Reliability Engineering and System Safety 122 (2014) 32–52

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

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

Site characterization of the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste

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ARTICLE INFO

Available online 3 July 2013

Keywords:
Site characterization
High-level radioactive waste
Spent nuclear fuel
Radioactive waste repository
Performance assessment
Yucca Mountain

ABSTRACT

This paper summarizes the investigations conducted to characterize the geologic barrier of the Yucca Mountain disposal system. Site characterization progressed through (1) non-intrusive evaluation and borehole completions to determine stratigraphy for site identification; (2) exploration from the surface through well testing to evaluate the repository feasibility; (3) underground exploration to study coupled processes to evaluate repository suitability; and (4) reporting of experimental conclusions to support the repository compliance phase. Some of the scientific and technical challenges encountered included the evolution from a small preconstruction characterization program with much knowledge to be acquired during construction of the repository to a large characterization program with knowledge acquired prior to submission of the license application for construction authorization in June 2008 (i.e., the evolution from a preconstruction characterization program costing $<\$0.04\times10^9$ as estimated by the Nuclear Regulatory Commission in 1982 to a thorough characterization, design, and analysis program costing $\$11\times10^9$—latter in 2010 constant dollars). Scientific understanding of unsaturated flow in fractures and seepage into an open drift in a thermally perturbed environment was initially lacking, so much site characterization expense was required to develop this knowledge.

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1. Introduction

In 1987, Congress selected Yucca Mountain as the sole location to be characterized for a potential disposal site for high-level radioactive waste (HLW), commercial spent nuclear fuel (SNF), and SNF owned by the US Department of Energy (DOE-owned SNF or DSNF) [1]. 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 repository since 1978. In 2008, DOE submitted the Safety Analysis Report for the construction License Application (SAR/LA) to the Nuclear Regulatory Commission (NRC) (Fig. 1). DOE had spent $\$15\times10^9$ (in 2010 US dollars) since site selection began in 1983 [2, p.10]. This cost included all waste management program costs required by the *Nuclear Waste Policy Act of 1982* (NWPA) [3] such as the Yucca Mountain Project (YMP) cost of $\$11\times10^9$. Although the Obama Administration and Congress brought a *de facto* halt to YMP by a lack of funding in 2010 and began the process of formulating new policy, much can be learned from the past scientific challenges encountered[2].

This paper summarizes information on site characterization 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* [4]. In keeping with the intended audience, this special issue devotes much to modeling and results; however, characterization of the natural barrier consumes much of the time and resources required to evaluate a geologic disposal system. Site characterization is at the heart of understanding the current behavior of components of the disposal system. Certainly, a description of the final understanding of the behavior of the Yucca Mountain disposal system is most satisfying academically, but re-examining the progression of this understanding, although somewhat tedious, provides a means for a future repository program to perceive the technical uncertainty that will exist at various phases of the project. The uncertainty that will exist cannot be grasped solely by examining the progression of characterization conducted at Yucca Mountain, but it provides a good starting point that can be enhanced by reading companion

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[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.

[2] At the time of submittal of the SAR/LA; DOE reported spending $\$13.5\times10^9$ with ~ $\$9.9\times10^9$ spent by YMP (in 2007 dollars) [4, Table, ES-1]. Most of the costs reported herein are for the year reported and have not been converted to a constant US dollar basis by accounting for inflation.

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http://dx.doi.org/10.1016/j.ress.2013.06.020

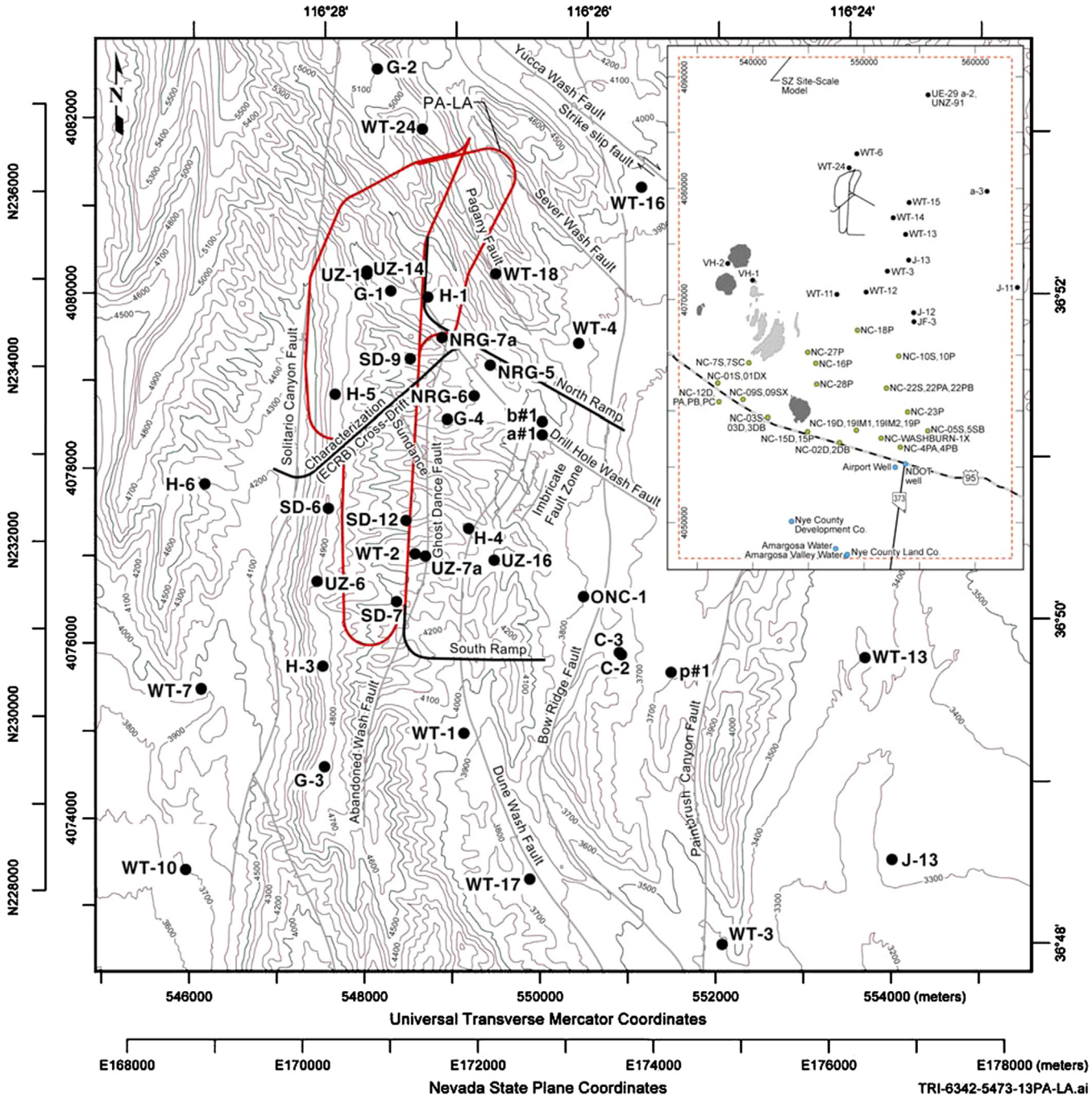


Fig. 1. Pertinent characterization wells at Yucca Mountain, Nevada in relation to repository for PA-LA.

papers, which describe the site selection, repository design, and evolution of the modeling system for the PA [5–13]. Some of the scientific issues encountered at Yucca Mountain have been summarized (e.g., [14–17]); however, this series of papers provides more background and historical context in order to examine potential technical implications for future repository programs.

As understanding of the disposal system has increased through characterization, the PAs have evolved from initial assumptions for site selection used in 1984, to extensive mathematical models used in the site recommendation (SR) in 2001, and finally to the partially validated mathematical models used in the SAR/LA in 2008. Seven PA iterations provide convenient points to discuss the status of YMP over the years.

In 1982 and 1984, deterministic calculations, designated collectively herein as PA–EA [18–20], were conducted for the draft and final Environmental Assessments (EA) required by NWPA [3]. PA–EA provides the initial marker for the paper. The first stochastic PA, conducted in 1991 (PA-91) [21], 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 [22, Fig. 1-1; 23]. The Congressionally requested viability assessment (PA–VA), completed in 1998, serves as the fifth marker [24]. The conclusion of site characterization culminated with an analysis in late 2000 for the site recommendation PA–SR and serves as the sixth marker [25]. PA–LA, which forms the basis of the SAR/LA, serves as the final marker.

2. Characterization of geologic barrier

After the United State's commitment to geologic disposal in 1980, the formal steps of selecting a site as outlined in NWPA were

followed (e.g., identify potentially acceptable sites, hold public hearings on issues to address in EA, nominate site, submit site characterization plan to NRC, etc.) [5, Table 2]. However, the examination of the YM disposal system progressed through study phases that are similar to the four phases that occurred at the Waste Isolation Pilot Plant (WIPP) for transuranic waste in southern New Mexico (Table 1): (1) the site identification analysis of PA–EA, which was based on borehole stratigraphy augmented with non-intrusive characterization data; (2) the feasibility analysis of PA-91, PA-93, and PA-95, which used mostly characterization data from the surface through well tests; (3) the suitability analysis of PA–VA and PA–SR, which added preliminary in-situ underground characterization data to study coupled processes; and (4) the compliance analysis of PA–LA, based on site characterization conclusions.

Some of the first characterization was done to better understand the potential igneous hazard during the site identification phase in 1979 [6]. Shortly thereafter, site characterization from the surface for the feasibility analysis was conducted to evaluate an important geologic feature, fractures in the tuff, and water migration through this feature. In-situ site characterization for the suitability analysis examined all types of water movement more thoroughly: (1) water infiltration, (2) water percolation above and below the repository in the unsaturated zone (UZ), (3) water movement near disposal drifts when heated by the waste, (4) water seeping into the disposal drifts, and (5) flow within the saturated zone (SZ) to the accessible

Table 1
Study phases at Yucca Mountain Project (YMP) and Waste Isolation Pilot Plant (WIPP).

Study phase	Disposal system	System studies and other activities
0. Commitment to mined, geologic disposal	YMP	ERDA, precursor to DOE, recommends geologic disposal (1976) Interagency Review Group recommends geologic disposal (1979) DOE generic EIS selects mined, geologic disposal (1980) NWPA (1984; 1987) [1,3]
	WIPP[a]	NAS recommends exploring disposal in salt (1957) [194] NAS concludes bedded salt satisfactory host media (1970)
1. Site identification analysis based on regional geologic characterization via literature search and analogous data	YMP	Literature search starts after President Ford request (1976) USGS suggests NTS (1976) [50, p. 4] UE-25a#1 drilled at NTS to confirm thick tuff (1978) Repository moved to UZ (1982) PA–EA: 1982 volcanism dose [18] 1984 groundwater releases [19] NWPA EA (1986) [195] NWPA SCP (1988) [65]
	WIPP	Literature search by Oak Ridge National Lab & USGS (1972–1973) AEC-6 & AEC-8 drilled in Delaware Basin (1974) ERDA-6 (1975) & ERDA-9 (1976) drilled at WIPP site Site characterization plans (SCP) (1975–1976)
2. Feasibility analysis demonstrating calculation procedures, and importance of system components based on rough measures of performance using surface exploration, waste process knowledge, and general laboratory experiments	YMP	G, H, WT, UZ series boreholes drilled (1981–1984) Heater tests in G-tunnel at NTS (1980–1989) [48] Bomb pulse ^{36}Cl measured in boreholes (1990) [87] PACE-90 [196] PA-91 [21], PA-PNNL-91 [197] ESSE (1992)[80] PA-93 [22], PA–M&O-93 [198] PA-95 [23], PA-96 [199], PA-97 [200], PA–SNL-95, PA–SNL-97 (for DSNF) [201,202]
	WIPP	Laboratory tests on transuranic (TRU) wastes (1976) Geologic characterization report (1978) EIS for site selection (1980) SAR for construction (1980) 1989 WIPP PA (extensive in-situ data available but modeling immature)
3. Suitability analysis demonstrating viability of disposal system based on environment-specific laboratory experiments and underground disposal system characterization, in-situ experiments after state permits issued, QA program completed, and reevaluation of SCP tests	YMP	SD series boreholes (1994–1998) Excavation of ESF and ECRB and fracture mapping (1994–1998) Infiltration monitoring (1984–1996) Seepage tests at niches (1997–1999) SHT in Alcove 5 (1996–1997) [25] DST in Alcove 5 (1997–2002) [25] Large-Block heater Test at Fran Ridge (1996–1997) [25] Migration tests at Busted Butte (1998–2003) [25] PA–VA (1998) [24], LADS (1999) [203] PA–SR (2000) [25], SSPA (2001) [204] EIS for SR (2002) (modeling and data progressively improved) [205]
	WIPP	1st (1981), 2nd (1982), 3rd (1985), and 4th (1988) shafts drilled Excavation of experimental rooms (1983–1984) Supplemental siting EIS (1990) 1990, 1991, 1992 WIPP PAs (modeling progressively improved)
4. Compliance analysis based on completed site-specific characterization	YMP	EIS for construction authorization LA (2008) [206] 2004 and 2005 drafts of PA–LA for internal review PA–LA/SAR—safety assessment for construction (2008) [4]
	WIPP	Draft Compliance Certification Application (1994) (1996) Compliance Certification Application EIS for operation (1997)

[a] For most WIPP activities and studies, refer to [207].

environment. Site characterization continued up to the start of the final compliance analysis in 2005.

