showed a significant increase in container lifetime when localized corrosion was prevented by eliminating drips during the thermal period using a drip shield [94, Section 5.12.5.2]. The sensitivity studies and other design options for the repository were again considered in a License Application Design Study (LADS), which was conducted in the winter of 1999 [95].

Based on LADS, titanium drip shields (each 2.5 m wide, 2.5 m high, 4.8 m long) were added as a second engineered barrier component to protect the packages when they were transitioning from hot to cool and were more susceptible to localized corrosion.[18] Because of concerns of pooling water above the repository during the first 10^3 yr, YMP set a repository design criterion to keep the center of pillars between drifts below boiling (<96 °C) to allow water drainage ("shedding") between the drifts. Hence, the spacing between drifts was increased to 81 m based on LADS, which required that the repository extend farther north than in PA-VA (Fig. 1). However, the spacing between containers was reduced to 0.1 m to promote more uniform heating of the repository drift regardless of the individual differences in radioactive decay heat between containers [6, Fig. 10]. Consistent with the design criterion and 81 m drift spacing, the maximum initial heat load of the packages was set at 11.8 kW/pkg (roughly 2.2 kW/m for a 5.2 m pkg and 0.1 m spacing in Table 3) possibly through blending of waste at the site (Table 1).

Underground support had been included earlier in the design for operational safety, but it was now useful to maintain drift support prior to placing the drip shields, which might be near the end of repository operations 30 or more years after emplacement of the first waste. The underground support was changed from pre-cast concrete liners to steel welded wire fabric with grouted rock bolts, based on LADS, because of the concern that the concrete might adversely increase the pH of seeping water and, thereby, increase degradation of the container and waste and mobilization of radionuclides (Fig. 9). Finally, the disposal drifts were reoriented to better align with the stress state of the tuff.

For the reference design in PA-SR, the disposal area was $\sim$4.6 km^2 and consisted of a total disposal drift length of $\sim$60 km. The average number of packages per drift was 215. For the fairly horizontal repository, 8% of the repository was in the middle non-lithophysal (Tptpmn), 80% was in the lower lithophysal (Tptpll), and 12% was in the lower non-lithophysal (Tptpln) [19, Figs. 2–7] (Fig. 11).

2.6.2. Package design in PA-SR

PA-93, PA-SNL-94, and PA-SNL-97 [73, Table 11-2] had shown the limited value of the carbon steel corrosion allowance layer of the container in the hot, humid environment of the repository after closure. This finding was also confirmed by LADS [95]. Hence with encouragement from NWTRB, the PA-SR design switched the layers: the 20-mm thick Alloy 22 was now the outer layer and steel was the inner layer. For PA-SR, 6-month, 12-month, and 24-month corrosion data from the LLNL corrosion facility were available to determine corrosions rates of Alloy 22 [93, Fig. 3-72].

Since the inner layer was now only for structural strength, the inner layer thickness was decreased to 50 mm. Also, the inner layer was changed to 316NG stainless steel to eliminate NWTRB concerns with "oxide-wedging" associated with carbon steel, increasing degradation of the breached container. However, this change increased the uncertainty somewhat about the presence of sufficient iron oxide rust to readily sorb radionuclides after waste degradation. Also, shrink fitting of outer barrier was abandoned to avoid tensile stresses that might increase likelihood of stress corrosion cracking [96]. In addition, an inner lid of Alloy 22, 10-mm thick, was added in addition to the outer 25 mm thick lid

[18] Winograd of USGS suggested ceramic or aluminum "umbrellas" as a secondary barrier as early as 1991 [63, Fig. 6].

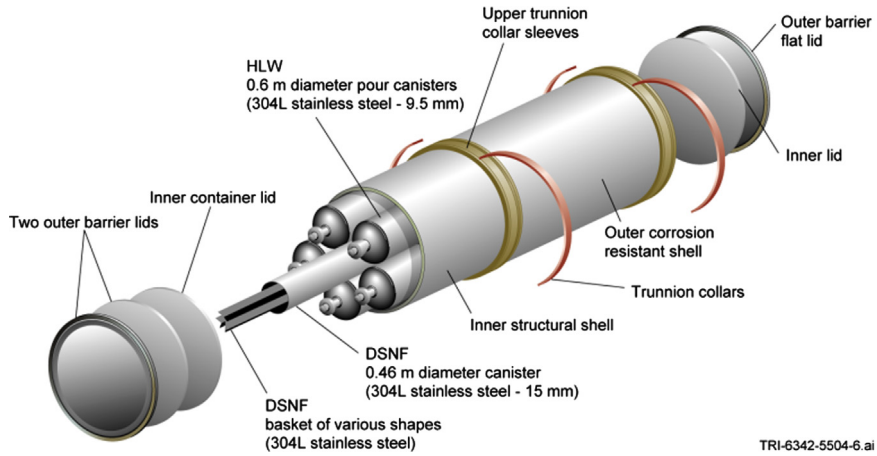


Fig. 10. HLW and DSNF co-disposal package for PA-VA and thereafter.

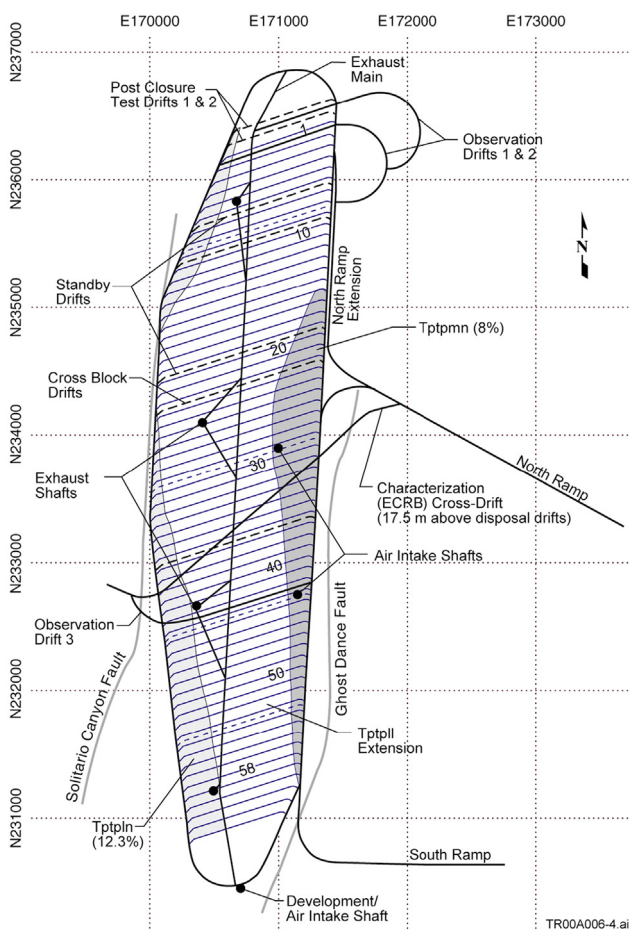


Fig. 11. Repository concept for PA-SR [19, Figs. 2–7].

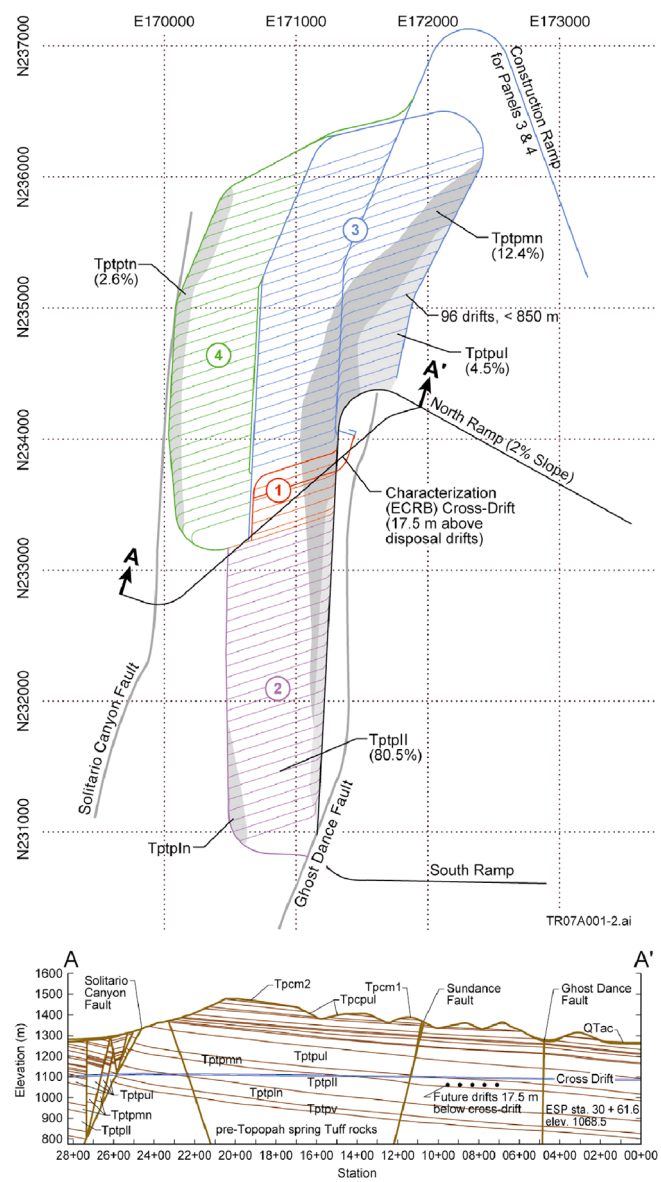


Fig. 12. Repository concept for PA-LA [32, vol. 1 Figs. 2 and 3].

and the lid design modified to mitigate residual stresses and the potential for stress corrosion cracking (Table 3).

