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Hazards and scenarios examined for the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste

Rob P. Rechard [a,*], Geoff A. Freeze [b], Frank V. Perry [c]

[a] Nuclear Waste Disposal Research & Analysis, Sandia National Laboratories, P.O. Box 5800, Albuquerque 87185-0747, NM, USA
[b] Applied Systems Analysis & Research, Sandia National Laboratories, P.O. Box 5800, Albuquerque 87185-0747, NM, USA
[c] Earth and Environmental Sciences Division, Los Alamos National Laboratory, EES-16, MS D452, Los Alamos 87545, NM, USA

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ABSTRACT

This paper summarizes various hazards identified between 1978 when Yucca Mountain, located in arid southern Nevada, was first proposed as a potential site and 2008 when the license application to construct a repository for spent nuclear fuel and high-level radioactive waste was submitted. Although advantages of an arid site are many, hazard identification and scenario development have generally recognized fractures in the tuff as important features; climate change, water infiltration and percolation, and an oxidizing environment as important processes; and igneous activity, seismicity, human intrusion, and criticality as important disruptive events to consider at Yucca Mountain. Some of the scientific and technical challenges encountered included a change in the repository design from in-floor emplacement with small packages to in-drift emplacement with large packages without backfill. This change, in turn, increased the importance of igneous and seismic hazards.

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1. Introduction

In June 2008, the United States (US) Department of Energy (DOE) submitted, and that September, the Nuclear Regulatory Commission (NRC) docketed the Safety Analysis Report for the License Application (SAR/LA) to construct a repository at Yucca Mountain (YM). Located ~160 km northwest of Las Vegas, Nevada on the Nevada National Security Site (formally known as the Nevada Test Site or NTS), the repository was for disposal of commercial spent nuclear fuel (CSNF), high-level radioactive waste (HLW), and DOE-owned spent nuclear fuel (DSNF) [1,2] (Fig. 1). However in 2010, the Obama Administration and Congress eliminated all funding and brought a practical stop to the Yucca Mountain Project (YMP). Instead, Congress funded DOE to form the *Blue Ribbon Commission on America's Nuclear Future* to review the current policy in the US for storage, processing, and disposal of CSNF, DSNF, and HLW. Recommendations for a new plan were presented to Congress in January 2012 that included a consent-based siting process [3].

As part of this Congressional evaluation, it is useful to identify and understand the scientific and technical issues that YMP faced, in addition to the many social and political conflicts encountered. This paper discusses two tasks of a performance assessment (PA) for geologic disposal at Yucca Mountain: (1) identification of hazards through selection of features, events, and processes (FEPs) and formation of scenario classes from these FEPs; and (2) development of models to evaluate scenario class probability in order to provide a historical perspective on the PA underlying the SAR/LA described in this special issue of *Reliability Engineering and System Safety*. Companion papers describe the site selection, disposal system characterization, and evolution of the modeling system for the YM PA [1,4–10].

For the two tasks discussed, seven PAs serve to demarcate events: (1) a deterministic evaluation of the consequences of igneous disruption in 1982 [11], and a deterministic evaluation of the consequences of the undisturbed behavior in 1984 [12], both of which supported the 1984 draft Environmental Assessment (EA) required by the *Nuclear Waste Policy Act of 1982* (NWPA) and collectively designated as PA–EA; (2) PA-91, the first stochastic PA of both undisturbed behavior and disturbed behavior from igneous and human intrusion [13]; (3) PA-93, also an analysis of undisturbed and disturbed igneous and human intrusion [14, Fig. 1-1]; (4) PA-95, an analysis of only undisturbed behavior [15]; (5) the viability assessment (PA–VA), which examined the influence of igneous and seismic events on undisturbed behavior in 1998 [16]; (6) the site recommendation (PA–SR), an analysis in 2000, which examined undisturbed behavior and igneous intrusion events [17]; and (7) PA–LA, which analyzed undisturbed, early failure, igneous intrusion, and seismic scenario classes and became the basis for SAR/LA [2].

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

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Fig. 1. View looking south down Solitario Canyon Fault with Yucca Mountain to the east and Lathrop Wells cinder cone to the west ~15 km away from repository boundary.