Because of the sometimes tight interplay of site characterization for (1) general understanding, and (2) identification of important features, events, and processes important to future behavior, the separation of the site characterization and hazard identification is somewhat arbitrary. For the purposes of this paper, site characterization includes discussion of features and processes of the undisturbed evolution of the repository environment, such as infiltration and percolation through fractures. Also discussed is climatic change because of its close relationship to infiltration and its inclusion as part of the normal evolution of the disposal system in YM PAs (rather than as a separate disruptive event). Disruptive events and the corresponding scenario classes analyzed in past PAs such as igneous, seismic, and human intrusion events are discussed with hazard identification [6]. Geochemical tests are briefly discussed with the evolution of the package design [7], and the use of the geochemical results are discussed along with companion papers on the waste package (WP) [10] and waste form degradation [11].

2.1. Geologic barrier characteristics in 1984 PA–EA

2.1.1. Stratigraphy in 1984 PA–EA

The tuff layers of Yucca Mountain of most interest were formed as hot erupted ash and fragments from a caldera complex 25 km to the north were deposited and quickly welded together (i.e., pyroclastic flow) between 14 and 12.5×10^6 years ago (i.e., 12.5 mega-annum or 12.5 Ma) in the Tertiary Period [22, Table 2-1]. The major welded tuffs units were from several eruptions of $\sim$1000 km^3 each and resulted in layers typically 100–300 m thick (Fig. 2) [4, vol. 1 Section 3.2]. In all, $\sim$2000 m of volcanic ash and reworked volcanic material were deposited [12, Figs. 4 and 8] Yucca Mountain uplifted about 7 Ma [25] as a normal fault block. The layers currently dip between 5° and 10° mostly to the east.

After the first borehole at Yucca Mountain was drilled in April 1978 (UE25a-1) [28], a concerted effort to gather information on the geologic barrier characteristics of Yucca Mountain started from the surface in 1980 with the drilling of stratigraphic borehole G-1 [29] and hydrologic borehole H-1 (Fig. 1) [30,31]. With the completion of six major geologic and hydrologic boreholes around the perimeter of the potential repository (G-2, G-3, GU-3 [32], H-3 [33], H-4, and H-5 [34]) and mapping of faults and fractures, USGS was able to develop a preliminary three-dimensional stratigraphic map of the Yucca Mountain area in 1982 [35]. By 1984, G-4 (at the proposed shaft location for the Exploratory Studies Facility[3]) [38], H-6 [39], and several water table and UZ series wells were completed such that a more complete stratigraphic map could be developed [40, p. 9].

From this early information, a reference stratigraphy for thermal–mechanical modeling was published in 1985 [27]. The stratigraphy was used for PA–EA and PA-91 hydrologic modeling (Fig. 2) [4, GI Fig. 5-30 and Table 5-30 and Chapter 2 Table 2.3.2-2; 26, Table 1; 27, Table 1; 41, Fig. 6-7]. Four main strata were encountered in the UZ. Starting with the surface unit, the *T*iva *C*anyon *w*elded tuff caprock on Yucca Mountain was designated as TCw in the PA–EA and PA-91 hydrologic model and consisted of $\sim$135-m thick welded *T*ertiary, *P*aintbrush Group, *c*rystalline *r*ich (i.e., high grain density) and *c*rystalline *p*oor (i.e., low grain density) tuff, designated formally as Tpcr and Tpcp, respectively, in the later 1996 geologic map [42].[4] The second, underlying layer was the 30–60 m thick bedded and nonwelded tuffs of the Yucca Mountain Formation and Pah Canyon Formation of the *P*aintbrush Group (PTn unit in early hydrologic models). The third layer is the 280–350 m thick *T*ertiary, *P*aintbrush Group, welded *T*opopah Spring crystalline rich (Tptr) and crystalline poor (Tptp) tuff (designated TSw2 in early hydrologic models). The third layer has alternating *u*pper, *m*iddle, and *l*ower layers containing *l*ithophysae and *n*on-lithophysae formed from trapped gases during cooling (designated Tptpul, Tptpmn, Tptpll, Tptpln in the later 1996 geologic map). The fourth major layer from the surface is the nonwelded, crystalline poor Calico Hills hydrologic unit with both vitric and zeolitic portions (CHn1, CHn2, and CHn3 in early hydrologic models or Tac in later geologic maps). The vitric portion of the Calico Hills unit is $\sim$290 m thick north of the repository area and thins to $\sim$40 m south of the repository.

To the south and east of the repository, the CHn forms a confining unit that separates an upper tuff aquifer, located in the TSw strata, from a lower tuff aquifer [12, Fig. 4]. The lower tuff aquifer, the primary aquifer of interest in the area, resides in the welded Prow Pass (PPw), welded Bullfrog (BFw), and welded Tram Tuffs (TRw), which are all units of the Crater Flat Group (Fig. 2). US Geological Survey (USGS) models and later PAs combined the units with the nonwelded units into the lower aquifer (and designated as nonwelded Crater Flat unit, CFn). An aquifer in carbonates of Cambrian to Devonian age lies much deeper below the Tertiary tuffs.

2.1.2. Precipitation, infiltration, and percolation in 1984 PA–EA

In 1982, USGS estimated percolation at 8 mm/yr based on the thermal gradient measured at Drill Hole Wash near Yucca Mountain [19,20,43,44]. By 1983, USGS had proposed, based on field observations of outcrops and rapid leakage of well fluids into the tuff in the UZ, that sufficient fracturing existed in the tuffs above the repository such that percolation would be primarily vertical and through fractures down to the repository horizon (except for matrix flow in PTn) and thus equal to infiltration [43,45]. For PA–EA, one estimate of net infiltration was $\sim$3% of precipitation (or between 4.5 and 6.0 mm/yr, based on an estimated precipitation of between 150 and 200 mm/yr) [43,46]. Below the repository, the 1983 conceptual model assumed vertical fracture flow except in the lower vitric nonwelded tuff with substantial lateral flow at the interface of the vitric portion with the zeolitic portions of Calico Hills unit (i.e., CHnv/CHnz) and then vertical percolation through the CHnz.

In 1984, USGS postulated that low fracture frequency and high porosity of the PTn would attenuate infiltration pulses and result in approximately steady state flow below the unit [26, p. 45-7]. Furthermore, USGS proposed a conceptual model where the transition from a high to low porosity at the interface between the PTn and TSw strata would cause percolation to be diverted laterally down slope to the faults and away from the repository. Hence, for PA–EA, another estimation of percolation below the interface was 0.5 mm/yr percolation (i.e., 89% reduction from 4.5 mm/yr percolation above the PTn [26; 43, p.26]. This later hypothesis, which was emphasized by the YMP through PA-95, represented an attempt to reconcile the observed fracturing in outcrops, the estimated net infiltration, and the $\sim$65% saturation in the TSw with the equivalent continuum modeling (ECM) or composite-porosity model formulation [9], which did not allow

[3] The experimental area was originally called the exploratory shaft facility (e.g., [36]) but the name was changed in March 1991 to exploratory studies facility to reflect its larger size and purpose [37, p. 1-1].

[4] The 1985 designations selected for the stratigraphic units have been used by the project up through PA–LA and will frequently be used herein since they generally correspond to major hydrologic modeling units. However, the formal stratigraphy and informal extensions developed by USGS in 1984 and revised in 1996 are frequently necessary when discussing units of the repository horizon.

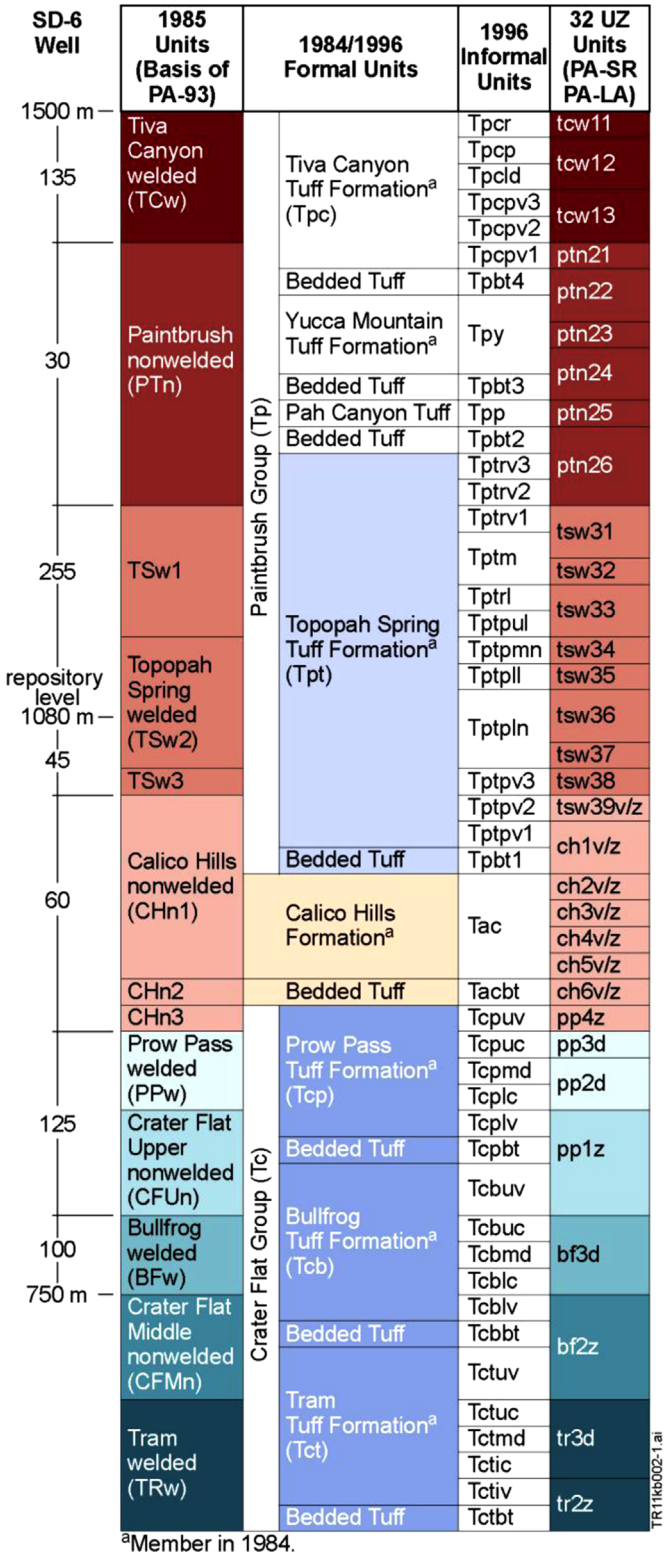


Fig. 2. Formal/informal stratigraphy and modeling layers of Yucca Mountain [4, vol. GI Fig. 5-30 and Table 5-30 and Chapter 2; Table 2.3.2-2; 26, Table 1; 27, Table 1; 41, Fig 6-7].

>1 mm/yr percolation through the TSw without fully saturating the tuff matrix.

Also during this period, USGS proposed that observed seepage in several fractures in G-tunnel (under Rainer Mesa to the north of Yucca Mountain) might be an analog for Yucca Mountain during a glacial period [26, p. 36-49]. Later, concerns were raised about the extensive disruptive testing in G-tunnel and so the idea was abandoned; however, because of the significant elevation difference, the measured precipitation at the surface above G-tunnel was later used for PA–VA, PA–SR, and PA–LA as an analog for precipitation during a glacial period. But in general, substantial increase in precipitation, infiltration, and ultimately percolation through the repository in the first 10^4 years was not anticipated during a climate change because Yucca Mountain was in the rain shadow created by the Sierra Nevada and Transverse Ranges.

2.1.3. Thermal-hydrology in PA–EA

As a type of underground research lab (URL), SNL began small diameter heater/water-migration experiments in welded tuff in G-tunnel in 1980 and reported some results by 1983 (Appendix A) [47,48]. SNL also completed a larger heated block experiment in G-tunnel in 1985 [25, p. 4–106; 49].

2.1.4. Regional and local SZ flow in PA–EA

USGS developed a conceptual model of regional groundwater flow around Yucca Mountain as early as 1975 as part of extensive characterization of NTS [46]. In fact, one reason USGS recommended NTS in 1978 was because of the general characterization that had already occurred [50]. This initial USGS conceptual model continued to influence computational models through the PA–LA [51, Section 6.7.7.3]. By 1981, USGS had drilled the first 11 of 16 shallow (<340-m deep) boreholes to the water table (the WT series wells in Fig. 1) to supplement the potentiometric data from the deep geologic and hydrologic wells and begun regularly scheduled, potentiometric measurements by 1983 (eventually, 33 wells were monitored at 41 intervals). In 1982, along with the definition of geologic strata mentioned above [35], USGS developed a regional groundwater flow model over a 175-km^2 area in the vicinity of Yucca Mountain [52]. The lack of changes in regional flow patterns around Yucca Mountain suggested percolation flux through Yucca Mountain did not contribute to the regional flow [19,52]. For the 1984 PA–EA, water table elevations indicated a general gradient of 3.4×10^{-4} but suggested some geologic feature, such as the Solitario Canyon fault to the west and other faults to the north of Yucca Mountain, were impeding eastward movement of groundwater [19, Fig. 6].

At the end of 1983 and through 1984, three boreholes, UE25c#1, #2, and #3 (collectively called C-well complex), were drilled $\sim$3 km east of the repository and pumping/injection tests conducted to estimate permeability and evaluate water flow down-gradient of Yucca Mountain (Fig. 1) [53]. Each well was drilled 914 m deep, with the water table at $\sim$400 m below surface and, together, formed a right angle spaced 30 and 77 m apart at the land surface. The wells penetrated the Calico Hills (CHn or Tac), and Prow Pass (PPw or Tcp), Bullfrog (BFw or Tcb), and Tram Tuff (TRw or Tct) Formations [54, Fig. A6-2] (Fig. 2).

Although the C-well complex would be used for tracer tests for later PAs, at the time of PA–EA, Los Alamos National Laboratory (LANL) estimated groundwater chemistry and retardation behavior in the UZ and SZ zones from laboratory experiments based on chemical conditions found in J-13 (Fig. 1), a nearby well producing from TSw units to supply water to NTS [55,56]. Also, the formation of Pu colloids was under study at this early stage of the project. [57,58]. However, by 1989 laboratory experiments with columns suggested that colloid-facilitated transport of radionuclides would not contribute significantly to releases [59]. This conclusion was eventually confirmed by PA–LA but the discovery in 1997 of Pu attached to colloids far from a bomb test at NTS would necessitate much more evaluation (Appendix A) [60].