2.7. Engineered system in PA-LA

At the end of 2010, radioactive waste destined for geologic disposal was stored in 39 states at 131 sites [97]. About 65,200 MTHM of CSNF had been generated and was stored at 72 reactor sites with 51,200 MTHM (~172,000 assemblies) in wet storage, and 14,000 MTHM (~54,000 assemblies) in 1390 dry casks using 20 different designs [41, Table 1]. Nine reactors at these sites were shutdown, with 5 completely dismantled. At the 9 shutdown

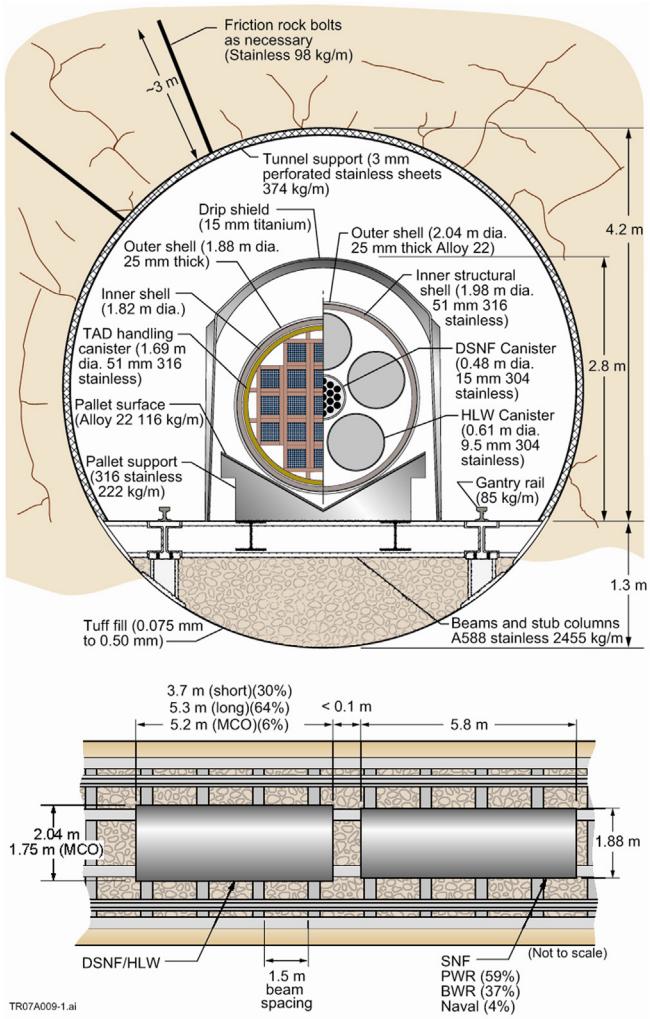


Fig. 13. Ground support, drip shield, and invert of EBS for PA-LA.

reactors ~2800 MTHM was stored with 7 sites using dry storage casks [98, Table 1].

At the end of 2010~2458 MTHM of DSNF had been generated with (a) 2130 MTHM stored at Hanford in ~400 multi-canister overpacks (MCOs); (b) 282 MTHM in mostly dry storage at Idaho National Laboratory (INL), which includes 25 MTHM (of eventually 65 MTHM) of Naval SNF; (c) 29 MTHM of DSNF in wet storage at SRS; (d) 15 MTHM of graphite blocks in vault storage at the dismantled Fort St. Vrain reactor in Colorado, and (e) 2 MTHM stored elsewhere. About 3175 canisters of HLW borosilicate class had been poured with 275 canisters stored at West Valley and the remainder stored at SRS. SRS was projected to produce another 6300 canisters, Hanford is projected to produce ~9700 canisters, and INL is projected to produce between 3590 and 5090 canisters [98, Figs. 10 and 11].

2.7.1. Repository design in PA-LA

For the PA-LA, the repository layout expanded farther to the east north of the north ramp than in PA-SR [32, vol. 1, Figs. 2 and 3] (Fig. 12). The layout also divided the repository into 4 independent panels areas with shortened but more uniform disposal drift lengths (average of 605 m with range of 355–808 m—Table 1), based on an 2001 options study [99]. For the nominal design, 108 drifts with a total length of 65 km were planned. The use of 4 panel areas allowed initial disposal without construction of the entire repository perimeter drift and ventilation system, which was more consistent with limited annual appropriations by Congress and somewhat akin to the early drill and blast designs with mining continuing throughout much of the operation period [39]. Use of a panel design also offered flexibility in changing the layout of future panels if the waste or containers changed [11;100]. Based on a repository area of 4.98 km^2, the design modification resulted in 4.5% in the upper lithophysal unit (Tptpul), 12.5% in the middle non-lithophysal unit (Tptpmn), 80.5% in the lower lithophysal unit (Tptpll), and 2.5% in the lower non-lithophysal unit (Tptpln). Although the highest percentage was still in the lower lithophysal unit (80.5%), the portion of the repository in the other units changed (e.g., the portion of the repository in the non-lithophysal units was reduced from 20% in PA-SR to 15% in PA-LA).

For PA-LA, 11,629 waste packages were emplaced horizontally end-to-end in the drifts, with a gap of <0.1 m (~110 packages in an average 605 m drift) [25, Table 6.3.7-1] (Fig. 13; Table 1). The ground-control was steel welded wire fabric as in PA-SR; however, friction rock bolts were substituted to further reduce the possibility of the grouted rock bolts changing the pH of seeping water.

As described in the final EIS, the construction period prior to receipt of the first waste was envisioned to be a little over 5 yr [97, pp. 2–17], similar to the 4 yr envisioned for PA-EA. The duration of emplacement operations was flexible and envisioned to be up to 50 yr (80% increase from the 28 yr estimated for PA-EA) to allow for extended cooling ventilation of the repository since extended surface storage was not planned [95]. Though not necessarily required by NRC (§63.111(e)), the duration of the monitoring phase was up to 50 yr after the emplacement of the final waste package, more than double the 22-yr duration estimated for PA-EA. Decommissioning the repository was estimated to require 10 yr (a factor of 3 above the 3 yr estimated for PA-EA 24 yr earlier).

2.7.2. Package design in PA-LA

For PA-LA, the manufacturing process, method of loading, and handling attachments were refined for the waste container. The thickness of the outer layer of Alloy 22 for CSNF packages was increased slightly from 20 to 25 mm to match the thickness adopted for HLW/DSNF and naval packages for PA-SR (Table 3). The available crevice corrosion experiments were used to bound corrosion rates of Alloy 22.[19] A major change for PA-LA, which influenced performance under seismic loads [6], was the decision in 2006 to use a 25-mm thick stainless steel Transportation, Aging, and Disposal (TAD) handling canister for CSNF (Fig. 7). The motivation for the TAD was similar to that of the MPC proposed for PA-95: the complex task of designing and subsequent high cost of a surface facility for handling large numbers of bare assemblies at the repository to achieve a throughput of 3000 MTHM/yr. Use of a canister that was loaded and sealed at the nuclear reactor eliminated handling assemblies whenever transporting, storing, or disposing of CSNF. Besides a stainless steel exterior, the TAD used stainless steel for internal support baskets. The canister had a massive 380-mm thick lid. The TAD forced some decisions, such as criticality control for extended storage and permanent disposal, to be made while designing the TAD. The 21 PWR TAD nominally held ~9.5 MTHM and the 44 BWR TAD nominally held ~7.9 MTHM. The heaviest disposal package was ~73.5 t, which consisted of the navel SNF handling canister of ~44.5 t with a disposal overpack of ~29 t. The 44 BWR disposal package was 42.5 t. The HLW/DSNF co-disposal package was 53 t [32, Section 2.3.4.5.1].

[19] A series of problems with the corrosion experiments at the LLNL facility was discovered after an initial NRC audit in January 2006 discovered uncalibrated humidity measurements and so the test results could only be considered bounding (Appendix A) [101].

Staging pads for up to 21,000 MTHM were planned at the repository to facilitate repository operations without having to immediately place the waste underground. Blending of CSNF at the repository was not possible when using a TAD because a nuclear utility was allowed to ship any waste more than 5 yr old and shipping young, thermally hot CSNF might have been in the best interest of a utility [102]. Also, much of the cool DSNF and some types of HLW may have been ready for shipment before CSNF. The repository operation needed the ability to receive these various waste types yet have the ability to select the waste packages for disposal to maintain a fairly uniform thermal load within the repository.