2. FEP selection and scenario development

2.1. Overview

Any type of analysis must decide what FEPs to model. Here features are objects, structures, or conditions of the disposal system (such as fractures in the host strata), events are natural or anthropogenic phenomena that occur over a short portion of the regulatory period (such as igneous and seismic disruption of the repository), and processes are natural long-term phenomena that occur over a significant portion of the regulatory period (such as water percolation and radionuclide transport through fractures). The event category was common to reliability of analysis in the 1960s and used in the Reactor Safety Study of 1975, which inaugurated large probabilistic risk assessments (PRA) [18]. When the PRA approach was expanded to geologic disposal in 1976 (in conjunction with two separate workshops with earth scientists) [19–21] (Fig. A1), analysis was broadened to include processes. In 1981, the International Atomic Energy Agency (IAEA) formally considered "undetected features" for evaluating the safety of geologic disposal [22]. Because a PA is used in the licensing arena to test compliance with the radiation protection standards promulgated by the Environmental Protection Agency (EPA) (either the generic 40 CFR 191 or the site-specific 40 CFR 197 [1]), the identification and selection of FEPs and formation of scenarios discussed herein is a formal task, and one aspect that sets PA apart from small-scale analysis. Along with the scenario development process, several of the more noteworthy disruptive events identified are discussed. Features and processes associated with the normal evolution of the disposal system are discussed in companion papers on YM models [6–10].

2.1.1. Regulatory criteria for FEP and scenario screening

EPA (in 40 CFR 191 and 40 CFR 197) and NRC (in 10 CFR 63 and the LA review plan) established the general universe of regulatory interest by identifying three criteria to exclude FEPs or scenario classes from the disposal system model [2, vol. 1, Fig. 2.2-1; 23, Fig. 1; 24, Fig. 2] (Fig. 2). One criterion was exclusion of FEPs or scenario classes based on regulatory fiat (e.g., guidance excluding changes in society or technology for inadvertent human intrusion [25, Section 197.15].

A second criterion was exclusion of FEPs or scenario classes based on low probability [25, Section 197.36], via (a) the rationale that a FEP or scenario class was not credible based on site, waste, or repository characteristics (e.g., lack of credible occurrence of tsunami event in the interior of North American continent), or (b) a quantitative demonstration that the probability of occurrence of a FEP or scenario class was less than 10^{-8} in one year (e.g., probability of massive meteor strike $\wp\{\mathcal{A}_{meteor}\}$, based on meteor frequencies observed in the past, is $<10^{-8}$ in any year). Prior to 2008, EPA stated the screening probability as 10^{-4} over 10^4 year; in the 2008 amendments, EPA stated it as an annual probability of 10^{-8} (i.e., "those that are estimated to have less than one chance in 100,000,000 per year of occurring" [27, Section 63.342(a)]). The former method emphasized that a FEP probability was estimated over a 10^4 period. The current method emphasizes that the underlying frequency for screening is constant; hence, the probability over 10^4 year is 10^{-4} and over 10^6 year is 10^{-2}.[1]

A third criterion was exclusion of FEPs or scenario classes based on low consequence to the time or magnitude of expected radiological exposure dose ($\overline{D}(t)$) (or cumulative radionuclide releases $\overline{R}$ prior to 2001) (i.e., "…if the expected results of the performance assessments would not be changed significantly in the initial 10,000 year period after disposal." [25, Section 197.36; 27, Section 63.342(a); 28, Section 2.2.1.2.1.3]. This criterion can be met in several ways, for example, (a) a reasoned rationale that inclusion of a FEP would not influence timing or magnitude of dose, (e.g., volcanic eruption far from repository); (b) directly calculating an expected dose from the FEP (i.e., the calculated dose from criticality) and showing that the dose is sufficiently small such that the omission of the FEP does not significantly change the magnitude and time of the resulting radiological total expected dose, or (c) calculating a measure that is indirectly related to dose of the FEP (e.g., a possible future igneous dike feature placed in the travel pathway of radionuclides directs the transport pathway from potential receptors).