2.2. Geologic barrier characteristics in PA-91

2.2.1. Characterization priorities

When NWPA was passed in 1982, NRC estimated that \$25–\$30 $\times 10^6$ would be sufficient to characterize 300 m of underground drift in sedimentary rock and \$40 $\times 10^6$ for crystalline rock (i.e., 30% increase) [61, preamble; 62, p. 142]. Also, in the House report that accompanied NWPA [63, Part I, p. 52], Congress emphasized "Site characterization activities are intended to be kept to the reasonable minimum expense and impact and are intended not to be so extensive as to result, through physical impact or through economic commitment, in the prejudicing of decisions regarding further development of the site". Yet, in 1986 Senate hearings, DOE estimated that site characterization would cost ~\$1 $\times 10^9$ [64]. The Site Characterization Plan (SCP), completed in 1988 to meet NRC requirements in 10 CFR 60, did indeed propose a vast array of experiments [65]. The high cost of characterizing a potential site was one reason Congress decided to choose a site to characterize first in the *Nuclear Waste Policy Amendments Act of 1987* (NWPAA) to help reduce the deficit in the *Budget Reconciliation Act of 1987* [1,5].

In response to the NRC critique of the SCP, DOE conducted a Calico Hills Risk/Benefit Analysis (CHRBA) in 1989 to study the usefulness of excavating the Calico Hills (CHn) when constructing the Exploratory Studies Facility (ESF). Two CHRBA studies concluded excavation of the CHn was not necessary, but it might reduce program risks and increase scientific confidence. Also in response to comments (e.g., [66]), DOE conducted a Test Prioritization Task (TPT), a simple study to rank the importance of site characterization experiments, in October 1991. In the TPT study, about 100 potentially adverse conditions from DOE siting guidelines 10 CFR 960 and NRC 10 CFR 60 were screened and consolidated into 32 concerns and then ranked based on management judgment and some technical assessments (i.e., the ranking was not based on a PA). Two major concerns were complex geology for groundwater flow, and complex geology for ^{14}C gas flow (where the later was important for the releases to the surface above the repository in the generic 40 CFR 191 radiation protection standard promulgated by the US Environmental Protection Agency (EPA) in 1985 [5,67]). Most other concerns and their corresponding tests were of little consequence to the issue of site feasibility and viability [68].

PA-91, the first stochastic PA, was completed that December and documented by July with recommendations as to modeling and parameter needs. However, PA-91 did not mention specific experimental needs nor rank the importance of the numerous experiments proposed in the SCP [21, Section 11].

2.2.2. Percolation at repository horizon in PA-91

In PA-91, the mean percolation flux 10 m above the repository was set at 1 mm/yr with a range up to 39 mm/yr. When percolation was below 1 mm/yr, percolation occurred mostly in the matrix flow in the prevailing conceptual model, ECM [9]. Yet by PA-91, enough circumstantial evidence had accumulated to suggest that the water could flow down fractures for long distances before the water (a) was carried away in air moving through the mountain, (b) was absorbed into the matrix pores, or (c) reached the deep aquifer. Deep fracture flow was consistent with the 1983 USGS conceptual model of UZ flow (Section 2.1.3). Hence, an alternative conceptual model of flow solely in the fractures was developed and evaluated [9]. The circumstantial evidence consisted of (1) USGS observation of continuous seepage from several fractures in G-tunnel in 1984 [26, p. 36–49], (2) LANL observation of calcite and opal on the walls of fractures and vugs in G-4 well core in 1985 [69]; (3) USGS discovery of drilling fluids in dry-drilled UZ-1, presumably from well G-1 300 m away in 1990 [70]; and (4) LANL discovery of elevated ^{36}Cl concentration in well UZ-6 in 1990 from atmospheric testing of nuclear weapons prior to July 1962 (i.e., bomb-pulse ^{36}Cl) [71] (Fig. 1).[5]

2.2.3. Regional and local SZ flow in PA-91

At the time of PA–EA, USGS was developing a 2-D, finite-element, steady-state, regional model of SZ flow. The composite properties of the 1000-m thick stratigraphic layers, including the upper unconfined volcanic aquifer in Topopah Spring Tuff (Tpt) and the lower confined volcanic aquifer in the Prow Pass Tuff (Tcp) Bullfrog Tuff (Tcb) and Tram Tuff (Tct) (Fig. 2), were calibrated by hand to match hydraulic heads in 26 wells around Yucca Mountain and 64 wells near Death Valley [73, Fig. 3]. This 1984 USGS model was one-third the size of the 1982 USGS model but extended 70 km to the southwest to Death Valley to include potential discharge areas at Franklin Lake playa and Furnace Creek [21, Fig. 4-26]. Similar to the 1982 USGS model, flow patterns in the 1984 USGS model provided no indication of percolation influx to the groundwater system from Yucca Mountain. In 1990,[6] USGS used the model to examine the geohydrology and evapotranspiration at the Franklin Lake playa [75]. The 1984 USGS model was the basis of the SZ site-scale flow model of PA-91 [21, Section 4].

2.3. Geologic barrier characteristics in PA-93

Since publishing the SCP in 1988 [65], DOE had sought permits from the State of Nevada for surface exploration but the state would not cooperate. Then in September 1990, the Court of Appeals for Ninth Circuit ruled Nevada's "effective notice of disapproval" was premature and could not compel DOE to cease investigations. By June 1991, the State issued an air quality permit for site investigations and by July the State issued an underground injection control permit [68]. The State Engineer granted a temporary groundwater permit for site characterization in August 1992 [76]. Therefore, some new data became available for PA-93. However, because of the delay and high cost, DOE decided in 1993 to reduce surface-based characterization through wells and move to underground studies once the ESF was completed [77].

A preliminary evaluation of Yucca Mountain against the DOE 10 CFR 960 guidelines, the Early Site Suitability Evaluation (ESSE), was published in January 1992. As in the 1986 EA, DOE found no disqualifying conditions, but the report suggested acquiring information in four areas: climate change, effects of earthquakes, source term for gaseous releases, and evaluation of fast percolation paths. The later area was related to the 10^3-yr travel time subsystem performance objective in NRC's 10 CFR 60 [5,78] and was a disqualifying condition in DOE's 10 CFR 960 [79]. An external review panel of the ESSE suggested three topics to study: potential for fast paths, the high water table to the northwest of the site, and the effects of thermal loading [80]. Several of these issues were already under study and evaluated in PA-93.

2.3.1. Climate change for PA-93

Based on the preliminary discussions of the National Academy of Sciences (NAS) on a site-specific regulation for Yucca Mountain (as mandated by Congress [5,81,82]) PA-93 switched to a simulation over 10^6 years. Hence, climate fluctuations became important. In 1993, USGS reported on U-isotopic dating of ancient spring deposits 18 km to the southwest of Yucca Mountain at the southern end of

[5] LANL had proposed and started using ^{36}Cl to evaluate infiltration and percolation at Yucca Mountain 3 years earlier in 1987 [72].

[6] USGS field characterization of infiltration and regional SZ flow was stopped between 1986 and 1991 by DOE to improve the quality assurance (QA) program. Also in 1988, NRC advised DOE that the fledgling QA program was inadequate [74].

Crater Flat and Sr-isotopic dating of calcites deposits in wellbores around Yucca Mountain [22, Section 8.8]. The U-isotopic dating suggested that the water table in the region had been between 80 and 115 m higher ~18 ka. Sr-isotopic dating found calcite deposits ~85 m above the current water table in core from G-2 [83]. Based on these USGS water table estimates, lake level estimates in 1990 [84], lacustrine deposits [85], and a USGS study of packrat middens from 1980 [86], PA-93 resolved the climate into two alternating periods: a dry interglacial period and a wet glacial period. PA-93 made the simple assumption of equal durations and cycle period of 10^5 years. However, at the time oxygen-isotope evidence from the ocean floor suggested short dry periods of 10,000–20,000, years followed by the remaining 80,000–90,000 years as wet [22, Section 8.4], and PA–VA would make use of the later cycles.

2.3.2. Percolation in PA-93

By PA-93, numerous core measurements of matrix porosity, matrix bulk density, matrix saturated hydraulic conductivity, and matrix water retention parameters were available to determine parameter values for modeling percolation flux below the repository. Also fracture properties from G-1, GU-3/G-3, G-4, and UE25a#1 were available [22, Section 7]. In 1993, LANL again reported on the discovery of elevated ^{36}Cl concentration in boreholes within the repository area (e.g., UZ-6) [87].

2.3.3. Regional and local SZ flow in PA-93

With the Congressional requirement to examine the use of dose as the measure of compliance [5,81], the amount of dilution and dispersion afforded by the natural barrier (in addition to the dilution provided at the withdrawal point) became important. To evaluate the limited dilution in an arid environment and limited dispersion in fractured flow present at Yucca Mountain, in turn, reinforced existing plans for more extensive characterization of the UZ (i.e., SD boreholes) and SZ (e.g., boreholes from the Nye County Early Warning Drilling Program, NC-EWDP, near US Highway 95 south of Yucca Mountain).

PA-93 improved the underlying process model of the SZ to model dilution. Two alternative conceptual models of flow in the SZ were investigated in order to explain the 300 m change in water table elevation 3 km north and west of the repository: One conceptual model allowed water to drain vertically out of the upper SZ aquifer north of the repository. The other conceptual model only allowed water to leave and enter the SZ domain laterally, but required the Solitario Canyon Fault and the Drill Hole Wash Fault to have a permeability 2 orders of magnitude lower than nearby hydrologic units to divert water around Yucca Mountain. Low permeability features to the north and west of Yucca Mountain would also be used in later process models of the SZ. The 2 models were calibrated to 26 well head measurements in the area (G-2, G-3, H-1, H-3, H-4, H-5, H-6, UE25b#1, UE25c#2, UE25c#3, UE25p#1, J-13, and 14 water table wells). Boundary conditions for the model were based on 3 of the 26 well head measurements on the domain boundary and the general heads calculated in the 1982 USGS regional flow model used for PA–EA [73,88].

2.4. Geologic barrier characteristics in PA-95

Although the geologic barrier characterization continued between PA-93 and PA-95, new information was not directly used in PA-95 except for preliminary infiltration data [89]. Rather PA-95 used much of the data from PA-93.

2.4.1. Infiltration in PA-95

In 1994, USGS reported very low infiltration in preliminary moisture observations in 99 shallow neutron boreholes. Some of the boreholes were drilled between 1984 and 1986 and the rest completed between 1991 and 1993. The estimated percolation (or net infiltration) below the evapotranspiration zone was 0.02 mm/yr over Tiva Canyon outcrops and 1.2 mm/yr along the crest of Yucca Mountain. These two estimates were used to define two infiltration cases in PA-95 [23; 89, p. 7-6]. Additional observations and analysis, however, changed the estimates dramatically for PA–VA [9, Fig. 5].

2.5. Geologic barrier characteristics in PA–VA

The 1988 SCP had anticipated the need to re-evaluate the usefulness of the SCP tests prior to determining the suitability of Yucca Mountain [65, p. 8.1-11]:

> …it is expected that some of the conceptual models for the site will be modified as result of the site characterization, and that the strategies may need to change. Accordingly, analysis of the results of the testing will be conducted as the testing proceeds to determine if the investigation set forth in the SCP needs to be completed or if the testing strategies need to be modified.

However, rather than specify a PA as means to evaluate the necessity of tests, a nebulous concept of "performance allocation" had been specified in the SCP that was proving difficult to implement by SNL. Hence, many of the tests outlined in the SCP were slated to be completed prior to determining the suitability of Yucca Mountain. Yet by 1993, it was clear that annual appropriations would not support all these tests sufficiently to complete them in a reasonable amount of time. Instead, DOE developed a new approach that distinguished between tests required to evaluate site suitability, tests required to support licensing and repository design, and tests required to confirm the safety of the repository before closure [90]. This distinction permitted phasing the tests and produced an experimental program more in line with anticipated funding. Furthermore, during 1994, DOE developed a proposed site suitability evaluation procedure, based on the existing 10 CFR 960 siting guidelines, through public and stakeholder participation at numerous public meetings, briefings, workshops, and responses provided to DOE through the *Federal Register Notices of Inquiry* [91].

Congress funded the new approach in 1995 appropriation with $\$0.51 \times 10^9$, a substantial increase over the previous year. However, Congress cut the 1996 appropriation to $\$0.32 \times 10^9$ compared to $\$0.63 \times 10^9$ requested. Instead a year later in 1997, Congress asked for a less expensive approach that focused on a VA to provide a less elaborate suitability evaluation [92]. The VA was to include (1) a PA; (2) a description of studies needed; (3) a preliminary design of repository and waste package, (4) costs to complete LA; and (5) costs to construct, operate, and close the repository. A year later in December 1998, YMP completed the five requests. YMP estimated the cost to complete the LA at $\sim\$1.1 \times 10^9$, above the $\$5.9 \times 10^9$ (1998 constant dollars) already spent [24, Overview p. 3]. A further reassessment of tests led DOE to conclude that some of the tests included in the SCP were no longer necessary. Much of the site characterization measurements and the calibration steps used in PA–VA were reported in a 1999 special issue of the *Journal of Contaminant Hydrology* (e.g., [93]).

2.5.1. Stratigraphy in PA–VA

A formal stratigraphy was published in 1996 [42,94], in which USGS upgraded member units defined in 1984 [40, p. 9] to formations, and more finely divided the geologic stratigraphy of

Paintbrush Group [42] (Fig. 2). USGS had developed a geologic framework model (GFM 2.0), which included dipping faults and additional rocks units for the UZ flow models in PA–VA. Along with redefining the formal stratigraphy, USGS in 1998 updated the geologic bedrock map originally created in 1994 and included fractures mapped in the ESF. The geologic map would be used to update infiltration studies in PA–SR [95,96; 97, Section 6.3.2].