3. Summary

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

Initially, a fairly generic repository layout and engineered barrier design was considered that was applicable to various geologic media. For PA-EA and PA-91, the repository design was vertical floor emplacement with small waste containers. While ramps were to be constructed using a tunnel boring machine, most of the underground facility was to be constructed with conventional drill and blast technology. PA-93 considered vertical floor emplacement but also considered in-drift emplacement with large packages (Fig. A1). Layout of the underground facility was redesigned to facilitate construction using a tunnel boring machine. Both vertical and in-drift configurations in PA-93 and thereafter considered corrosion resistant material for the containers. The appeal of in-drift emplacement of large packages in PA-95 and thereafter was the ability to more easily receive 3000 MTHM/yr of SNF and HLW since less packages were emplaced, and to save excavation costs. A mountain site facilitated use of large packages since gently inclined ramps could be used to move large, heavy packages into the repository.

Use of the UZ presented YMP the option to not backfill the repository (at least for an extended period) and allow convection and especially radiative heat transfer in the open drifts to maintain lower temperatures on the large package surface and still thermally load the repository to fairly high values (between 28 W/m^2 in PA-93 and 18 W/m^2 in PA-LA). However, some flow percolating through fractures could become drips, even though a large drift cavity provided a capillary barrier. Titanium drip shields were added for PA-SR and PA-LA to avoid drips on the package and, thereby, reduce the potential for localized corrosion during the thermal period. Analyzing these new features and processes necessitated an extensive experimental program to resolve phenomena uncertainty.

PA-LA added a 25-mm thick TAD handling canister loaded and sealed at the utility, which eliminated handling assemblies whenever transporting, storing, or disposing of CSNF (Fig. A1). The TAD was similar in function to the MPC proposed and evaluated for PA-95. By using a large TAD similar in size to dry storage casks, the YM repository in the UZ was reasonably able to directly link CSNF shipments from nuclear reactors and still accommodate the needs for limited disruption of pool storage operations at nuclear reactors.

In contrast, a centralized storage facility would be of great benefit to decouple operations at nuclear reactors from operations at future repositories, because smaller packages and extended storage may be necessary to accommodate lower thermal load limits required for crystalline, clay/shale, and possibly salt media in the SZ at other sites [103]. Indeed, a strategy of small packages, which held 3 or 4 PWR assemblies and 6 or 10 BWR assemblies that could be used in various saturated and unsaturated geologic media, was initially adopted in the early 1980s to maintain flexibility, prior to tightly linking operations at the nuclear reactor with the unsaturated Yucca Mountain repository. A TAD-like handling canister, loaded at a centralized storage facility, might still be advantageous to avoid handling bare fuel after extended storage but of smaller size while the US formulates a new disposal strategy.

Eventually, the YMP embraced a staged construction approach for the repository and surface facilities as tentatively proposed in the 1986 EA. In addition, YMP developed a design strategy for the repository underground and surface facilities that was modular; thus, the design was more flexible and consistent with the annual funding available. The modular design of the surface facilities, could be adopted to other repository sites with different assumptions of waste receipt schedules and smaller packages.

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. Furthermore, the extensive time some scientists and engineers devoted to the design of the YM disposal system and the handoff between different scientists and engineers as YMP transitioned through four study phases (site identification, feasibility analysis, suitability analysis, and compliance analysis [2, Table 1]) is more evident if some of the persons and organizations are acknowledged here. Engineers supervising the early design include L. Scully, SNL (SCP conceptual design [50]); H.R. MacDougall, SNL (SCP conceptual design [51]); J.R. Tillerson, SNL (SCP conceptual design [51]); J.A. Fernandez, SNL (borehole and shaft sealing [35]; S.G. Bertram, SNL (options for construction [36]). The evaluation of construction methods for the ESF in 1991 involved a number of contributors [58]: L.S. Costin, SNL, R.E. Finley, SNL; A. Dennis, SNL; M.W. Parsons, SAIC; W.J. Boyle, RE/SPEC now at DOE; P. Gnirk, RE/SPEC; D.K. Parrish, RE/SPEC; N. Elkins, LANL; R.W. Craig, USGS; M.D. Voegele, SAIC; W. Kennedy; and L. Merkhoffer, ADA (decision analysis). The repository design became a major task of the engineering branch of the Management and Operator Contractor after 1995 (first TRW from 1995 to 2000 and then BSC—Bechtel SAIC Company—from 2000 to 2008) and included H. Benton, G. Gordon; D. Bullock; M. Johnson; D. McKenzie; R. Sandifer; R.D. Snell. However, analysis of design options continued to occur by individuals in other branches, for example, L.D. Ramspott, LLNL and T.A. Buscheck, LLNL (champions of a hot repository design for PA-93 [59] and thereafter [60], respectively), E.L. Hardin, LLNL/BSC now at SNL [104] and D.A. Chesnut, LLNL. Furthermore, the License Application Design Selection (LADS) study [95] was a particularly large design analysis, which evaluated the influence of design modifications on

PA-VA and, thus, involved many of the persons acknowledged in a companion paper on the PA progression [4]. As part of the LLNL role in characterizing the near field and analyzing waste package performance [104], several experiments on the long term behavior of the waste container corrosion were conducted and persons contributing include W. Clarke; G.E. Gdowski (PA-95, PA-VA, and PA-SR); J.C. Farmer (PA-95, PA-VA and PA-SR [93]; R.D. McCright; J.A. Blink; R.B. Rebak, now at GE; B.S. El Dasher; J.C. Estill; K.J. Evans; D.V. Fix; T. Lian, now at EPRI; C. Orme; J.A. Rard; T.J. Reshel; M. Sutton; and S.G. Torres. For PA-LA, others also contributed: J.H. Payer, Case Western Reserve University (also peer review for PA-VA [105] and PA-SR); F.D. Wall, SNL (experimental and model review of LLNL results [106]); D.G. Enos, SNL (experimental and model review of LLNL results); and K.B. Helean, SNL (experimental and model review of LLNL results). Other contributors included Gopal De, BSC (experimental modeling PA-SR) and oversight of the corrosion work at TRW/BSC included *P* Pasupathi [93] (PA-VA and PA-SR), D. Stahl (PA-95, PA-VA, and PA-SR), and N.R. Brown, BSC/LANL now at SNL (PA-LA) [106]. Contributors to experiments on CSNF degradation were AJ Rothman, LLNL (cladding degradation at time of PA-EA [107]); R.B. Stout and W.L. Bourcier of LLNL (waste form characteristics for PA-91, PA-93, and PA-95); S.A. Steward, LLNL (experimental analysis of un-irradiated fuel for PA-95, PA-VA, PA-SR); C.N. Wilson, PNNL (batch tests of CSNF dissolution for PA-91 [108] and PA-93); and W.J. Gray, PNNL (CSNF dissolution data from single-pass, flow-through tests used for PA-VA and thereafter [109]); and B. Hansen, PNNL (oxic degradation of CSNF for PA-VA and PA-SR and re-analysis of CSNF dissolution data for PA-LA). In addition, J. Bates, ANL [110], conceived of and later J. Cunnane, ANL led the hot-cell CSNF drip experiments that provided surface area data to supplement data by W.J. Gray for PA-LA. The ANL drip test were supported first by P.A. Finn, ANL [111] and then R. Finch, ANL now at SNL [112]. J. Bates also supervised early evaluation of HLW glass degradation (PA-EA [113]). Later, W.L. Bourcier, LLNL (conducted experiments of HLW glass degradation for PA-95 [88]). Finally, W.L. Ebert, ANL was the prominent contributor to HLW degradation experiments (PA-VA, PA-SR [114], PA-LA). Contributors to the analysis of experiments for inclusion in models are acknowledged in companion papers on container degradation [6] and waste form degradation [7]. Because so many engineers and scientists were involved in repository design, container design and corrosion experiments, and waste form degradation experiments at YMP, the authors recognize that this list is unavoidably incomplete, and we apologize for omissions and oversights.

Appendix A. Progression of Yucca Mountain Disposal System Design and Evaluation

1963 Dec: Idaho National Lab (INL) begins oxidation of defense high-level waste (DHLW) to form solid calcine for storage [115].

1966 West Valley, NY plant for reprocessing commercial spent nuclear fuel (CSNF) begins operation and continues until 1972 [116, p. 98].

1968 Because of some leakage from 149 single-shell tanks built between 1944 and 1965, Hanford begins constructing 28 double-shell tanks for DHLW. The last tank completed in 1986.

1973 Jun: Leakage from Hanford single shelled tank widely reported.

1976 Weapons effect facility 425 m below surface in Climax granite at Nevada Test Site (NTS) is modified for underground research lab (URL) by Lawrence Livermore National Lab (LLNL) [117].

1980 Congress authorizes cleanup of West Valley, which produces 275 HLW canisters by 2001 [118]. **Apr-May:** 11 CSNF canisters and 6 simulated canisters placed remotely in Climax [119]. By 1982, ~4700 people had visited Climax facility [120, p. 14].