A subtle question is whether the basis of the low consequence rationale should use calculations completely separate from the PA analysis and demonstrate exclusion of, for example, the criticality FEP prior to the current iteration of the PA or whether a less straight forward approach is equally valid whereby one makes an hypothesis that a FEP can be screened, conducts the PA, and then verifies that the assumption of exclusion is correct by using specifics of the PA results (e.g., concentrations of fissile material). The advantage of using consequence calculations completely separate from the PA analysis is that the rationale for excluding a FEP may be less ephemeral since they are not tied to a particular PA analysis. Furthermore, this avoids the question of whether the PA analysis is conducted at the proper scale to screen a particular FEP. Hence, a consequence rationale was generally developed separate from the PA for YMP. However, as a counter argument, a consequence rationale to exclude a FEP or scenario classes is always based on the significance of, for example, the estimates of

[1] A subtle difference is that some events, such as early waste container failure, might be treated as independent of time and, thus, would be excluded from the PA using a probability of 10^{-4} over 10^4 year, but would be included in the PA using a probability of 10^{-8} over one year unless the dependence on time was introduced.

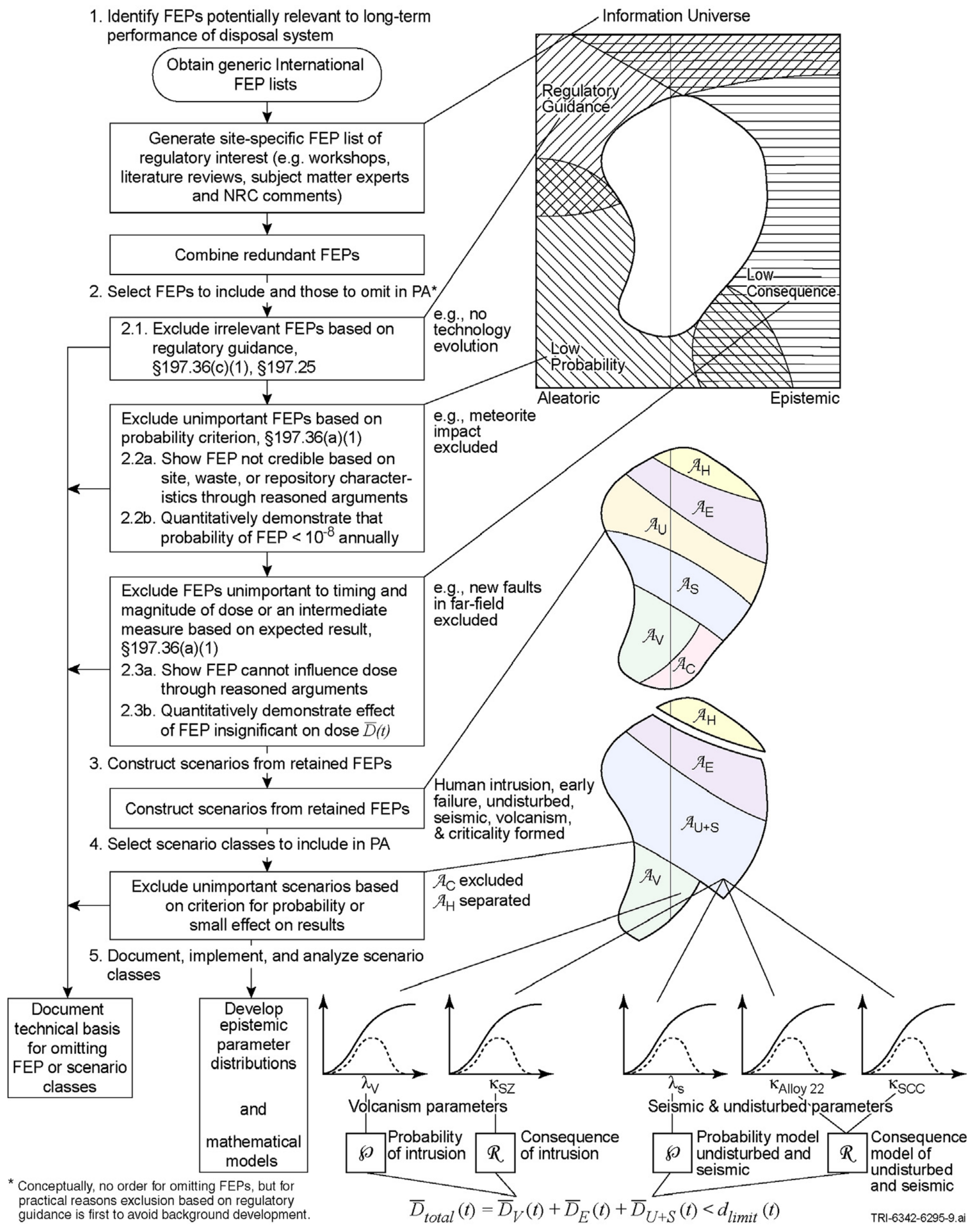

Fig. 2. Steps and associated activities of screening features, events, and processes (FEPs) and developing scenario classes [2, Fig. 2.2-1; 23, Fig. 1; 24, Fig. 2; 26, Figs. 3.1-1 and 3.1-2].