2.5.2. Infiltration in PA–VA

For the 10^6-yr regulatory period [82], PA–VA added a third future precipitation climate event (Fig. 3) [19; 24, p. 3–14; 25, Table 4-11; 98, Fig. 7.1.1.3-1]: hence, the climates for PA–VA were (1) a current (arid) climate, (2) a long-term average (LTA) climate, and (3) a short-term super pluvial (SP) climate (new) that occurred about every 250,000 years [9, Fig. 5]. In support of this conceptualization, USGS completed two major deliverables: moisture measurements in 99 shallow neutron boreholes in 1995 [99] and an infiltration model, INFIL v1.0 in 1996, which used a few of the moisture measurements for calibration [9; 100; 101, Section 2.4.2.2]. As input to INFIL, the synthetic average daily precipitation over a 100-yr period for the arid climate state was stochastically developed from the 36-yr record at weather station AJA 15 km east of the repository [101, Section 2.4.2.3]. The synthetic, 100-yr average for the arid climate was 150 mm/yr ($\overline{q}^{\text{precip}}_{arid}$) (Fig. 3).

PA–VA assumed the duration of the LTA climate was between 80,000 and 100,000 years since a reevaluation of paleohydrologic evidence (available since PA-93) showed wetter, glacial climates to have dominated over the last million years. Also by 1996, recent weather conditions and some models of anthropogenic climate change had suggested more continuous El Niño conditions that corresponded to higher precipitation around Yucca Mountain (e.g., 70% more precipitation at Amargosa Valley) [101, Section 2.4.1.1]. The daily precipitation for the LTA climate, corresponding to an average of pluvial and glacial conditions, was developed from records from nearby Rainier Mesa above G-tunnel (~2 times current precipitation). The synthetic 100-yr average was 289 mm/yr ($\overline{q}^{\text{precip}}_{LTA}$). For the SP climate (~3 times current precipitation), the synthetic daily precipitation was developed from records at South Lake, CA and had a 100-yr average of 427 mm/yr ($\overline{q}^{\text{precip}}_{SP}$) [102].

For PA–VA, YMP formed five expert elicitation panels to examine (1) UZ flow (UZEE), (2) flow and transport in SZ (SZEE), (3) engineered barrier system (EBS) near-field/altered-zone coupled effects (EBSEE), (4) waste package degradation (WPDEE), and (5) waste form degradation (WFEE). Unlike two previously formed panels for (1) volcanic hazard, and (2) seismic hazard [6], these panels dealt with the immediate needs of PA–VA to aggregate disparate data available in the literature prior to completion of project experiments [103]. The UZEE panel consisted of 7 experts (4 from outside DOE complex and USGS) to provide guidance on the conceptual model and uncertainties in (a) parameters underlying infiltration, (b) the 3-D mountain-scale model (UZ-97 noted below), and (c) seepage [103,104]. The UZEE panel was completed in May 1997. The UZEE panel estimate for infiltration was similar to the INFIL calculation. The expert's combined estimated percolation flux at the repository horizon, as discussed below, had a mean of 10.3 mm/yr and median of 7.2 mm/yr [4, p. 2.3.2–74].

2.5.3. UZ flow in PA–VA

For PA–VA, a 3-D mountain-scale model (UZ-97), which covered ~43 km^2, was developed to evaluate percolation flow fields. Based on GFM v2.0, the ESF drift, tilt of faults, and 24 homogenous layers were modeled down to the water table [24, vol. 3 Section 3; 105, Table 1; [106]]. Although contrasts in hydrologic properties between units could cause lateral flow, particularly at TCw/PTn

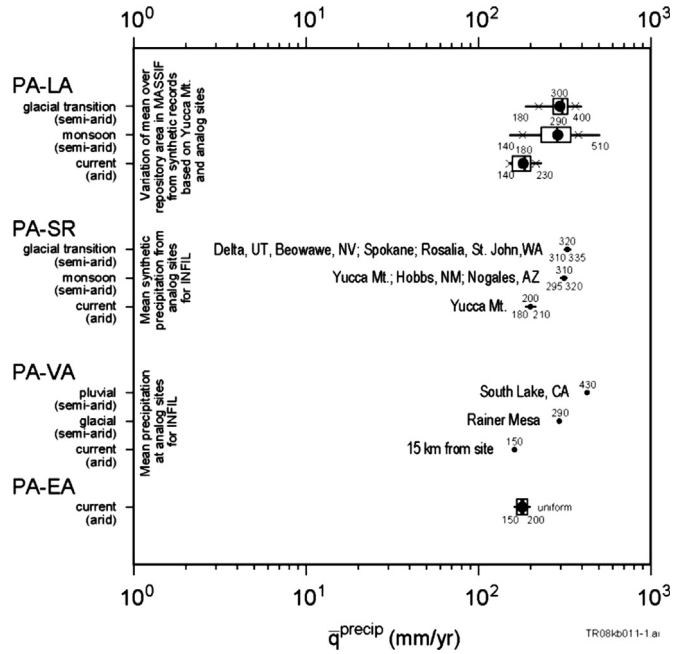


Fig. 3. Comparison of precipitation as function of climate states in PAs for Yucca Mountain [19; 24, p. 3–14; 25, Table 4-11; 98, Fig. 7.1.1.3-1]. For estimates of percolation at the repository horizon refer to [9, Fig. 5].

contact (Fig. 2), the UZEE panel agreed with the recent YMP conclusion that the diversion would be less than tens of meters; thus, percolation at the repository would be approximately equal to net infiltration. The UZEE panel also surmised from the LANL claim of finding bomb-pulse (< 50 years old) ^{36}Cl that flow in the tuff was predominantly in fractures [103,104,107]. This conclusion supported the use of a dual-permeability model (DKM) formulation for the UZ-97 process model that represented fractures (high permeability, low porosity) and matrix (low permeability, high porosity) as distinct continua that could interact through mass transfer terms at every point within the model domain [9, Eqs. (24)–(27)].

Usually 15 hydrologic properties had to be assigned for each of the 24 homogenous layers of the model.[7] The 5 matrix properties were van Genuchten air-entry parameter (α_m), van Genuchten pore-size-distribution parameter (m_m), residual liquid saturation (s_m^{res}), porosity (ϕ_m), and permeability (k_m). The 10 fracture properties were the same as the first four matrix property parameters (α_f, m_f, s_f^{res}, ϕ_f) plus the horizontal and vertical fracture permeability ($k_{f,xy}$, $k_{f,z}$), fracture spacing (b_f), fracture-matrix coupling parameter (γ_{fm}), fracture shape factor a_f^{shape}, and fracture-matrix surface area (A^{fm}).

USGS laboratory measurements on well core were used to set the 5 initial matrix properties [109]. For example, (a) the matrix porosity of 0.089 was the mean of all borehole measurements for the repository middle Topopah Spring tuff unit (Tptpmn) [109, p. 44]; (b) the initial matrix saturation was 0.92 based on SD-9 [109, p. 50]; (c) the matrix van Genuchten parameters was based on three samples from UZ-16 [109, pp. 19–54]; and (d) the matrix permeability for the repository Tptpmn was set at 4.0×10^{-18} m^2 [109, p. 44].

[7] As a comparison, four years earlier in 1996, two phase flow modeling of the host salt at WIPP (two equations at each grid block) also required at least 15 parameters for each of 30 regions (and sometimes many more because parameters would change in four or five time periods) [108, Table 6].

The Detailed Line Survey (DLS), performed by the USGS/Bureau of Reclamation, provided a set of fracture density measurements in the ESF [110]. Fracture density measurements from core samples were used for layers for which ESF data did not exist [106, Section 7]. Initial mean fracture permeability was calculated from individual air-injection tests in SD-12, UZ-16, NRG-6, and NRG-7a boreholes [111, p. 4–32]. These fracture density measurements and air-injection experiments were used to set the 10 fracture properties for the model layers [101, p. 2–36].

The PA–VA calibration consisted of three steps, which were also used in later PAs [101, Section 2.4.3.1.3]. The initial calibration of 1-D column, single-phase (liquid) DKM models located at wells, used adjusted matrix properties (such as k_m) on the scale of a drift using matrix saturation from well core measurements and matrix water potential from in-situ well measurements [93; 109, p. 40–3, 48–53]. The initial calibration of matrix properties was followed by the use of pneumatic in-situ data available (from SD-7 and SD-12 for PA–VA) to calibrate fracture permeability (k_f) in 1-D models with two phases (gas and liquid) (which doubles the number of equations for a total of 4 equations for a DKM model at a grid block) [112]. The third step was manual calibration of a 3-D, single phase, DKM model to adjust properties to form perched water below the repository at the known well locations (G-2, UZ-14, SD-7, SD-9, SD-12, and NRG-7a for PA–VA) [101, Section 2.4.3.4; 105; 113,114]. Finally, geochemistry data on chloride and strontium [114], ^{36}Cl [107], and in-situ temperature measurements [105] were used to qualitatively check the sensibility of the calibrated parameter set.

2.5.4. Thermal-hydrology in PA–VA

In May 1996, YMP began a year-long Single Heater Test (SHT). A 5-m long heater with 3.86 kW output was placed in the ESF in the Tptpmn unit [25, p. 4–113; 115, Chapter 10; 116]. The observations showed that conduction (rather than convection) was the dominant heat transfer mechanism [117]. The observations also showed that the ECM formulation under-predicted temperatures because ECM produced artificial thermally driven water movement (refluxing). The DKM conceptualization matched experiment temperatures better than ECM [103; 116, Section 3.4.5]. The calibrated hydrologic properties (as described above) were adjusted to improve the match with the SHT experimental results before they were used in PA–VA [117].

In 1997, Lawrence Livermore National Laboratore (LLNL) started a Large-Block Test (LBT) in Tptpmn tuff, located at Fran Ridge near Yucca Mountain [25, p. 4–107; 118; 119, Fig. 2] (Fig. 4). The purpose of the test was to evaluate movement of water after thermally heated at the base of the block but the potential for mineral deposition to occur in fractures and alter permeability around a disposal drift was also explored. Specifically, the test measured the water evaporated at the bottom of the block (maintained at 140 °C) and condensed at the top of the block (maintained at 60 °C). Preliminary results found [103] (1) temperatures in the rock were much higher than predicted suggesting bulk thermal properties used for tuff were somewhat different than for laboratory specimens, (2) formation of heat pipe occurred within hours; and (3) significant dry-out of the rock occurred. Similar to the SHT, the temperature data in the LBT showed that the dominant heat transfer mechanism was heat conduction, but some coupled thermal-hydrologic effects were also evident [120].

For PA–VA the results of the SHT and LBT were summarized for use in the PA–VA and reviewed by the EBSEE Panel [121]. The EBSEE panel, which evaluated coupled processes for PA–VA, concluded that thermal-hydrologic-*mechanical* effects on permeability were within the range of the spatial variability and would mostly be reversible and, thus, insignificant; however, the EBSEE panel considered that thermal-hydrologic-*chemical* effects (that had been explored in LBT) were worthy of further experimentation and consideration in later PAs [24, vol. 3 p. 3–30].

2.5.5. Seepage in PA–VA

Similar to PA-93 and PA-95, the seepage process was simplified to a distribution of seepage flow rate and a distribution of the fraction of waste packages contacted in PA–VA. However, in PA–VA these probability distributions were based on modeling. The UZEE panel agreed with project scientists that a capillary barrier would exist around the drifts and likely divert water flow. To evaluate this capillary influence in PA–VA, a local-scale model of a 45-m segment of a single drift was developed. The local-scale model had much more detail than the mountain-scale UZ flow model mentioned above (UZ-97). Fracture permeability (k_f) from air injection tests conducted by Lawrence Berkeley National Laboratory (LBNL) in preparation for the large Drift-Scale Test (DST) [122] was used to select permeability fields for the local-scale model (Fig. 4). The range of k_f observed in the DST air-injection tests was similar to those obtained a year earlier for the SHT [101, p. 2–88; [171,123]. The geometric mean of k_f was 10^{-13} m^2.

2.5.6. SZ flow and transport in PA–VA

By PA–VA, USGS had developed a steady-state, 3-D regional flow model of the entire closed Death Valley basin ($\sim 2 \times 10^4$ km^2), using natural no-flow boundaries [124]. The regional SZ flow model consisted of 3 layers and grid blocks 1500 m square. The model incorporated stratigraphic and head data from 700 wells near Yucca Mountain and around NTS that had been compiled over the past 30 years. The recharge in the region was set using a modified version of the Maxey-Eakin method for estimating net infiltration (rather than using INFIL, which required too much data that was unavailable) [124, p. 52–5]. This regional USGS model was used to set head boundary conditions for a site-scale model of SZ flow and transport near Yucca Mountain for PA–VA and thereafter.

A smaller site-scale flow and transport model was based on the LANL Finite Element Heat and Mass (FEHM) code and calibrated with the commercial code PEST [125]. This code combination would be used thereafter for the SZ site-scale model. USGS models were also used to evaluate the influence on regional flow because of climate change. The volcanic aquifer units are thick ($\sim$2000 m) under the site but gradually disappear beyond the 10 km accessible environment boundary used in the 1984 PA–EA (i.e., between 10 and 20 km), after which the aquifer consists of mostly unconfined alluvium deposits, which offers the potential for retardation of radionuclides. Wells available at the time of PA–VA (and PA–SR) could not precisely locate the interface, and so the interface was uncertain in PA–VA to properly reflect the uncertainty in the potential radionuclide retardation.