1982 Jan: Sandia National Labs (SNL) begins seal development for shafts and boreholes at Yucca Mountain (YM) [34]. **Apr:** Department of Energy (DOE) forms Ad Hoc Working Group to evaluate exploratory studies facility (ESF) shaft designs at YM; group selects conventional drill/blast mining [120, p. 14]. **Jun:** Drilling begins at G-4, proposed location of ESF shaft [44]. **Jul:** US Geological Survey (USGS) suggests ~350-m thick Topopah Spring Fm (TSw) in unsaturated zone (UZ) [121]. **Aug:** Conceptual Title I (preliminary) design of ESF completed [122]. **Oct:** Title I design of surface and subsurface facilities completed [120, p. 19]. **Dec:** SNL reports on preliminary design for a tuff repository [20]. LLNL reports on preliminary design for SNF waste package [42]. Based on Nuclear Regulatory Commission (NRC) draft of 10 CFR 60, DOE requests more robust waste package for disposal.

1983 Jan: In *Nuclear Waste Policy Act (*NWPA), Congress (a) states DOE SNF (DSNF) and DHLW will go to 70,000-MTHM commercial repository unless President objects; (b) directs DOE to advise Congress on site for Monitored Retrievable Storage (MRS); and (c) creates Nuclear Waste Trust Fund (NWTF) via 0.1¢ fee on every kW-hr of nuclear energy produced. **Feb:** SNL completes formal evaluation of 4 tuff layers at YM: Tram (TRw) and Bullfrog (BFw) units in SZ and Tuffaceous Beds of Calico Hills (CHn1) and Topopah Spring (TSw2) units in UZ, SNL recommends Topopah Spring (TSw2); report released following year [21]. **Mar:** 3-yr test of SNF at Climax completed; all 11 SNF canisters removed; one cut open and 2 rods tested; rock temperature and displacements monitored for 6 months [120, p. 21]. **Aug:** Inclined access ramp for waste and tuff adopted for repository [123]. Construction of ESF to begin in 1985 pending completing requirements imposed by NWPA [120, p. 20]. SNL analyzes (a) vertical shaft and inclined access ramp, and (b) vertical floor and horizontal pillar emplacement [37]. **Sep:** LLNL reports on container design using stainless steel and high-nickel alloys [43]; same design proposed for salt, basalt, and tuff [44]. Tests started to evaluate geochemical conditions around packages in UZ [120, p. 20]. In response to Swedish concept, DOE asks LLNL to evaluate copper alloys for containers [46]. LLNL reports on degradation rates of CSNF and HLW glass [124].

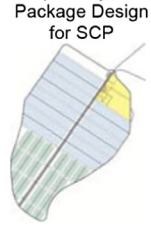
Repository Uses Floor/Pillar Disposal

1984 SNL reports on area for tuff repository [33]. **May:** LLNL reports on geochemical tuff/water interaction using J-13 well water [125]. **Aug:** SNL reports on repository sealing concepts [35] and ESF construction methods [36]. Also, seals in G-4 and UE-25p#1 are cored to measure permeability, porosity, density. **Sep:** LLNL reports on corrosion mechanisms for CSNF cladding [107]. SNL designs stair-step repository to keep horizontal and in lower non-lithophysal welded tuff (Tptpln) [28]. **Nov:** LLNL and Argonne National Lab (ANL) report on leaching tests on HLW glass in gamma field to evaluate radiolysis influence [126]. Hanford Engineering Development Laboratory completes plan for corrosion tests of CSNF cladding for LLNL [127].

1985 President Reagan approves disposal of DSNF/DHLW with CSNF. DOE closes Climax URL rather than upgrade ventilation [117]. **Apr:** DOE suggests 3 MRS sites in Tennessee (TN). **Aug:** TN sues since not consulted as per NWPA. **Sept:** SNL compares vertical floor, horizontal pillar, and horizontal in-drift emplacement [128]. SNL proposes 2 stages over 8 yr for excavating repository; changes to 1984 design include use of 2 ramps at north end rather than one [90]; concept adopted by 1986 Environmental Assessment (EA). Study of metal dry storage casks completed for DOE [129]. **Oct:** TN Clinch River Task Force supports MRS if several stipulations adopted. **Dec:** *Gramm-Rudman-Hollings Act* (GRHA) passed to balance Federal budget [130].

1986 NRC licenses DOE/utility demonstration of dry casks for storing CSNF at Surry reactor in Virginia. **Jan:** TN Gov formally rejects MRS because unnecessary and stigma (not safety) [131, p. 146]. **May:** YM final EA assumes a 5 km^2 repository 390 m below the surface and 170 m above water table with heat load of 14 W/m^2. Both floor and pillar emplacement is considered. Construction by either drill/blast and tunnel boring machine (TBM) is considered [39]. **Nov:** 6th Appeals Court rules DOE does not have to consult with TN for MRS when 1st suggested.

Repository and Package Design for SCP



1987 GRHA amendments place YMP under spending cap even though NWTF from fee for service (not tax) [132]. Also, Office of Management and Budget (OMB) sets one yearly budget for DOE; thus YMP must compete with other DOE programs. **Mar:** DOE selects MRS site in TN for 15,000-MTHM facility to consolidate rods into small canister [133]. **Apr:** In hearings for *Nuclear Waste Policy Amendments Act* (NWPAA), former Director of Oak Ridge National Lab, Weinberg, proposes US use Swedish approach of long-lived containers (<300,000 yr) [53]. **Apr & Nov:** Pacific Northwest National Lab (PNNL) reports on radionuclide release from bare CSNF in batch tests [134]. **Sep:** In 6 volumes, SNL describes repository design for Site Characterization Plan (SCP). The 5.6-km^2 repository follows the ~6° down dip of Tptpln, and remains >200 m below the surface and <183 m above water table. Both floor and pillar placement still considered. Design commingles CSNF and HLW to keep heat load uniform at 14 W/m^2. Design consolidates CSNF so that 6 PWR or 18 BWR rods fit into container [51]. **Dec**: In NWPAA, Congress (a) forms Nuclear Waste Technical Review Board (NWTRB) to advise DOE and Congress; (b) revokes choice of TN for MRS; (c) for MRS sited by DOE, adopts TN Clinch River Task Force suggestion for 15,000-MTHM MRS linked to repository schedule, which limits flexibility and role; (d) sets up voluntary program with negotiator for alternative MRS or repository.

1988 Feb: ANL reports on degradation of HLW glass during gamma irradiation [135]. **Dec:** SCP published [31; 49].

1989 Jun: Based on NWPAA, DOE re-evaluates MRS and decides advantage is system flexibility; also, rod consolidation not desired [77]. **Sep:** ANL reports secondary U minerals formed in new drip tests on CSNF [110]. **Nov:** MRS Review Commission, setup by NWPAA, notes no strong preference for MRS but flexibility and cost savings if MRS decoupled from repository schedule and if repository substantially delayed; otherwise, build a 2000-MTHM federal emergency and a 5000-MTHM user-funded storage facilities.

1990 Mar: 1st NWTRB report [56] (a) criticizes plan to use drilling/blasting to excavate ESF shafts; (b) suggests replacing shaft with an inclined ramp, which would cross several faults and tuff units; (c) suggests excavating a 2nd east-west drift across strata and faults. **May:** NRC states DOE may take credit for a package lasting longer than 1000 yr (i.e., 300-1000 yr requirement in 10 CFR 60 minimum range) [54]. **Sep:** In response to NWTRB and NRC critique of draft SCP, SNL explores alternatives to shafts in ESF alternative study; top 3 options out of 34 are (a) inclined drifts to TSw and lower Calico Hills (CHn) tuff; (b) inclined drift to TSw and internal shaft to CHn; or (c) 1 inclined drift,1 shaft to TSw and CHn, and 1 internal shaft to CHn [58].

1991 May: In 3rd report [57], NWTRB (a) praises ESF Alternative Study; (b) recommends DOE evaluate other alternatives including different power loads; (c) again requests DOE minimize waste handling during storage, transportation, and disposal. **Jun:** DOE workshop explores package designs that last $>10^3$ yr. Ideas adopted include (a) multi-barrier materials to reduce uncertainty; (b) multipurpose canister (MPC) to reduce handling; and (c) simplified design to ease fabrication [55]. **Dec:** In response to $\$30\times10^6$ cut for FY92, DOE curtails engineered barrier system (EBS) study, postpones EBS design until FY93, and postpones boring ESF until FY94 [55]. Lack of state permits and NRC compliant QA program also contribute to postponement [55] (i.e., co-locating ESF with the repository necessitates NRC compliant QA).

Fig. A1. Design of repository and engineered barrier and evaluation of waste form for YM disposal system [115–150].

1992 Congress ratifies *Strategic Arms Reduction Treaty* (START I), which reduces offensive arms by 30% [74]. In response, DOE halts reprocessing and proposes direct disposal of DSNF. Also, 50 tonnes Pu declared surplus [75]. PNNL completes experiments on CSNF degradation; data used in PA-95 and thereafter [109]. **May:** ANL reports that HLW glass forms colloids as it degrades [136]. **Nov:** MRS conceptual design considers wet pools and dry casks and vaults [99]. **Dec:** In 6th report, NWTRB urges DOE to conduct system study of storage, transportation, and disposal and consider MPCs with high capacity and shielding [87].