For the SZ site-scale flow and transport model, the SZEE panel concluded that the large dispersion used in earlier PAs was unrealistic [126, p. 8–26]. Thus, the SZEE panel estimated dilution in the lower tuff aquifer to range between 2 and 100 times with a median of 10. This estimate was used directly in PA–VA. The SZEE panel examined the large hydraulic gradient northwest of the site, but concluded that identifying the cause was not important. The panel did express concern about the lack of data for key hydraulic properties [127] and recommended (1) field tests to evaluate hydraulic properties of faults and (2) tracer tests in addition to those already conducted at the C-wells [103].

2.5.7. Biosphere characteristics

A telephone survey of dietary habits and lifestyle of residents within an 80-km radius of Yucca Mountain was completed in June 1997 to obtain data for the biological transport model used in PA–VA

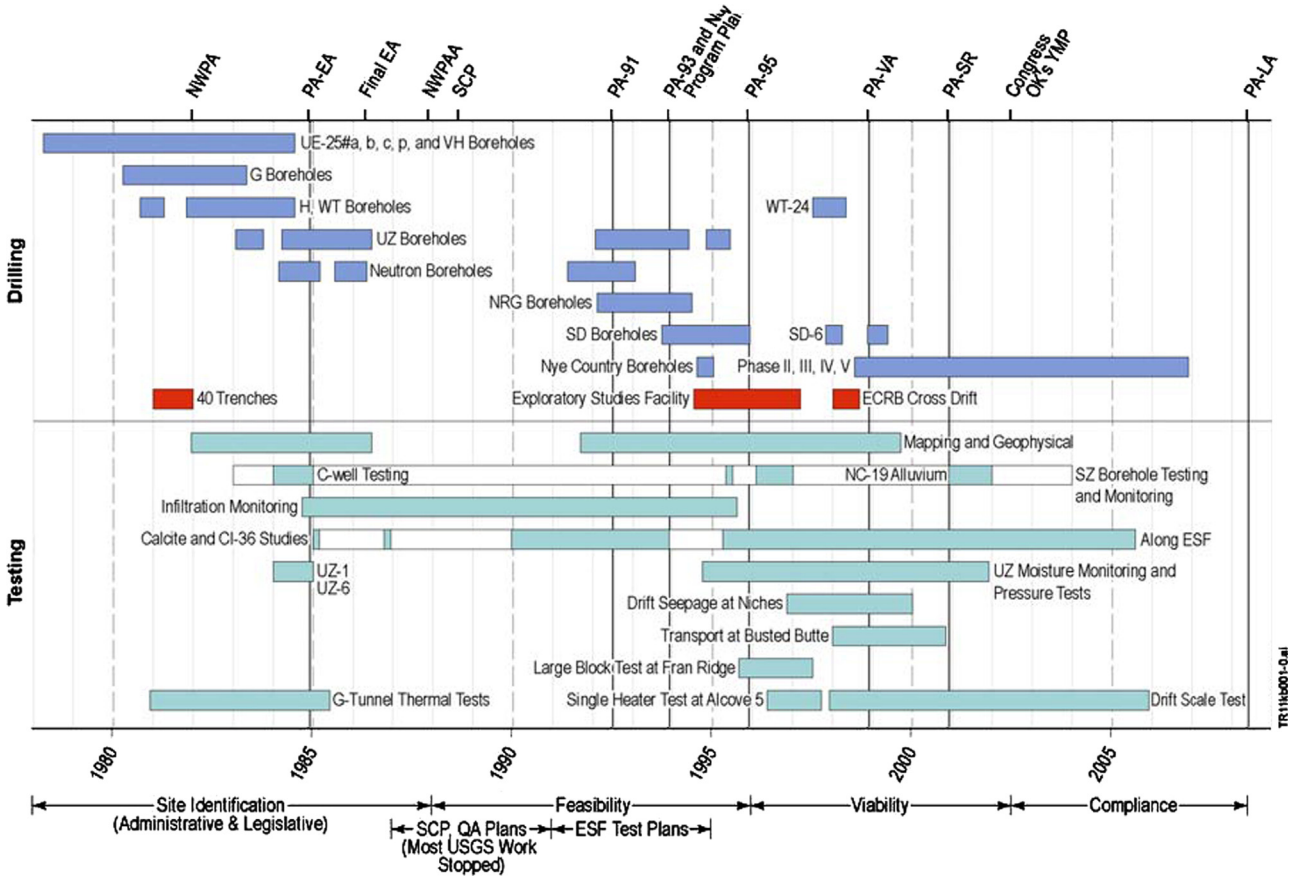


Fig. 4. Summary of field testing of geologic barrier near Yucca Mountain [119, Fig. 2]. A field testing hiatus occurred between 1986 and 1991 while an NRC-compliant QA program was completed, the US Court of Appeals compelled the State of Nevada to issue permits, and sufficient Congressional funding was available [68].

and thereafter. About 6725 households (~13,000 adults) exist within the survey area. About 43% of the 452 households, encompassing ~900 adults, within the Amargosa Valley were surveyed. Other communities surveyed were Beatty (33% of 751 households surveyed), Indian Springs (12% of 529 households surveyed), and Pahrump (11% of 4993 households surveyed) [24, vol. 3, Table 3-23] Residents spent about 10 h/day outdoors on weekdays. Nearly 88% of the Amargosa Valley residents consumed well water (~1.8 L/day) and nearly 80% consumed some type of locally produced food (such as leafy and root vegetables, fruit, beef, pork, fish, poultry, eggs, milk) [24, vol. 3, Fig. 3-77, Section 3.8.1]

2.6. Geologic barrier characteristics in PA–SR

Soon after completing the PA–VA in December 1998, planning was begun for the SR. The PA–SR was completed two years later in December 2000. By this time YMP had spent $\$8.2 \times 10^9$ (2007 constant dollars) on site characterization, repository and package design, PA, and documentation [128, Table ES-3].[8] Besides the extensive summary in the 2001 *Yucca Mountain Science and Engineering Report* [25] and its revision in 2002, site characterization information was also summarized in a 2003 special issue of the *Journal of Contaminant Hydrology* (e.g., [119]).

2.6.1. Stratigraphy for PA–SR

For PA–SR, the 3-D mountain-scale UZ flow process model (UZ-99) was improved using the stratigraphy in the USGS GFM v3.1. The GFM v3.1, which covered 170 km^2, used (a) the new USGS bedrock geologic map, (d) new borehole data from SD-6 and WT-24 for a total of 51 boreholes, (c) a consistent set of correlated borehole lithostratigraphic data, (d) geologic data from the Enhanced Characterization of the Repository Block (ECRB) cross-drift above the planned disposal drifts, which had been completed in 1998 [129] (Fig. 4), (e) more rock layers, and (f) more curvature of dominant faults with a slight decrease in fault dip with depth (concave-upward shaped faults). [97, Section 6.3.2; 130].

2.6.2. Infiltration in PA–SR

The basic formulation of INFIL and the 228 km^2 model domain remained the same as used in PA–VA. As with PA–VA, analog sites were selected for estimating precipitation and temperature in future climate states for use in INFIL; yet, the selection was more thorough in that (a) timing of precipitation and temperatures at analog sites was more carefully matched to that anticipated at Yucca Mountain, and (b) 8 analog sites were selected for low and high levels of infiltration rather than simply dividing or multiplying the base infiltration by 3 (Fig. 3) [131, Tables 6-4–6-6, 6-8]. For current conditions, PA–SR used 2 of the 6 NTS sites available (AJA and Area 12 Mesa) with 36 and 35 years of data, respectively, to create a 100-yr synthetic record for the simulation [131, Table 6-1]. The model was calibrated with precipitation and some temperature data collected between 1980 and 1995 from 10 near-by sites (6 NTS sites, 2 Yucca Mountain sites, and 2 National Climatic Data Center sites at Amargosa Valley and Beatty). Also, several parameters of the improved root-zone model (i.e., bedrock layer thickness, bedrock storage capacity, and relative density of roots in

[8] Separate costs for site characterization are not readily available.

each layer) were calibrated using measured storm discharge at five stream gages operating during 1994–1995 [131, Section 6.8]. The synthetic annual precipitation over the repository area had a mean of (a) 200 mm/yr for the current climate ($\overline{q}_{arid}^{precip}$); (b) 310 mm/yr for the monsoon climate between 600 and 2000 years ($\overline{q}_{monsoon}^{precip}$); and (c) 320 mm/yr for the glacial transition climate between 2000 and 10^4 years ($\overline{q}_{trans}^{precip}$) (Fig. 3) [131, Tables 6-10, 6-14, 6-19].

2.6.3. UZ flow in PA–SR

For PA–SR, the basic approach to estimating the percolation at the repository level remained the same as in PA–VA. For PA–SR, however, the calibration process was more extensive and an active fracture model was used to more accurately simulate UZ flow [9, Eqs. (30) and (31); 132,133]. For PA–SR. 1-D columns were built at 11 boreholes with matrix saturation, matrix water potential, or fracture pneumatic pressure measurements (NRG-5, NRG-6, NRG-7a, SD-6, SD-7, SD-9, SD-12, UZ-4, UZ-14, UZ-16, and WT-24) (Fig. 1). As the first calibration step, matrix saturation from core measurements was available from 7 of the 11 wells. Matrix water potential in-situ measurements were available at multiple depths from 4 of the 11 wells collected over 7 years from October 1994 to December 2001 (for NRG-6 and NRG-7a, the records used were from November 1994 to March 1998; for UZ-4, from June 1995 to March 1998; and for SD-12, from November 1995 to March 1998) [4, Section 2.3.2.3.2]. As a second calibration step, 30 days of pneumatic data (collected between 1994 and 1999) at multiple depths from gas pressure transducers were used from 5 wells (NRG-5, NRG-6, NRG-7a, SD-7, and SD-12) to set fracture permeability (k_f) [134, Table 6]. In all, 6 parameters were calibrated for the 30 unique layers (k_m, k_f, α_m, α_f, m_m, m_f); a seventh active fracture parameter (f^{fm}) was calibrated for 7 layer groups for the 1-D calibrations. In total, 187 hydrologic properties (199 including the 2 non-unique layers) were calibrated [134, Table 13].

As a new third calibration step, the hydrologic parameters of faults were calibrated in a 2-D model using UZ-7a, which intersects the Ghost Dance Fault [134, Table 6]. As the fourth step, the calibrated properties from the 11 boreholes were then used in a 3-D model, and this 3-D model calibrated manually to cause perched water to form at the TSw/CHn interface as observed in 7 wells (the 6 wells available for PA–VA plus WT-24) [135, Fig. 6-1]. Similar to PA–VA but with more data and analysis, the reasonableness of the flow fields was examined by comparing measurements in the ESF and ECRB of ^{36}Cl and precipitation of calcite in fractures.

2.6.4. Thermal-hydrology in PA–SR

In December 1997, YMP began an 8 yr Drift-Scale heater Test (DST) in a 47.5-m long section of ESF located in Tptpmn (Fig. 4). The test consisted of 9 waste-package-sized heaters to simulate the heat from the disposal in the drift ($\sim$5 kW/m) and 50 heaters in the walls to simulate the heat from adjacent drifts [103]. The purpose of DST was to compare observations from more than 3500 temperature, chemical, mechanical, and neutron sensors with modeling predictions of thermal, mechanical, hydrologic, and chemical responses such as initial dry-out and later rewetting, thermally driven buoyant flow of air and water vapor, and determine whether refluxing of water could occur via water vapor condensing above the drift and flowing back toward the drift [136]. The DST found that water did not pool above the drift but rather drained to either side of the experimental drift. Similar to SHT [117], modeling of DST results indicated heat conduction was the primary means of heat transfer rather than heat convection [122,137,138]; however, the detailed behavior of the thermal, hydrological, and chemical (THC) data could only be explained using a model, under development at LBNL, that coupled these processes [139,140]. The THC model would be used to estimate the evolution of the chemistry of water dripping on the waste package in PA–SR [10].

2.6.5. Seepage in PA–SR

The evaluation of the seepage in PA–SR was much more elaborate than in PA–VA. For PA–SR, a Seepage Calibration Model (SCM) on the scale of one drift was developed [141, 142]; 143, Section 3.9.4]. The initial hydrologic properties for SCM were based on the mountain-scale calibrated UZ flow model. The model fracture properties for the local drift scale were then calibrated using data from water release tests conducted since 1997 for the Drift Seepage and Niche Moisture Study (Fig. 4). In the tests, water was injected from a horizontal borehole located less than a meter above the roof (i.e., back) in niches along the ESF. The injected mass was roughly 1 kg, with injection rates between 0.5 g/s and 2.9 g/s (or $\sim 10^5$ to 10^6 mm/yr), which is 4–5 orders of magnitude greater than present-day or future-climate percolation. Injected water that dripped into the niche was collected on 0.3×0.3 m^2 trays. The mass and the timing of drips were recorded.

At the time of PA–SR, 40 water-release tests at 16 intervals in the holes bored above Niche 3650 in the middle non-lithophysal layer (Tptpmn) near the Sundance fault were available [141] (Fig. 1). Niche 3650 (constructed at station 36+50 along the ESF) was a 9-m long drift in stable rock with a moderate fracture density. For the PA–SR calibration, 5 water-release tests at one interval in one borehole conducted in late 1997 and early 1998 were used to calibrate the fracture porosity $\phi_f(\mathbf{x})$ and the fracture van Genuchten capillarity parameter $\alpha_f(\mathbf{x})$ [25, Fig. 4-36]. Then, 4 water-release tests from another interval of the same borehole were used to validate that the permeability fields ($k_f(\mathbf{x})$), and the adjusted $\phi_f(\mathbf{x})$ and $\alpha_f(\mathbf{x})$ were reasonable.

2.6.6. SZ flow and transport in PA–SR

By 1996, USGS reported that the permeability of the large volumes of rock measured from the multi-well tests at the C-well complex (Fig. 1) was similar for the CHn hydrologic unit but was up to $\sim$100 times greater than the permeability measured around single hole tests for the PPn, BFw and TRw units [25, p. 4–316; 144]. Also, based on analysis of testing at the C-well complex, NRC had estimated a horizontal (x:y) anisotropy in the SZ permeability of 1:5 [145]. A higher permeability in the north-south direction, which matches the prevailing faulting, could reduce the amount of eastward flow and, thereby, reduce the amount of flow through the porous alluvium located to the southeast of Yucca Mountain. Reducing the flow in the alluvium, which more readily sorbs radionuclides, could reduce the retardation of radionuclides in the SZ. Consequently two alternative models were developed for PA–SR, one with and one without horizontal anisotropy.