1993 DOE changes construction method to TBM with mildly inclined access drifts [16, §4.4]. **Mar:** LLNL suggests using a high heat load to dry tuff around drifts to enhance repository performance [61].

In-Drift Disposal and High Heat Load Adopted

1994 ANL reports on actinides and colloids in CSNF drip tests [137] **Apr:** SNL completes guidelines for when, where, and how to seal boreholes [138]. **Jun:** YMP specifies package and repository design [79]: (a) in-drift emplacement; (b) drift designed for 100 yr retrievability; (c) no backfill used; (d) repository designed for both a high 22-28 W/m^2 and low 7-10 W/m^2 heat load; (e) container lifetime >10^3 yr; (f) container for high-temperature repository has inner layer of Alloy 825 and outer layer of mild steel and for low-temperature repository has inner layer of Alloy 825, middle layer of mild steel, and outer layer of Monel 400; (g) package transported by rail underground; (h) no self-shielding; (i) burn-up credit considered in package criticality control; and (j) period of concern for criticality is 10^4 yr. DOE plans EIS on disposal options for surplus weapons-grade Pu because of START I. Options include Pu use in mixed-oxide fuels (MOX), disposal with HLW; deep borehole disposal; and accelerator destruction [75]. **Sep:** YMP uses TBM to bore large 7.6-m diameter ESF; progress is slow [85]. To avoid influencing experiments, little water is used to suppress silica dust. DOE decides to use a moderately high heat-loading (21 W/m^2) to save costs of boring ~200 km of drifts, which allows repository to fit west of Ghost Dance Fault [85]. DOE completes MPC evaluation to better integrate waste management [86].

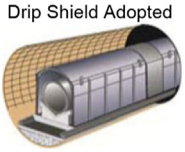
1995 Jan: Voluntary repository and MRS siting program expires without success; yet, Goshute Skull Valley Indian tribe in Utah starts direct negotiations with utility consortium. **Feb:** SNL analyzes direct disposal of DSNF in separate section of repository and robustness of graphite fuel beads [72]; 2nd analysis in 1998 commingles DSNF with CSNF [73]. **Apr:** ESF progress improves after YMP finds enough money to add conveyer to TBM to remove rock [84]. Boring of ESF averages ~26 m/day in Sep, Oct, and Nov [85]. **Oct:** YMP budget cut from $630×10^6 to $315×10^6. Congress stops MPC development because of cost for transportation, added handling costs to utilities, and perceived lack of fairness in bidding for only one vender [92]. **Dec:** Boring of ESF sets a world record of 218 m in 5 days.

1996 Feb: Boring slows to 15 m/day as TBM encounters unstable rock [84]. **Sep:** Container corrosion tests begin at LLNL after funds found to complete corrosion facility [85]. YMP stops TBM to suppress dust and require full-face masks because silica dust exceeds Occupational Safety and Health Administration (OSHA) limits [85].

1997 Apr: Boring of 8-km ESF is completed (12 m/day average). **Aug:** Waste Package Degradation expert elicitation (WPDEE) panel (6 experts with 4 from outside DOE complex) completes evaluation of container corrosion, including microbial enhancement (started in Mar) [94, §5.3]. Experts like steel corrosion rates used in PA-95. Experts reluctant to define localized corrosion rates of Alloy 625, which replaced Alloy 825 in 1996 [139]. Experts suggest using a mass balance on nutrients and water to evaluate possibility of microbial enhanced corrosion. **Nov-Dec:** Waste Form expert elicitation (WFEE) panel (6 experts with 3 outside DOE complex) complete 1st and 2nd workshop on degradation of SNF and HLW. Experts conclude waste degradation data adequate for PA-VA. Experts find sufficient data on generalized corrosion but insufficient data on localized corrosion of cladding; hence, no recommendation on role of cladding for PA-VA [18, p. 3-93].

1998 Feb: To increase container lifetime, YMP replaces Alloy 825 with Alloy 22. WPDEE panel holds 1-day meeting to discuss corrosion of Alloy-22 [94, §5.3]. **Mar:** Based on strong NWTRB suggestion in 1st report and thereafter [41, p.92], YMP starts boring 2.8-km long, 5-m diameter enhanced characterization of repository block (ECRB) cross drift with smaller TBM from Super Collider project; ECRB is 15 to 27 m above ESF and penetrates lower lithophysal unit (Tptpll) where majority of repository will exist [140]. **Jun:** YMP starts constructing ¼-scale drip shield/container at Atlas facility in North Las Vegas [96]. **Oct:** ECRB completed to Solitario Canyon fault [96]. **Dec:** License Application Design Selection (LADS) study begins to select repository/package design for site recommendation (SR) and license application (LA) [95].

Drip Shield Adopted



1999 Tests start on ¼-scale drip shield and container to evaluate condensation under drip shield and amount of water drawn under invert [96]. **Apr:** YMP completes LADS. Ti drip shield added to protect package during transition from hot to cool when susceptible to localized corrosion. Alloy 22 switched to outer container layer; stainless steel used for inner support layer. Waste blended to 11.8 kW/pkg and packages spaced 0.1 m apart to keep temperatures similar. Drift support changed from concrete to steel mesh and rock bolts. Drift spacing increased to 81 m to lower pillar temperatures and allow water to pass and thereby avoid ponding water above repository. LADS also examines ways to reduce peak construction costs, which becomes basis of 2001 modular study [95]. **Jul:** In draft EIS, various repository sizes are considered (70,000 to 105,000 MTHM) [141].

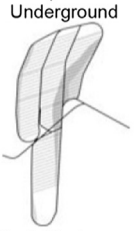
2000 Aug: Nevada scientists describe conditions when Alloy 22 might corrode to NWTRB (traces of Pb, As, Hg at high temperature) [142].

2001 May: YMP completes study to increase operation flexibility by using modular surface buildings and subsurface construction [99].

2002 Feb: In deference to Russia and lack of budget, DOE rejects options to dispose surplus Pu at YM, in deep boreholes, or accelerator destruction and selects option to convert to MOX for reactor use [143].

2003 NAS suggests staged repository schedule in DOE sponsored study [144]. **Nov:** NWTRB comments that YMP has not convincingly screened out localized corrosion on drip shield or container because [145]: (1) deliquescence could produce corrosive water high in Cl^- and lacking nitrate; (2) corrosive seepage water could be present; and (3) the thermal conditions in 1st 1000 yr are not well modeled since (a) thermal conductivity may be too high, (b) insulation of the package by rockfall is not modeled, and (c) the natural ventilation not modeled. Scientists report that U may form studtite that could trap Pu and Np and prevent nuclide migration [146].

Modular Design Adopted for Underground



2004 May: YMP presents test results to NWTRB that show no localized corrosion of Alloy 22 induced by salt deliquescence trace minerals for hot repository [147]. **Sept:** CSNF drip tests at ANL stopped; analysis of specimens continues to 2005.

2005 May: NRC approves license for Private Fuel Storage (PFS) at Goshute tribe reservation for 40,000 MTHM [148]. **Oct:** Because of high cost of handling facility for large volume of CSNF, DOE adds Transport, Aging, and Disposal (TAD) handling canister that is loaded at reactor (similar to MPC) [149]. Repository moved farther north with 4 modular panels to increase flexibility in construction. Based on 2001 YMP study, smaller modular surface facilities added for receipt, wet handling, and sealing; concrete pads added for buffer storage [100].

TAD Handling Canister Adopted

2006 Jan: Acting Director Golan announces a new path: implement TAD for CSNF. Also, Alloy 22 layer thickness increased from 20 to 25 mm for CSNF. In audit, NRC finds that LLNL never calibrated its measurements of humidity in corrosion tests; DOE stops corrosion work at LLNL. Eventually, 5 yr and 9.5 yr corrosion work eliminated [41, p.24]. **Sept:** Bureau of Indian Affairs (BIA), nullifies lease between Goshute tribe and PFS, claiming storage might be permanent and federal, tribal, local police inadequate to protect [100].

2007 Jun: DOE announces requirements for TAD canisters; ~7800 TADs to be built by various vendors for CSNF disposal [150]. Although similar to MPC, dry casks at utilities now exceed size of TAD [41, p.44].

2010 Dec: ~65,200 MTHM of CSNF has been generated; 2458 MTHM of DSNF has been generated (includes 25 MTHM of Naval SNF); 3175 HLW canisters poured. Waste is stored in 39 states at 131 sites [97].

2012 Jan: Blue Ribbon Commission (BRC) recommends restarting repository sitting and implementing centralized storage to avoid high costs of stranded storage as reactors are decommissioned [98].

Fig. A1. (continued)

References

[1] Rechard RP, Cotton TA, Voegele M. Site selection and regulatory basis for the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste. Reliability Engineering and System Safety. http://dx.doi.org/10.1016/j.ress.2013.06.021, this issue.