By 1999, measurements from the first 8 Nye County boreholes (NC-EWDP wells) were available (Figs. 1 and 4) and included among 115 wells available over the 1350 km^2 domain of the SZ site-scale flow model [25, Fig. 4-131]. For PA–SR, LANL calibrated the SZ model by varying permeability in the 19 hydrologic layers. The goals of the calibration were to (1) match water levels in the 115 well head measurements [25, Fig. 4-138; 51], Section 6.4, Fig. 6, Table 7]; (2) match the permeability from the C-well tests; and (3) bound the specific discharge estimated by SZEE panel conducted for the PA–VA. At the end of the calibration most goals had been met: (1) the specific discharge of 1 m/year bounded the SZEE panel estimate of 0.71 m/year at the 5 km boundary; (2) the permeability of the BFw was near the mean of the C-well tests

($10^{-10.9}$ m^2 versus mean of 10^{-11} m^2); and (3) the permeability of PPn unit was only slightly more permeable than the 95% confidence limit ($10^{-11.1}$ m^2 versus 95% confidence value of $10^{-11.4}$ m^2). Only the permeability of the TRw unit was much less than the C-well value, but it was still much greater than the single well test value ($10^{-12.6}$ m^2 versus $10^{-10.2}$ m^2 and 10^{-14} m^2, respectively) [51, Fig. 14].

For transport calculations for PA–SR and PA–LA, the flowing interval spacing (i.e., the spacing between fracture zones with measurable flow) was determined from flow meter survey data available from 8 wells (H-1, H-3, H-4, G-4, UE25c#1, c#2, c#3, UE25p#1) with a total of 32 measurements in 5 hydrogeologic layers (CHn, PPn, BFw, TRw, and lithic tuffs for lower confining unit) [146, Fig. 6-2].

2.7. Geologic barrier characteristics in PA–LA

2.7.1. Stratigraphy in PA–LA

At the culmination of site characterization, USGS completed data qualification and refined the geologic framework model for PA–LA (GFM v2000) (Appendix A); however, the refinements had little impact on the UZ and SZ flow models for PA–LA [97, Section 4.1]. Stratigraphic information from a total of 71 boreholes was used. The additional boreholes included since PA–SR were 10 shallow N series wells of the 23 boreholes drilled for infiltration studies using neutron logging, 8 wells that had been omitted because they were very near others (e.g., c#1 and c#2 of the C-well complex) [130, Table 4] and 3 wells RF#3, RF#8, and RF#13 recommended for inclusion during internal review of GFM v3.1. Also, USGS added another fault for a total of 43.

2.7.2. Infiltration in PA–LA

In October 2005, DOE directed SNL to repeat implementation of the infiltration model and directed Idaho National Laboratory (INL) to review the technical merit of INFIL v2.0 and compliance with QA procedures [74]. This reevaluation occurred because the YMP discovered correspondence between USGS geohydrologists in November 2004 that raised questions about fabrication of QA records (such as when computer programs related to INFIL were installed) while reviewing old e-mails for submission to the Licensing Support Network (LSN). The LSN was to support the formal hearings on Yucca Mountain by the NRC Atomic Safety Licensing Board. The 26 questionable e-mails, dated between 1998 and 2004, were written during the period when reports were being written under a tight schedule to complete documentation for the PA–SR and later when preparing documentation for the first iteration of PA–LA. By February 2006, DOE had found that the net infiltration rates were corroborated by independent studies of infiltration in the southwest [147]. By April 2006, the DOE Inspector General had found that although misconduct was suggested in the 26 e-mails, misconduct was not substantiated [148]. However, the Inspector General concluded there was inadequate compliance with some QA procedures (obvious backdating of a QA step) and software input files were not controlled. Hence, while the work was technically reasonable, it was not suitable for the formal LA, and SNL continued to develop a new implementation of the infiltration model (MASSIF). MASSIF (1) added uncertainty in soil depth, (2) added uncertainty in bedrock conductivity, (3) improved the synthetic average daily precipitation record, and (4) greatly improved modeling of evapotranspiration. For precipitation, SNL calculated synthetic 1000-yr records for 10 nearby stations (5 Yucca Mountain sites, 4 NTS sites, and one National Climatic Data Center site at Amargosa Valley) (Fig. 3). LANDSAT images from three representative precipitation years (dry, moderate, and wet) were used for estimating the basal transpiration coefficient for vegetative cover on Yucca Mountain in order to adjust the reference evapotranspiration [9].

The Nuclear Waste Technical Review Board (NWTRB), formed by NWPAA, commented that MASSIF provided a more complete representation of parameter uncertainties but did not consider all data previously used by USGS, was not calibrated with rock properties from USGS infiltration measurements, and did not sufficiently account for evapotranspiration from bedrock fractures, and, thus, was less consistent with temperature and ^{36}Cl concentration [149]. Since the models gave similar results with similar parameters, the NWTRB suggested that YMP qualify the other USGS infiltration data and include evapotranspiration from fractures in shallow buried bedrock for a future iteration of the YMP PA.

2.7.3. UZ flow in PA–LA

For calibration of the UZ flow model in PA–LA, sixteen 1-D columns were built at 16 boreholes with core matrix saturation, in-situ matrix water potential, or in-situ fracture pneumatic pressure measurements. The 5 additional boreholes (from the 11 boreholes used in PA–SR) were a subset of 23 shallow neutron logging, *N*-series boreholes (mostly located above the TSw unit) that were drilled for the USGS infiltration study in which matrix saturation had been measured from well core.

The calibration consisted of the same four steps used in PA–SR. The initial calibration used matrix saturation from 15 well core measurements (versus 7 wells in PA–SR) and matrix water potential in-situ measurements from 4 wells (same wells as used in PA–SR) [150, Table 6-4]. Four parameters were calibrated for 32 model layers (matrix permeability—k_m, matrix and fracture van Genuchten parameters—α_m, α_f, and active fracture parameter $\gamma^{fm}(\mathbf{x})$). The initial calibration was followed by 1-D calibration of fracture permeability k_f with pneumatic data for 16 layers that were available for 5 wells (same wells as used in PA–SR). The calibration of k_f was followed by a 2-D model to calibrate fault properties from the UZ-7a well at the Ghost Dance fault. The final step was the manual calibration of the 3-D model to cause perched water to form at the same seven wells used in PA–SR [9].

For PA–LA, YMP also sought to validate the presence of bomb-pulse ^{36}Cl on fracture surfaces within a few 100 mm of the walls of the ESF. Between March and October 1999, USGS/LLNL took 50 core samples 4 m or 10 m into the walls where LANL had previously found bomb-pulse ^{36}Cl in two zones along the ESF: (1) at the Sundance fault (40 boreholes), and (2) at Drill Hole Wash fault (10 boreholes). The most broken areas of the core, suggesting more fracturing, were leached and analyzed for chemical constituents. Some samples from Niche 3566 (near the Sundance fault) were also analyzed. No bomb-pulse ^{36}Cl was found by USGS/LLNL [16, p. 278; 151]. LANL repeated their analysis near Drill Hole Wash fault and Niche 3566 by again taking small samples from fracture surfaces. Bomb-pulse ^{36}Cl was not found at Drill Hole Wash this time, but LANL still observed bomb-pulse ^{36}Cl at Niche 3566 in concentrations similar to those first reported in 1996 [152]. In addition, scientists at the University of Nevada-Las Vegas, who tried to replicate the LANL sampling technique, had only one sample with possible bomb-pulse ^{36}Cl. Although contamination in the ESF or laboratory may have been a possible cause, the information collected did not point to this difficulty (e.g., LANL did not report bomb-pulse ^{36}Cl in samples provided by USGS) and the report did not come to any conclusions other than bomb-pulse ^{36}Cl was not corroborated by the USGS/LLNL using a different sampling method (i.e., leaching from a larger core specimen about a fracture rather than microprobe analysis of the fracture surface) [151].

2.7.4. Seepage in PA–LA

By PA–LA, more data had been collected by LBNL's Drift Seepage and Niche Moisture Study (Fig. 4). Data included air injection tests to estimate initial air permeability and 81 liquid release tests conducted at 3 niches along the ESF, one niche in the ECRB Cross-Drift, and in 3 boreholes drilled into the roof of the Cross-Drift. Data from Niche 3650 along the ESF had been used for PA–SR. The other 2 tests along the ESF, completed shortly after PA–SR, were at Niche 3107 and Niche 4788. Niche 3107 was a 6.3 m long drift located in an area of relatively low fracture density along the ESF where the Cross-Drift crosses 20 m above (Fig. 1). Niche 4788 was an 8.2-m long drift located in an intensely fractured zone. The tests in the ECRB Cross-Drift, completed in 2004, were located in Tptpll at Niche 1620. In all, 22 seepage tests (13 in Tptpmn and 9 in Tptpll) in 10 different interval/test-locations were used for the calibration of the seepage [153].

2.7.5. SZ flow and transport in PA–LA

For the PA–LA, more well data were available for construction of the site-scale SZ flow model. Stratigraphic, potentiometric, and single- and multi-well pumping data from 16 wells (completed by 2004 in Phases II, III, and IV of the NC-EWDP) were available for calibration (Fig. 4). Five wells from Phase V were available for validation [54, Table D-2]. A total of 161 potentiometric data were used for the calibration, which included the water table measurements from the 115 wells used for PA–SR and potentiometric data from other hydrologically isolated layers (e.g., 16 NC-EWDP wells provided 33 potentiometric measurements for different layers). The wells suggested that the alluvium became unconfined, with a hydraulic conductivity between 2 and 5 m/day except in an isolated zone where the conductivity was 12–13 m/day. A subset of the wells, known as the Alluvium Testing Complex (NC-22S, 22PA, 22PB of Fig. 1), was also able to better delineate the boundaries of the alluvium such that only the uncertainty in the northern boundary was included in PA–LA. Finally, USGS updated the Death Valley Regional Flow System model by 2004 ($\sim 10^5$ km^2) to provide updated boundary conditions of the site-scale SZ flow model [154].

Related to the transport in the SZ, the sorption properties of the SZ had been estimated in the laboratory by LANL for PA–VA [155,156]. The batch experiments were initially designed to determine whether various types of tuff adsorbed above a certain threshold. A bounding type of analysis was consistent with the NRC reasonable assurance standard of proof put forth in 10 CFR 60 and applicable to PA–EA, PA-91, PA-93, and PA-95, and proposed in the draft 10 CFR 63 as used for PA–VA and PA–SR [5]. However, NWTRB asked for more realistic analysis after PA–SR. Furthermore, a more realistic type of analysis was more appropriate for the reasonable expectation standard of proof expected by the EPA (and adopted by NRC after 2001) and used for PA–LA [5, Section 2.2.3]. Hence, the adsorptive properties of tuff had to be re-interpreted for PA–LA [157–159].

3. Summary

Similar to WIPP, site characterization at Yucca Mountain progressed through four phases (Table 1): (1) literature search, non-intrusive evaluation, and boreholes completed to determine stratigraphy for the site identification study phase, which supported PA–EA; (2) exploration from the surface through well testing for the feasibility study phase, which supported PA-91, PA-93, and PA-95, (3) more extensive well testing and exploration underground to evaluate coupled processes for the suitability phase, which supported PA–VA and PA–SR; and (4) completion and reporting on conclusions of all site-specific experimentation for the compliance phase, which supported PA–LA. Once a reasonably good site had been identified in the first phase, the focus of the characterization in the second and third phases was on what could go wrong with the Yucca Mountain disposal system and the uncertainty associated with the system. Much micro-scale complexity was discovered during site characterization; yet, Yucca Mountain, on a macro-scale, remained fairly simple and consisted of mildly tilted unsaturated layered strata with mostly vertical water percolation down to the deep water table from limited amounts of precipitation in a desert environment.

Most of the wells drilled near the repository (G, H, WT, and UZ well series as well as many of the N series neutron probe boreholes) were completed for 1984 PA–EA and the site selection phase (Fig. 4); however, extensive testing in these wells was implemented after completing the SCP in 1988 (Appendix A). By PA-91, evidence for deep fracture flow had been found in UZ-1 and UZ-16 and prompted consideration of an alternative fracture flow conceptual model. By PA–VA, site characterization had collected data on net infiltration into the mountain, bomb-pulse ^{36}Cl concentrations, and movement of water around single heater (SHT) and large block tests (LBT). Site characterization had also conducted hydraulic tests on core samples, pneumatic tests in existing wells, and mapped fractures in the ESF (Fig. 4). By PA–SR, site characterization had evaluated seepage in niches and the chemical environment around the Drift-Scale heater Test (DST). By PA–LA, Nye County in cooperation with DOE had completed Phases I through IV of the series of wells south of Yucca Mountain to better define fluid flow and radionuclide transport in the SZ (Fig. 4). Also, many tests had been completed that allowed PA models to be partially validated. However, an attempt to validate the presence of bomb-pulse ^{36}Cl in fractures within the ESF using different measurement techniques was unsuccessful.

NRC initially estimated the cost of in-situ characterization of a hard rock repository, such as Yucca Mountain, $< \$40 \times 10^6$ in 1982 [14,61], under the assumption that much knowledge would be acquired during construction, similar to the situation that occurred at WIPP. But after some surface exploration to evaluate the feasibility, the cost of characterization of candidate sites was estimated at $\sim \$1 \times 10^9$ per site in 1987 during hearings for NWPAA [64]. Under the revised expectation that most knowledge would be acquired prior to construction authorization by NRC, the YMP costs for the site suitability/viability phase (for site characterization, repository and package design, PA, and documentation) had increased to $\$8.2 \times 10^9$ (2007 constant dollars) in 2001. For the licensing compliance phase, the cost had increased further to $\sim \$11 \times 10^9$ (2010 constant dollars), 20 years after NWPAA [2, p.10; 128, Tables ES-1 and ES-3].