[2] Rechard RP, Liu HH, Tsang YW, Finsterle S. Site Characterization of the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste. Reliability Engineering and System Safety. http://dx.doi.org/10.1016/j.ress.2013.06.020, this issue.

[3] Rechard RP, Freeze GA, Perry FV. Hazards and scenarios examined for the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste. Reliability Engineering and System Safety. http://dx.doi.org/10.1016/j.ress.2013.06.014, this issue.

[4] Rechard RP, Wilson ML, Sevougian SD. Progression of performance assessment modeling for the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste. Reliability Engineering and System Safety. http://dx.doi.org/10.1016/j.ress.2013.06.026, this issue.

[5] Rechard RP, Birkholzer JT, Wu Y-S, Stein JS, Houseworth JE. Unsaturated flow modeling in performance assessments of the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste. Reliability Engineering and System Safety. http://dx.doi.org/10.1016/j.ress.2013.06.025, this issue.

[6] Rechard RP, Lee JH, Hardin E, Bryan CR. Waste package degradation from thermal and chemical processes in performance assessments of the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste. Reliability Engineering and System Safety. http://dx.doi.org/10.1016/j.ress.2013.06.027, this issue.

[7] Rechard RP, Stockman CT. Waste degradation and mobilization in performance assessments of the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste. Reliability Engineering and System Safety. http://dx.doi.org/10.1016/j.ress.2013.06.028, this issue.

[8] Rechard RP, Arnold BW, Robinson BA, Houseworth JE. Transport modeling in performance assessments for the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste. Reliability Engineering and System Safety. http://dx.doi.org/10.1016/j.ress.2013.06.031, this issue.

[9] Rechard RP. Results from past performance assessments of the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste. Reliability Engineering and System Safety. http://dx.doi.org/10.1016/j.ress.2013.06.030, this issue.

[10] Rechard RP, Blink JA, Halsey WG, Cotton TA. Integrated waste management system for spent nuclear fuel and high-level waste. In: International high-level waste radioactive waste management conference, Albuquerque, NM, April 10–14, 2011. La Grange Park, IL: American Nuclear Society; 2011.

[11] Williams JR, Cotton TA, Rechard RP. Role of flexible design in staged development of repositories for spent nuclear fuel and high-level waste. In: International high-level waste radioactive waste management conference, Albuquerque, NM, April 10–14, 2011. La Grange Park, IL: American Nuclear Society; 2011.

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

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

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

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

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

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

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

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

[20] Scully LW, Rothman AJ. Repository and engineering barriers design. DOE/NWTS-30. In: 1982 National waste terminal storage program information meeting, Las Vegas, NV, December 14-16, 1982. Las Vegas, NV: US Department of Energy; 1982.

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

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

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

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

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

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

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

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

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

[30] O'Neal WC, Ballou LB, Gregg DW, Russell EW. Nuclear waste package design for the Vadose Zone in tuff. In: Waste Management 1984, Proceedings of the symposium on waste management, Tucson, AZ, March 11–15, 1984, vol. 1; 1984. p. 547-51.

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

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

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

[34] Tillerson JR, Meyers CW. Data for evaluation of containment and repository/engineered barrier design. DOE/NWTS-30. In: 1982 National Waste terminal storage program information meeting, Las Vegas, NV, December 14–16, 1982. Las Vegas, NV: US Department of Energy; 1982.

[35] Fernandez JA, Freshley MD. Repository sealing concepts for the Nevada nuclear waste storage investigations. SAND83-1778. Albuquerque, NM: Sandia National Laboratories; 1984.

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

[37] Mondy LA, Wilson RK, Bixler NE. Comparison of waste emplacement configurations for a nuclear waste repository in tuff: IV. Thermo-hydrological analysis. SAND83-0575. Albuquerque, NM: Sandia National Laboratories; 1983.

[38] SKB (Svensk Kärnbränslehantering AB). Long-term safety for KBS-3 repositories at Forsmark and Laxemar – a first evaluation. Main report of the SR-Can Project. SKB TR-06-09. Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Co./Svensk Kärnbränslehantering AB; 2006.

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

[40] DOE (US Department of Energy). Draft environmental assessment: Yucca Mountain Site, Nevada research and development area, Nevada. DOE/RW-0012. Washington, DC: US Department of Energy; 1984.

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

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

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

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

[45] DOE (US Department of Energy). Final environmental impact statement, management of commercially generated radioactive waste. DOE/EIS-0046F. Washington, DC: US Department of Energy; 1980.
[46] McCright RD. An annotated history of container candidate material selection. Livermore, CA: Lawrence Livermore National Laboratory; 1988.
[47] NRC (US Nuclear Regulatory Commission). 10 CFR Part 61: Licensing requirements for land disposal of radioactive waste; final rule. Federal Register 1982;47(248):57463-77.
[48] Weren BH, Capo MA, O'Neal WC. Nuclear criticality safety analysis of a spent fuel waste package in a tuff repository. UCRL-15575. Submitted by Westinghouse Electric Corporation. Livermore, CA: Lawrence Livermore National Laboratory; 1983.
[49] DOE (US Department of Energy). Site characterization plan: Yucca Mountain Site, Nevada research and development area, Nevada. DOE/RW-0199-Vol.1 through vol. 7. Washington, DC: Office of Civilian Radioactive Waste Management, US Department of Energy; 1988.
[50] Scully LW, MacDougall HR, Tillerson JR. Site characterization plan conceptual design report. SAND84-2641. Albuquerque, NM: Sandia National Laboratories; 1987.
[51] MacDougall HR, Scully LW, Tillerson JR. Site charaterization plan: Conceptual design report, vols. 1–6. SAND84-2641/Vol. 1-6. Albuquerque, NM: Sandia National Laboratories; 1987.
[52] NWTRB (Nuclear Waste Technical Review Board). Second report to the US Congress and the US Secretary of Energy. Arlington, VA: Nuclear Waste Technical Review Board; 1990.
[53] Weinberg A. Statement in U.S. Congress, nuclear waste program, hearings before the Committee on Energy and Natural Resources, U.S. Senate, first session, Part 2. Washington DC: US Government Printing Office; 2–3.
[54] NRC (US Nuclear Regulatory Commission). NRC high-level radioactive waste program annual progress report: Fiscal year 1996. NUREG/CR-6513, No. 1. Washington, DC: US Nuclear Regulatory Commission; 1997.
[55] NWTRB (Nuclear Waste Technical Review Board). Fourth report to the US Congress and the US Secretary of Energy. Arlington, VA: Nuclear Waste Technical Review Board; 1991.
[56] NWTRB (Nuclear Waste Technical Review Board). First report to the US Congress and the US Secretary of Energy. Arlington, VA: Nuclear Waste Technical Review Board; 1990.
[57] NWTRB (Nuclear Waste Technical Review Board). Third report to the US Congress and the US Secretary of Energy. Arlington, VA: Nuclear Waste Technical Review Board; 1991.
[58] Dennis AW. Exploratory studies facility alternatives study final report. SAND91-0025. Albuquerque, NM: Sandia National Laboratories; 1991.
[59] Ramspott LD. The constructive use of heat in an unsaturated tuff repository. In: Proceedings of the second international conference on high-level radioactive waste management, Las Vegas, NV, April 28–May 3, 1991. LaGrange, IL: American Nuclear Society; 1991. p. 1602–7.
[60] Buscheck TA, Nitao JJ, Ramspott L. Localized dry-out: an approach for managing the thermo-hydrological effects of decay heat at Yucca Mountain. In: Symposium on scientific basis for nuclear waste management XIX, November 27–December 1, 1995, Boston, MA: Material Research Society; 1995.
[61] Buscheck TA, Nitao JJ. Repository-heat-driven hydrothermal flow at Yucca Mountain: Part 1. Modeling and analysis. Nuclear Technology 1993:418–-48104(3) 1993:418–48.
[62] NWTRB (Nuclear Waste Technical Review Board). Report to the US Congress and the Secretary of Energy, January to December 2000. Arlington, VA: Nuclear Waste Technical Review Board; 2001.
[63] Winograd IJ. Yucca mountain as a nuclear waste repository–neither myth nor millennium. Open-File Report 91-170. Reston, VA: US Geological Survey; 1991.
[64] Alley WM, Alley R. Too hot to touch: The problem of high-level nuclear waste. Cambridge, UK: Cambridge University Press; 2013.
[65] Daling PM, Van Luik AE, Rhoads RE. Preliminary characterization of waste management system risks: Literature-based analysis. In: High-level radioactive waste management, proceedings of the international topical meeting, April 8–12, 1990, Las Vegas, NV, vol. 2. New York, NY: American Society of Civil Engineers; 1990. p. 1328–33.
[66] Daling PM, Rhoads RE, Van Luik AE, Fecht BA, Nilson SA, Armstrong GR, Rowe M, Hill D, Stern R. Preliminary characterization of risks in the nuclear waste management system based on information in the literature. PNL-6099. Richland, WA: Pacific Northwest National Laboratory; 1991.
[67] SNL (Sandia National Laboratories). Postclosure analysis of the range of design thermal loadings. ANL-NBS-HS-000057, Rev 0. Las Vegas, NV: Sandia National Laboratories; 2008.
[68] NRC (US Nuclear Regulatory Commission). Cladding considerations for the transportation and storage of spent fuel. SFST-ISG-11, Rev 3. Washington, DC: US Nuclear Regulatory Commission; 2003.
[69] Barnard R. Disruptive events. Chapter 10 of total system performance assessment-viability assessment (TSPA-VA) analyses technical basis document. B00000000-01717-4301-00010 REV 00. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 1998.
[70] Halsey WE. Total system performance assessment-viability assessment (TSPA-VA) analyses technical basis document: Chapter 6, waste form degradation, radionuclide mobilization, and transport through the engineered barrier system. B00000000-01717-4301-00006 REV 01. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 1998.
[71] Leigh C, Rechard RP. Radioisotope inventory for TSPA-SR. In: Ninth international high-level radioactive waste management conference (IHLRWM), Alexis Park Resort, Las Vegas, NV, April 29–May 3, 2001. La Grange Park, IL: American Nuclear Society, Inc.; 2001.
[72] Rechard RP. Performance assessment of the direct disposal in unsaturated tuff of spent nuclear fuel and high-level waste owned by US Department of Energy, vols. 1–3. SAND94-2563/1,2,3. Albuquerque, NM: Sandia National Laboratories; 1995.
[73] Rechard RP. Update to assessment of direct disposal in unsaturated tuff of spent nuclear fuel and high-level waste owned by US Department of Energy. DOE/SNF/REP-015, INEEL/EXT-98-00185, SAND98-0795. Washington, DC: US Department of Energy; 1998.
[74] USCongress. The START Treaty; report of the Committee on Foreign Relations, United States Senate, together with additional views to accompany Treaty Doc. 102-20 and Treaty Doc. 102-32. 102nd Congress, 2nd Session. Executive report 102-53. Washington, DC: US Government Printing Office; 1992.
[75] DOE (US Department of Energy). Notice of intent to prepare a programmatic EIS (PEIS) for the long-term storage and disposition of weapons-usable fissile materials. Federal Register 1994;59:31985-90.
[76] Lytle JE. Disposal of DOE-owned high-level waste and spent nuclear fuel, interoffice memorandum to D.A. Dreyfus, US Department of Energy, Office of Civilian Radioactive Waste Management from J.E. Lytle (Office of Environmental Management). US Department of Energy; 1995.
[77] DOE (US Department of Energy). The DOE position on the MRS facility. DOE/RW-0239. Washington, DC: US Department of Energy; 1989.
[78] NWTRB (Nuclear Waste Technical Review Board). Disposal and storage of spent nuclear fuel — finding the right balance, a report to Congress and the Secretary of Energy by the Nuclear Waste Technical Review Board. 1996.
[79] CRWMS (Civilian Radioactive Waste Management System). Controlled design assumption document (CDA). B00000000-01717-4600-00032 REV 00A. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 1994.
[80] NWTRB (Nuclear Waste Technical Review Board). Report to the US Congress and the US Secretary of Energy, 1994 findings and recommendations. Arlington, VA: Nuclear Waste Technical Review Board; 1995.
[81] NWTRB (Nuclear Waste Technical Review Board). Report to the US Congress and the US Secretary of Energy, 1995 findings and recommendations. Arlington, VA: Nuclear Waste Technical Review Board; 1997.
[82] NWTRB (Nuclear Waste Technical Review Board). Underground exploration and testing at Yucca Mountain—a report to Congress and the Secretary of Energy. Arlington, VA: Nuclear Waste Technical Review Board; 1993.
[83] NWTRB (Nuclear Waste Technical Review Board). Report to the US Congress and the US Secretary of Energy, January to December 1993. Arlington, VA: Nuclear Waste Technical Review Board; 1994.
[84] NWTRB (Nuclear Waste Technical Review Board). Report to the US Congress and the US Secretary of Energy, 1995 findings and recommendations. Arlington, VA: Nuclear Waste Technical Review Board; 1996.
[85] NWTRB (Nuclear Waste Technical Review Board). Report to the US Congress and the Secretary of Energy, January to December 1996. Arlington, VA: Nuclear Waste Technical Review Board; 1997.
[86] DOE (US Department of Energy). Multi-purpose canister system evaluation. DOE/RW-0445. Washington, DC: US Department of Energy; 1994.
[87] NWTRB (Nuclear Waste Technical Review Board). Sixth report to the US Congress and the US Secretary of Energy. Arlington, VA: Nuclear Waste Technical Review Board; 1992.
[88] Bourcier WL, Carroll SA, Phillips BL. Constraints on the affinity term for modeling long-term glass dissolution rates.Scientific basis for nuclear waste management XVII, Boston, MA, vol. 333. Pittsburgh, PA: Material Research Society; 507–12.
[89] Steward SA, Gray WJ. Comparison of uranium dissolution rates from spent fuel and uranium dioxide. In: Fifth international conference on high-level radioactive waste management, Las Vegas, NV, May 22–26, 1994. La Grange Park, IL: American Nuclear Society and New York, NY: American Society of Civil Engineers; 1994.
[90] MacDougall HR, Scully LW, Tillerson JR. Two-stage repository development at Yucca Mountain: an engineering feasibility study. SAND 85-1351 (Rev. 1). Albuquerque, NM: Sandia National Laboratories; 1985.
[91] SNL (Sandia National Laboratories). Multiscale thermohydrologic model. ANL-EBS-MD-000049, REV 03, ADD 03. Las Vegas, NV: Sandia National Laboratories; 2008.
[92] Pub. L. 104-46. Energy and Water Development Appropriations Act of 1996; 1996.
[93] Farmer JC, Pasupathi V. Waste package degradation process model report. TDR-WIS-MD-000002, REV 00. CRWMS M&O 2000h. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 2000.
[94] Lee JH, Mon KG, Longsine DE, Bullard BE. Waste package degradation modeling and abstraction. Chapter 5 of total system performance assessment-viability assessment (TSPA-VA) analyses technical basis document. B00000000-01717-4301-00005 REV 01. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 1998.