Scientific understanding of igneous processes in the area and unsaturated flow in tuff fractures was initially lacking and so much site characterization time and expense was required to improve this scientific understanding, resulting in an impressive body of scientific work. Yet, the needs of the PA, which examines the disposal system as a whole, can set boundaries on what is necessary to fully understand the natural barrier. Specifically, in the siting guidelines in 10 CFR 963 (promulgated by DOE in 2001), the disqualifying conditions for the YM repository relied upon the results of a PA (which followed the precedence of the NRC in 10 CFR 63) [5, Section 2.2.3]. As suggested by NRC, perhaps more active use of PA results at the early stages of YMP could have helped prioritize SCP tests [160, Section 2.1] (i.e., a PA was not conducted for guiding the SCP completed in 1988). None the less, a reevaluation of the characterization program occurred later in the 1990s, but was prompted by limited annual Congressional appropriations [14,91].

Characterization of future potential repository sites will likely adopt a phased approach, similar to the phases followed

informally by YMP, where limited site characterization is conducted during the site identification and feasibility phases (Table 1). Activities would not proceed to the suitability/viability characterization phase, because of the high costs encountered at Yucca Mountain, until a host community and associated state or tribe have provided preliminary consent to proceed with the repository program (as formally specified in the current Canadian site selection process[9]). Yet, note the limited understanding that existed at Yucca Mountain during PA-91 through PA-95 versus the more complete understanding for PA–VA and PA–SR once in-situ underground experimental data were available. Certainly, part of the dramatic shift in understanding was due to the micro-complexity of UZ flow at Yucca Mountain. Hence, if several potential sites are available, high costs of characterization of sites with more complex geology and/or phenomena might be used to rank the desirability of proceeding to the suitability/viability phase and seeking an NRC license for construction.

Yet, a more subtle question is the type of laboratory and in-situ experiments to conduct during site identification and when evaluating site feasibility versus those necessary to conduct for evaluating site suitability/viability. Upon reflection, this paper provides some insights, but answering the question will require more thought and discussion among experimentalists and analysts.[10] The state of knowledge about various phenomena also enters into this evaluation. For example, a simple experimental design with batch experiments was used to determine if sorption was above a certain threshold in order to evaluate site feasibility of Yucca Mountain in the 1990s [155,161]. However, more elaborate adsorption experiments were desirable to determine a distribution of reasonably expected behavior in order to evaluate the suitability/viability and compliance of the site. Fortunately, the state of knowledge of sorption had advanced sufficiently such that the threshold-type experiments could be re-interpreted for sorption in the UZ and SZ for PA–LA without repeating the experiments by using addition literature data and surface complexation modeling [157–159]. Hence, advancing the state of knowledge broadened the use of existing characterization data.[11]

Acknowledgments

Sandia National Laboratories (SNL) is a multi-program laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the DOE National Nuclear Security Administration under Contract DE-AC04-94AL85000. The authors wish to thank L.A. Connolly, SNL, for help with references, and S.K. Best, Raytheon, for illustration support. The historical perspective and opinions presented are those of the authors and are not necessarily those held by reviewers, SNL, or DOE. As a historical perspective, the authors are reporting on the work of others; however, any interpretative errors of documentation are those of the authors alone. Each performance assessment discussed in this paper required numerous participants with expertise in many areas of science and technology. The most complete listing of these participants is made by examining the extensive reference list; however, many of references are corporate documents without authors. Therefore, some of the persons, who made an important contribution to characterization of the YM disposal system, are acknowledged here. Specifically, geologists at the USGS were involved extensively in characterizing the geology, hydrology, climatology such as W.W. Dudley, Jr.; W.E. Wilson (conceptualization of major tuff aquifer units [26]); R.B. Scott (original USGS conceptual model of flow through YM [45] and geologic map of Yucca Mountain for PA–EA [40]); P. Montazer (groundwater modeling [26]); J.B. Czarnecki (groundwater modeling [73]); R.K. Waddell (groundwater modeling [52]); J. Witney; D. Hoxie [80]; D. Bish; R. Herbst. Some of the individuals cited several times include those analyzing the stratigraphy and hydrology of early hydrologic drill holes R.W. Craig [39], R.W. Spengler [28]; W. Thordarson [33]; F.E. Rush [31]; C.B. Bentley [34,38]; E.P. Weeks [30]; D.A. Sawyer geologic map for PA-95 and later [94]; G.D. LeCain (air-injection testing [111]); A. Flint and L. Flint (infiltration measurements in PA–VA [99,100] and PA–SR [43]); A.L. Geldon (analysis of C-well complex [53,144]; and J.B. Paces (attempt to validate presence of bomb-pulse ^{36}Cl in ESF [151]). Also, scientists at LBNL were involved in characterizing the UZ including G.S. Bodvarsson (development of UZ flow experimental team); H-H. Liu (calibrated UZ flow properties [150]); Y.W. Tsang (testing and analysis of UZ flow [163] and drift seepage [123]); C-F. Tsang (testing and analysis of drift seepage UZ flow [123]; J.S.Y. Wang (testing and analysis of UZ flow [119,163] and drift seepage [141]); C.F. Ahlers (analysis of pneumatic data [112] and calibration of flow properties [134]); S. Mudhopadhyay (testing and analysis of UZ flow [120]; S. Finsterle (characterization of pneumatic response [112] and geostatistical inverse modeling [142])). Early in-situ thermal experiments were conducted in G-tunnel at NTS for PA–EA: R.M. Zimmerman, SNL [49], B.S. Langkopf, SNL [48]; J.K. Johnstone, SNL; L.D. Tyler, SNL [48]; B. Stanley, SAIC; and M.D. Voegele, SAIC). Later, scientists at LLNL were involved in near field characterization through (a) analysis of thermal experiments, such as the large block test (LBT): E.L. Hardin now at SNL [121]; W. Lin, S.C. Blair, J.A. Blink, T.A. Buscheck [118,121]; and D. G. Wilder [118]); and (b) development of thermal–chemical coupled models: T.J. Wolery, W. Glassley, and J. Johnson. Also, LBNL scientists developed a coupled thermal–hydrologic–chemistry (THC) model which was used in analysis of drift-scale heater test (DST) [139]: E.L. Sonnenthal, LBNL; N. Spycher, LBNL; and M. Peters, TRW now at ANL was involved as the DST lead. Later, R.L. Jones led thermal testing. Some SNL scientists also involved with characterization include C.A. Rautman (geostatistical analysis of the tuff layers [22]); A Stevens; and R. Steinbaugh. LANL had a primary role in characterizing the geochemistry such as AE Ogard and J.R. Kerrisk [55], and LANL scientists conducting radionuclide sorption measurements and assigning uncertainty distributions include I.R. Triay (formation of sorption and colloid-facilitated experimental teams [155]); A. Meijer (sorption distributions for PA–VA [155], and re-evaluation for PA–LA in UZ [158] and SZ [159]); R.S. Rundberg [58]; K. Wolfsberg [56]; P.W. Reimus [156]; and B.A. Robinson. In addition, LANL scientists first proposed and searched for bomb-pulse ^{36}CL to evaluate the possibility of deep fracture flow, consistent with 1983 USGS conceptual model: A.E. Norris [72]; J. T. Fabryka-Martin [87] and A.V. Wolfsberg [152]. Contributors to the characterization of igneous and seismic hazards are discussed in a companion paper [6]. Because so many scientists and engineers were involved in site characterization at YMP, the authors recognize that this list is unavoidably incomplete, and we apologize for omissions and oversights.

[9] See www.nwmo.ca.

[10] As noted in a companion paper [13, Fig. 3a], the change in philosophy for characterizing uncertainty over the years confounds an easy interpretation by PA analysts.

[11] A similar approach was adopted when initially designing experiments for evaluating container corrosion in the site water chemistry, but the limited ability of process models to predict corrosion behavior, the great length of time necessary to observe minute corrosion, and problems with executing the experiments confounded the ability to use these data except as bounding/threshold information [7, Appendix A; 162].

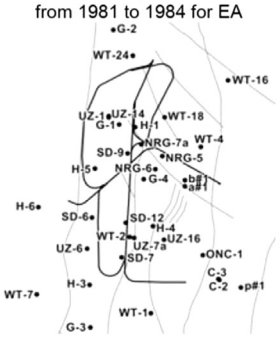
Appendix A. Progression of site characterization at Yucca Mountain

1978 Apr: US Geological Survey (USGS) drills 1st borehole (#a-1) at Yucca Mt (YM) [28]. **May:** Sandia National Labs (SNL) proposes small heater/water-migration and rock mechanic tests in tuff in G-tunnel at Nevada Test Site (NTS) as part of underground research lab (URL) [48]; SNL along with Los Alamos National Lab (LANL) and Argonne National Lab (ANL) also propose nuclide transport tests, but nuclide field tests never completed, only lab tests conducted..

1980 Apr: USGS dates fossil rat middens from middle Wisconsin through Holocene age to determine climatic changes at NTS [86]. **Apr-May:** USGS cores G-1 geologic borehole to 1.9 km at YM [29]. **Sep:** H-1 hydrologic borehole drilled 1.9 km into saturated zone (SZ) [31].

1981 Jan: G-2 borehole completed to 1.9 km. USGS digs 5 trenches in Crater Flat, next to YM to determine age: 2 trenches dug at ancient springs (~0.1 Ma) and 3 trenches dug at 2 faults that occurred with Red, Black, Little Cones (~1.1 Ma) [164].

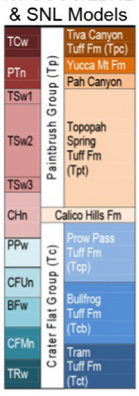
USGS Completes 5 G, 6 H, 9 UZ, and 16 WT Wells, and 40 trenches from 1981 to 1984 for EA



1982 Four major boreholes completed (G-3, H-3, H-4, and H-5) and 2 more boreholes started (H-6, UE-25p#1); 6 of the 7 holes bored along the perimeter of the potential repository; UE-25p#1 located to reach the deep carbonate aquifer [35, p. 14]. USGS suggests variation in temperature of groundwater around YM is from groundwater percolation of up to 8 mm/yr [44]. USGS develops 3-D model of stratigraphy of YM [35]. USGS develops 2-D model of regional groundwater flow (175-km^2) in SZ at NTS [52]. **Jun:** In preparation for field fracture flow tests in G-tunnel, SNL conducts design calculations [165; 166]. Drilling of G-4 begins at the proposed location of the ESF shaft, using air/foam. **Jul:** Yucca Mountain Project (YMP) moves repository to UZ in ~350-m thick welded Topopah Spring Fm (TSw) [167].

1983 Based on fractured outcrops at YM, USGS proposes precipitation percolates directly through UZ [45]. USGS completes UE-25p#1, H-6, and G-4. G-4 drilled to depth of 950 m [38]; H-6 drilled to 1.2 km; UE-25p#1 drilled to 1.3 km. USGS drills eleven 340-m deep holes holes to locate water table (WT) around YM [35]. USGS begins periodic water table measurements. High water table/perched water noted northwest of repository. **Jan:** Congress passes *Nuclear Waste Policy Act of 1982* (NWPA) defining site selection process [3]. Nuclear Regulatory Commission (NRC) estimates <\$40 ×10^6 for characterizing 300 m of underground drift [61]. **Jun:** Small-diameter heater tests completed in G-tunnel [49]. LANL reports on sorption of nuclides on tuff [56].

Stratigraphy Defined for USGS/LBNL & SNL Models



1984 USGS continues mapping of faults and fractures around YM and proposed location of ESF [168] and completes geological map of area [40, p. 9]. USGS notes continuous seepage from several fractures in G-tunnel under Rainer Mesa and postulates Rainer Mesa as analogue for YM during the glacial period [26, pp. 36-49]. To reconcile equivalent continuum model (ECM) with observed fracturing, estimated 3% infiltration, and 65% TSw matrix saturation, USGS proposes most water percolating through Tiva Canyon Fm (TCw) (4.5 mm/yr), is diverted laterally by Paintbrush Fm (PTn) to faults and only 0.5 mm/yr moves downward through TSw as matrix flow [26, pp. 36-49]. USGS creates new 2-D regional model and matches hydraulic heads in 26 wells around YM and 64 wells near Death Valley [73, Fig. 3]. Model is ~1/3rd size of 1982 USGS model. Infiltration study begins: boreholes drilled across washes and on crest to measure changes in water-content from precipitation [43]. Also, 11 stations set up around YM to measure chemical composition of precipitation [35]. **May:** Lawrence Livermore National Lab (LLNL) reports on geochemical tuff/water interaction tests; water from J-13 used to simulate groundwater composition [169]. **Aug:** LANL reports on water chemistry solubility limits for nuclides along flow path [55; 170]. **Nov:** Los Alamos National Lab (LANL) reports on potential for colloidal Pu [58]. **Dec:** At end of 1983 and through 1984, UE-25c#1, #2, and #3 (C-wells), are drilled ~3 km east of repository and permeability estimated using pumping tests [53].

1985 LANL finds calcite and opal on deep fracture surfaces from well core that suggest deep fracture flow [69]. **Oct:** SNL defines stratigraphy for thermal-hydrologic modeling (e.g., TCw, PTn, TSw); similar to USGS 1975 and 1984 model layers [27].

1986 Department of Energy (DOE) issues stop-work order to USGS to revise QA procedures for collecting data; some work continues for irretrievable data. Order lifted in 1991 after 1990 NRC QA audit [74].

1987 Jan: In hearings before Senate, DOE reports that site characterization now estimated at ~\$1×10^9 per site [64]. **Apr:** LANL measures ^{36}Cl/Cl ratios in water extracted from UZ tuff and proposes data be used to evaluate percolation at YM [72]. **Jul, Aug, Dec:** LANL models kinetic sorption [171] and traditional sorption [172] on tuff using test results conducted between 1977 and 1985 [173]. **Dec**: *Nuclear Waste Policy Amendment Act* (NWPAA) (a) selects YM out of 3 sites partially to lower characterization costs; (b) establishes Nuclear Waste Technical Review Board (NWTRB) to advise DOE and Congress [1, §5001]; and (c) designates Nye County as affected unit; designation allows DOE to fund independent investigations by Nye Country such as the Early Warning Drilling Program (NC-EWDP); DOE Secretary later defines 9 other affected units.

1988 Jan: DOE publishes draft SCP. **Jul:** As required by NWPA, NRC comments on draft Site Characterization Plan (SCP); NRC criticizes QA program and lack of alternative conceptual models; NRC notes possibility of test interference and that co-location of test facilities with disposal drifts requires test facility construction meet QA licensing criteria. **Dec:** DOE publishes final 9-volume SCP with ~300 activities for surface, underground, and laboratory test and corresponding models to answer licensing questions and all concerns raised by stakeholders, but no performance assessment available to rank studies [65].

1989 Behavior of artificial colloids tested in lab columns; results suggest colloid transport not significant at YM [59]. YMP stops thermal testing in G-tunnel because of cost to update ventilation [174]. **Jul:** In response to NRC critique of SCP, YMP studies excavating Calico Hills Fm (CHn) in Calico Hills Risk/Benefit Analysis (CHRBA) since it could be important natural barrier; 1st study finds that repository will meet requirements without testing; 2nd study suggests testing could reduce program risks [175]. **Aug:** NRC publishes final comments on SCP [176].

1990 9th Appeals Court compels Nevada to issue permits [68]. LANL finds ^{36}Cl in well UZ-6 [71] and USGS finds drilling fluids in dry-drilled UZ-1 from well G-1, 300 m to SE, suggesting deep fracture flow [70]. USGS examines hydrology near Franklin Lake playa using 1984 model [75]. **Sep:** Responding to NWTRB, LANL holds sorption workshop.

1991 Oct: YMP conducts Test Prioritization Task (TPT) to rank SCP test importance. 3 major concerns are ^{14}C gas flow; complex geology for gas flow; and complex geology for groundwater flow [68].

1993 USGS develops regional-scale, quasi 3-D model that includes deep carbonate aquifer [177]. USGS begins drilling SD well series; completed in 1999. **Mar:** After 10 months, UZ-16 borehole completed with new continuous core air drill rig (LM-300) to avoid contaminating borehole with water. It would take ~29 yr to complete planned 40 boreholes with total length of 30 km using LM-300 5 days/week at annual cost of ~\$5.6 ×10^6 [174]. DOE decides to reduce surface drilling and move to underground once ESF completed [77].

1994 May: PA-95 uses very low infiltration (0.02 and 1.2 m/yr) based on USGS preliminary results for neutron boreholes [89]. **Nov:** USGS begins tests of matrix water potential and gas permeability in several wells [150, Table 6-4]. **Dec:** DOE proposes new site characterization structure that categorizes SCP tests into tests specifically needed for evaluating site suitability [91].

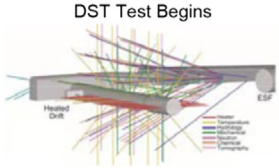
1995 Mar: USGS completes mapping of Ghost Dance Fault at surface; fault ~200 m wide; Northwest-trending Sundance fault traverses Ghost Dance; thus, Ghost Dance is inactive [178]. **Apr:** Underground calcite and ^{36}Cl sampling, and moisture monitoring start at ESF North Ramp [179]. LANL tests for ^{36}Cl at faults as boring progresses along ESF [151, §2], LANL reports that Sr-isotopic dates of calcite deposits in wellbores and U-isotopic dates of spring deposits in Crater Flat suggest water table rise of 80 to 115 m during last glaciation 18 ka [22, §8.8]. **May-Jun:** USGS conducts interference test at C-wells [144]. **Sep:** USGS reports on moisture observations in 99 neutron boreholes [99].

Fig. A1. Characterization of geologic barrier at Yucca Mountain [164-193]

USGS Finishes Infiltration Tests and Model

1996 USGS publishes formal stratigraphy of YM. USGS upgrades member units to formations, and divides the stratigraphy of Paintbrush Group [42]. **Feb**: USGS conducts pumping test in Bullfrog Fm (BFw) at UE25c#3; other C-wells (c#1, c#2), ONC-1, H-4, WT-3, and WT-14 are observation wells. LLNL turns on heaters at Large-Block Test (LBT), located at Fran Ridge near YM to evaluate water movement, mineral deposition in fractures, and design future thermal tests [103]. **May-Nov:** Sorbing/nonsorbing tracers injected into borehole UE25c#2 while pumping c#3 (first conservative tracer test) [156]. **Aug:** YMP begins yr long Single Heater Test (SHT), 5-m long heater with 3.86 kW output at Alcove 5 in ESF, 530 sensors in 41 boreholes [180]. **Nov:** In response to Congressionally mandated PA-VA, YMP forms 5 expert panels to examine: (1) UZ flow, (2) flow and transport in SZ, (3) waste container degradation, (4) waste form degradation, (5) near-field/altered-zone coupled effects [103]. YMP forms UZ panel 1st (7 experts with 4 from outside DOE complex and USGS) [104]. **Dec:** LANL summarizes ^{36}Cl data [152]. USGS completes infiltration model, INFIL based on water balance and field capacity of soil and bedrock [100].

DST Test Begins



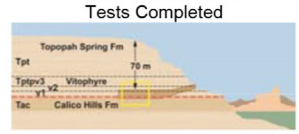
1997 USGS develops a 3-layer, 3-D, steady-state regional flow model of SZ for the closed Death Valley basin (~2×10^4 km^2) [124]. For PA-VA, USGS develops a site-scale model with boundary conditions set by regional model [125]. **Jan:** A new conservative tracer test begins at C-wells. Test ends in Nov. **Feb:** LLNL turns on heaters at Large-Block Test (LBT), located at Fran Ridge near YM to evaluate water movement, mineral deposition in fractures, and design future thermal tests [180]. **May:** Heat turned off in SHT; test shows conduction rather than convection is dominant heat transfer process [117]. Dual permeability model (DKM) matches temperatures better than ECM [103; 116, §3.4.5]. UZ expert elicitation completed and agree (a) percolation equal to infiltration above repository; (b) percolation 10 times greater than PA-95; (c) flow in TSw mostly in fractures based on presence of bomb-pulse ^{36}Cl; and (d) capillary barrier would exist around drifts and divert water [107]. **Jun:** YMP completes survey of dietary habits of residents within 80 km [24, Vol. 3 Table 3-23]. **Jul:** Drilling of WT-24 begins with vacuum-reverse air circulation rig; completed May 1998 [119]. **Aug:** DOE accepts NWTRB suggestion for a 2nd test drift: the enhanced characterization of the repository block (ECRB). **Sep:** LLNL and LANL report on migration of 0.8 pCi of Pu via colloids 1.6 km from 1.15-million ton Benham bomb test detonated in 1968 below water table at NTS [60]. **Nov:** LBNL reports on seepage tests in niche at Station 3650 [25, Fig. 4-17]. Drilling of SD-6 begins with similar rig as WT-24; completed April 1998 [119]. **Dec:** YMP begins \$50 $\times10^6$ Drift Scale Test (DST) in 50-m long section of Alcove 5. Test uses 9 WP-sized heaters, 50 heaters in walls to simulate adjacent drifts, and 147 boreholes for thermal and strain responses and sampling hydrology& chemistry [103; 180]. LANL summarizes more ^{36}Cl data [181].

Drip Tests Conducted

1998 DOE funds USGS over 5 yr to update regional flow model. For PA-VA, USGS defines future climate at YM based on precipitation at analog sites: Rainer Mesa above G-tunnel for LTA and South Lake, CA for short-term pluvial conditions [24, p 3-14]. USGS updates geologic bedrock map first created in 1984 [96]; including fractures in ESF [95]. Also, YMP completes seismic imaging between the ESF and the surface [182]. Testing at C-wells shows aquifer permeability orders of magnitude greater than permeability found in core and ~2 orders of magnitude greater than single-well tests [144]. Water levels in wells 3 km away influenced [127]. Expert elicitation of 5 experts (4 from outside DOE complex) on issues related to SZ groundwater flow and transport conducted for PA-VA. The experts examine the high water table northwest of the site; but conclude that identifying the cause is not important to PA. As in PA-EA to PA-95, the experts affirm that water from YM does not reach the deep carbonate aquifer but remains in the 2 tuff aquifers. The experts consider the large dispersion used in the PA-95 unrealistic and estimate dispersion between a factor of 2 and 100 of distance. **Jan-Feb:** LBNL conducts seepage tests at Niche 3650. SHT finished. **Mar-Aug:** LBT heat turned off. LBNL conducts percolation test at North Portal of ESF: water uniformly distributed at surface; seepage observed 30 m below in Alcove 1 (TCw); tests also conducted Jan to Jun 1999 and up to Jan 2000 [183]. **Jul:** Because no funding for TBM to bore to CHn as, LANL begins 3-yr test on flow and transport in partially excavated 5 m block of CHn 70 m below the surface at Busted Butte, a small butte 8 km southeast of YM [184]. **Sep:** LBT finished. **Oct-Nov:** LBNL inject water at fault in PTn; water imbibed into matrix; thus, episodic fracture flow attenuated [185]. **Dec:** DOE estimates YMP spent \$5.9$\times10^9$ (1998 \$) [24, Overview]. LANL summarizes more ^{36}Cl data [186].

1999 1st 8 wells (Phase I) of NC-EWDP completed [25, Fig. 4-131]. **Mar-Oct:** USGS/LLNL drill 50 boreholes in ESF at Sundance and Drill Hole Wash faults to validate high ^{36}Cl found by LANL [151, §3.2]. **Jun:** ~1 km of ECRB sealed to observe seepage near Solitario Canyon fault.

Busted Butte Validation Tests Completed



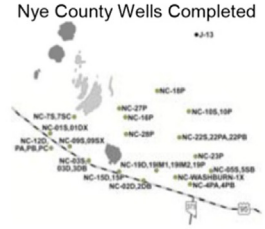
2000 Mar: For UZ flow, LBNL concludes from 1998-99 flow tests [143] (a) some percolation is diverted to faults by non-welded layers: 4% near surface, 15% at PTn, and 35% at CHn; (b) ~84% of percolation is through fractures. **Jul-Nov:** Pump test at NC-19D in alluvium completed [187, Fig. 7-4]. **Oct:** Busted Butte tests completed. Transport dominated by capillary flow [184]. Thermal-hydrologic-chemistry simulations run for DST [188; 189] and SHT [115, §10].

2001 DOE estimates \$8.2$\times10^9$ spent (2007 \$) [128, Table ES-3]. **Feb:** Condensate found at bulkhead in closed end of ECRB; testing continues to confirm water is condensate and not seepage [190]. **Dec:** NC-EWDP finds evidence of past hot water in faults south of site [191]. Also, vertical variation in water chemistry found in wells.

2002 Jan: Heaters turned off in DST. During the test, 6-7 m of tuff dried out (drift diameter 5.5 m). **Oct:** Water levels in a few wells increased in last 10-yr, but most of 43 wells near YM have not changed since 1960.

2003 Mar: DOE starts Science and Technology program with \$1.7 $\times10^6$ to improve understanding and develop technology to reduce uncertainty and costs. **Nov:** Based on work at Busted Butte, LANL reports zeolites in CHn below repository readily sorb short-lived Sr, Cs, and Ba [184].

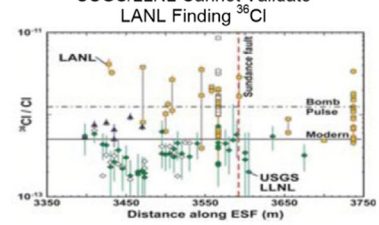
Nye County Wells Completed



2004 USGS completes update to regional SZ flow model [154]. **Nov:** 16 new NC-EWDP wells mostly completed (Phases II, III, IV); wells suggest alluvium unconfined [187, Fig. 7-4]. When reviewing old e-mail for LSN, YMP finds e-mail between 3 USGS geo-hydrologists from 1998 to 2004 that raise questions about collection of infiltration data, when INFIL installed, fabrication of QA records [74].

2005 Feb: 1st evidence of natural seepage found near ESF entrance. **Mar:** DOE Inspector General investigates USGS e-mails [74]. **Oct:** DOE directs SNL to redo infiltration model and directs INL to review technical merit of INFIL [149]. **Dec:** DST completed.

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



2006 Feb YMP finds that infiltration corroborated by other studies in southwest [147]. YMP reports to NWTRB that Eh tests at wells suggest a reducing zone exists down gradient from YM that may retard ^{99}Tc, whose solubility is sensitive to oxidation [192]. **Apr:** Although misconduct suggested in 26 USGS e-mails, it was not substantiated; thus, no criminal charges filed [74]. **Aug:** No conclusions reached between LANL finding and USGS/LLNL not finding ^{36}Cl in ESF [151, Fig. 6-1].

2007 Apr: SNL completes analysis using MASSIF. MASSIF predicts 2.5 times more infiltration with more uncertainty. SNL replacement cost ~\$12.9 $\times10^6$; and investigation cost another ~\$12.7$\times10^6$ [193]. **Dec:** NWTRB concludes MASSIF represents uncertainties better, but does not consider all data previously used by USGS in INFIL and does not sufficiently account for evapotranspiration from bedrock fractures; thus, MASSIF less consistent with evidence of temperature and ^{36}Cl concentration [149].LA cost \$9.9$\times10^9$ (2007 \$) [128, Table ES-1]

Fig. A1. (contd.).

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