[95] CRWMS (Civilian Radioactive Waste Management System). License application design selection report. B00000000-01717-4600-00123 REV 01 ICN 01. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 1999.
[96] NWTRB (Nuclear Waste Technical Review Board). Report to the US Congress and the Secretary of Energy, January to December 1999. Arlington, VA: Nuclear Waste Technical Review Board; 2000.
[97] DOE (US Department of Energy). Final supplemental environmental impact statement for a geologic repository for the disposal of spent nuclear fuel and high-level radioactive waste at Yucca Mountain, Nye County, Nevada. DOE/EIS-250 F-S1F. Las Vegas, NV: Office of Civilian Radioactive Waste Management, US Department of Energy; 2008.
[98] BRC (Blue Ribbon Commission). Report to the Secretary of Energy. Washington, DC: Blue Ribbon Commission on America's Nuclear Future; 2012.
[99] BSC (Bechtel SAIC Company). CRWMS modular design/construction and operation options report. TDR-CRW-MD-000002 REV 03. Washington, DC: Bechtel SAIC Company 2001.
[100] Kim D, Cotton TA. Yucca Mountain and the Global Nuclear Energy Partnership. In: WM 2007 conference, Tucson, AZ, February 25–March 1, 2007; 2007.
[101] Rogers K. Yucca feeling heat on humidity. Las Vegas Review-Journal, Thursday, February 23, 2006.
[102] DOE (US Department of Energy). 10 CFR Part 961: Standard contract for disposal of spent nuclear fuel and/or high-level radioactive waste; final rule. Federal Register 1983;48:16599.
[103] Hardin E, Blink JA, Greenberg HR, Sutton M, Fratoni M, Carter JT, Dupont M, Howard R. Generic repository design concepts and thermal analysis (FY11). FCRD-USED-2011-000143 Rev. 2, SAND2011-9275P. Idaho Falls, ID: US Department of Energy Fuel Cycle Technology Program; 2011.
[104] Hardin EL. Near-field/altered-zone models report UCRL-ID-129179 DR. Livermore, CA: Lawrence LIvermore National Laboratory; 1998.
[105] Budnitz B, Ewing RC, Moeller DW, Payer J, Whipple C, Witherspoon PA. Peer review of the total system performance assessment-viability assessment final report. Las Vegas, NV: Total System Performance Assessment Peer Review Panel; 1999.
[106] Wall FD, Brown NR. Long-term corrosion testing plan. SAND2009-0923. Albuquerque, NM: Sandia National Laboratories; 2009.
[107] Rothman AJ. Potential corrosion and degradation mechanisms of Zircaloy cladding on spent nuclear fuel in a tuff repository. UCID-20172. Livermore, CA: Lawrence Livermore National Laboratory; 1984.
[108] Wilson CN. Results from NNWSI series 2 bare fuel dissolution tests. PNL-7169. Richland WA: Pacific Northwest National Laboratory; 1990.
[109] Gray W, Leider H, Steward S. Parametric study of LWR spent fuel dissolution kinetics. UCRL-JC-110160. Richland, WA: Pacific Northwest National Laboratory; 1992.
[110] Bates JK, Tani BW, Veleckis E. Identification of secondary phases formed during unsaturated reaction of UO2 with EJ-13 water. In: Meeting, Boston, MA, November 27-December 2, 1989. Materials Research Society; 1989.
[111] Finn PA, Tsai Y, Cunnane JC. Corrosion tests of LWR fuels—nuclide release. In: Scientific basis for nuclear waste management XXV, Boston, MA, November 26–30, 2001. Materials research society symposium proceedings; 2002, vol. 713. p. JJ14.1.
[112] Finch RJ, Buck EC, Finn PA, Bates JK. Oxidative corrosion of spent fuel in vapor and dripping groundwater at 90 °C. In: Scientific basis for nuclear waste management XXII, materials research society symposium. 1999, vol. 556. p. 431–8.
[113] Bates J, Oversby VM. The behavior of actinide containing glasses during Gamma irradiation in a saturated tuff environment. In: Materials research society meeting, Boston, MA, November, 1984. Materials Research Society; 1984.
[114] Ebert W. Defense high-level waste degradation. ANL-EBS-MD-000016 REV 00, ICN 1. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 2000.
[115] Perge A. Historical overview. CONF-820845. In: Alpha-Contaminated Waste Management Workshop, Gaithersburg, MD, August 10–13, 1982. Oak Ridge, TN: Oak Ridge National Laboratory; 1982. p. 17–30.
[116] Carter LJ. Nuclear imperatives and public trust: dealing with radioactive waste, Resources for the Future, Inc. Baltimore. MD: John Hopkins University Press; 1987.
[117] Patrick W. Spent fuel test—climax: An evaluation of the technical feasibility of geologic storage of spent nuclear fuel in granite, final report. UCRL-53702. Livermore, CA: Lawrence Livermore National Laboratory; 1986.
[118] Pub. L. 96-368. West Valley Demonstration Project Act of 1980. (94 Stat. 1347; 42 U.S.C. 2021 et seq.); 1980.
[119] Duncan JE, House PA, Wright GW. Spent fuel handling system for a geologic storage test at the Nevada Test Site. In: Proceedings of the American nuclear society, Las Vegas, NV, June, 1980. La Grange Park, IL: American Nuclear Society; 1980.
[120] DOE (US Department of Energy). Bibliography of the published reports, papers, and articles on the Nevada nuclear waste storage investigations. NVO-196-24 (Rev. 5). Las Vegas, NV: Nevada Operations Office, US Department of Energy; 1985.
[121] Roseboom EH. Disposal of high-level nuclear waste above the water table in arid regions. Circular 903. Denver, CO: US Department of the Interior, Geological Survey; 1983.
[122] DOE (US Department of Energy). Project management plan for exploratory shaft at Yucca Mountain, Nevada nuclear waste storage investigation. NVO-255. Las Vegas, NV: Nevada Operations Office, US Department of Energy; 1983.
[123] Scully LW, Hunter TO. NNWSI repository design approach. SAND84-0104C. In: 1983 Civilian radioactive waste management information meeting, Washington, DC, December 12–15, 1983. Washington, DC: US Department of Energy; 1983.
[124] Oversby VM. Performance testing of waste forms in a tuff environment. In: 1983 Civilian radioactive waste management information meeting, Washington, DC, December 12–15m 1873. Washington, DC: US Department of Energy; 1983. p. 265–9.
[125] Knauss KG, Delany J, Beiriger JM, Peifer D. Hydrothermal interaction of topopah spring tuff with J-13 water as a function of temperature. In: Materials research society meeting, Boston, MA, November, 1984. Materials Research Society; 1984.
[126] Bibler N, Wicks G, Oversby VM. Leaching Savannah river plant nuclear waste glass in a saturated tuff environment. In: Proceedings of the materials research society annual meeting, Boston, MA, November 13–18, 1984. Boston, MA: Materials Research Society Meeting; 1984.
[127] Smith HD. Zircaloy spent fuel cladding electrochemical corrosion-scoping experiment. HEDL-TC-2562. Richland, WA: Hanford Engineering Development Laboratory; 1984.
[128] Gram HF, Scully LW, Braiser RI, Wheeler ML. Comparative study of radioactive waste emplacement configurations. SAND83-1884. Albuquerque, NM: Sandia National Laboratories; 1985.
[129] Rechard RP, McCord J, Knowlton RG. Guidelines for consistent treatment of parameter uncertainty in TSPA-LA. In: Proceedings of the 10th international high-level radioactive waste management conference (IHLRWM), Las Vegas, NV, March 31–April 3, 2003. La Grange Park, IL: American Nuclear Society; 2003.
[130] Pub. L. 99-177. Balanced Budget and Emergency Deficit Control Act of 1985. (99 Stat. 1038); 1985.
[131] Colglazier EW. Evidential, ethical, and policy disputes: admissible evidence in radioactive waste management. In: Mayo DG, Hollander RD, editors. Acceptable evidence: Science and values in hazard management. New York, NY: Oxford University Press; 1991.
[132] DOE (US Department of Energy). Alternative means of financing and managing the civilian radioactive waste management program. DOE/RW-0546. Washington, DC: Office of Civilian Radioactive Waste Management, US Department of Energy; 2001.
[133] DOE (US Department of Energy). Monitored retrievable storage (MRS) facility conceptual design report. TSO.92.0323.0257. Vienna, VA: TRW Environmental Safety Systems; 1992.
[134] Wilson CN, Oversby VM. Summary of results from the series 2 and series 3 NNWSI (Nevada nuclear waste storage investigations) bare fuel dissolution tests. PNL-SA-15207; UCRL-21013. In: Symposium on the scientific basis for nuclear waste management XI, Boston, MA, November 30–December 3, 1987, vol. 112. Pittsburg, PA: Materials Research Society; 1987. p. 473.
[135] Abrajano TA, Bates JK, Gerding TJ, Ebert WL. The reaction of glass during Gamma irradiation in a saturated tuff environment: Part 3, Long-term experiments at 1 × 10 to the 4th rad/hour. ANL-88-14. Chicago, IL: Argonne National Laboratory; 1988.
[136] Bates J, Bradley J, Teetsov A, Dradley C, Buchholtz ten Brink M. Colloid formation during waste form reaction: Implications for nuclear waste disposal. Science 1992;256:649–51.
[137] Finn PA, Buck EC, Gong M, Hoh JC, Emery JW, Hafenrichter LD, Bates JK. Colloidal products and actinide species in leachate from spent nuclear fuel. Radiochimica Acta 1994;66/67:197–203.
[138] Fernandez JA, Case JB, Givens CA, Carney BC. A strategy to seal exploratory borehoes in unsaturated tuff. SAND93-1184. Albuquerque, NM: Sandia National Laboratories; 1994.
[139] CRWMS (Civilian Radioactive Waste Management System). Waste package materials selection analysis. BBA000000-01717-0200-00020 REV 00. Las Vegas, NV: Civilian Radioactive Waste Management System Management and Operating Contractor; 1996.
[140] NWTRB (Nuclear Waste Technical Review Board). 1997 findings and recommendations, report to the US Congress and the Secretary of Energy. Arlington, VA: Nuclear Waste Technical Review Board; 1998.
[141] DOE (US Department of Energy). Draft environmental impact statement for a geologic repository for the disposal of spent nuclear fuel and high-level radioactive waste at Yucca Mountain, Nye County, Nevada. DOE/EIS-250D. Las Vegas, NV: Office of Civilian Radioactive Waste Management, US Department of Energy; 1999.
[142] Dornan G. Scientists say metal in nuclear casks could corrode dangerously fast. Nevada Appeal; August 2, 2000.
[143] DOE (US Department of Energy). Surplus Plutonium Disposition Program. Department of Energy. Federal Register 2002;67(76):19432-5.
[144] NA/NRC (National Academies/National Research Council). One step at a time: the staged development of geologic repositories for high-level radioactive waste. Washington, DC: National Academy Press; 2003.
[145] NWTRB (Nuclear Waste Technical Review Board). An evaluation of key elements in the US Department of Energy's proposed system for isolating and containing radioactive waste. Arlington, VA: Nuclear Waste Technical Review Board; 2003.

[146] AP (Associated Press). Chemists' new findings raise concern about Yucca. Las Vegas Review-Journal, November 18, 2003; 2003.
[147] Johnson J. DOE defends 'hot' repository design. C&EN; May 31, 2004.
[148] NYT (New York Times). The nuclear waste site in Utah, editorial. New York Times; September 16, 2005.
[149] NWTRB (Nuclear Waste Technical Review Board). Report to the US Congress and the Secretary of Energy; January 1, 2005 to February 28, 2006. Arlington, VA: Nuclear Waste Technical Review Board; 2006.
[150] Werner E. DOE releases design requirements for nuclear transport canisters. Associated Press in Las Vegas Sun; June 19, 2007.