doses for criticality ($\overline{D}_C(t)$) relative to the total dose $\overline{D}_{total}(t)$ and, thus, any consequence screening rational must to some extent recognize the current PA estimate of $\overline{D}_{total}(t)$ if the estimates of $\overline{D}_C(t)$ are anything but trivially small. Because this relative comparison is an important aspect of FEP screening, it is not unexpected that a phenomenon that was screened out in earlier PA iterations, would be screened in for later PA iterations (e.g., seismic events).

2.1.2. Mechanics of FEP and scenario development

The approach to constructing scenarios and scenario classes consist of four basic steps [2, Section 2.2; 23; 24; 29; 30] (Fig. 2)[2]: (1) identify the universe of FEPs potentially relevant to long-term performance of the disposal system; (2) select FEPs to include and those to omit in PA (i.e., screen FEPs); (3) construct scenario classes from retained FEPs; and (4) select scenario classes to include in PA (i.e., screen scenarios). The four steps were informally followed for PA-84 through PA–VA. For PA–SR, the NRC/SNL (Sandia National Laboratories) FEP methodology was formally implemented to document reasoning for excluding FEPs [24,29]. The screening rationale was further refined for PA–LA [30–32]. Each pass through the steps rendered inclusion and exclusion of slightly different FEPs and scenario classes for the PAs, as described below.

In addition for PA–SR and especially PA–LA, the propagation of uncertainty was more formal in that two classes of uncertain parameters were identified in the calculation as discussed in this special issue [6, Fig. A1; 33, Appendix A; 34]: aleatoric and epistemic. Aleatoric uncertainty represents future aspects of the disposal system that have a random character, whose uncertainty

[2] In the Glossary for the review plan for the YM repository [28], NRC defines a scenario as “a well-defined, connected sequence of FEPs that can be thought of as an outline of a possible future condition…” (i.e., a “future”). NRC defines scenario class as “a set of related scenarios sharing sufficient similarities that they can be aggregated for the purpose of screening analysis…”.

is deemed irreducible by further site characterization. Epistemic uncertainty represents uncertainty about aspects of the disposal system that are imprecisely known, but in principle could be rendered more precise by further observation or experiment.

The strategy for propagating uncertainty through the PA analysis differed for these two types of uncertainty. For the purposes of this discussion (although overly simplistic), the primary strategy for propagating epistemic uncertainty in the PA iterations (except PA–EA) was to use alternative conceptual consequence models or use probability density functions (PDF) to represent the uncertainty of the value for parameters of the mathematical consequence models (and occasionally mathematical probability models) (e.g., frequency of igneous activity for the probability model in Section 3.1). The primary strategy for propagating aleatoric uncertainty in PA iterations (except PA–EA, PA-95, and aspects of PA–VA) was by defining scenario classes whose probability of occurrence were expressed with mathematical probability models (e.g., igneous intrusion scenario class). In addition for PA–SR and PA–LA, the aleatoric parameters of the scenario class were explicitly identified (e.g., time and number of occurrences for igneous intrusion) and dealt with separately from the epistemic parameters [6, Fig. A1].

Although other theoretical divisions of the class of uncertain parameters are possible, this particular taxonomy was useful in understanding the source of uncertainty in the results, in indicating how uncertainties might be better characterized (or possibly reduced) by the collection of more data, and in explaining the structure of the calculation for PA–SR and PA–LA [35]. Further distinction between the two classes of uncertain parameters is discussed elsewhere in this special issue.

The four basic steps of scenario development and the distinction between aleatoric and epistemic uncertain parameters can be visualized using the parameter domain of the conceptual consequence and probability models of the disposal system. The parameter domain is first culled to the domain of regulatory interest, and then divided and grouped into specific scenario classes for probability and consequence modeling (Fig. 2).

2.2. Hazards and scenario classes for PA–EA

2.2.1. Evaluation of volcanic consequences in 1982

Although advantages of geological disposal of radioactive waste are many, a PA analysis tends to focus on potential disadvantages of a site through identification of FEPs that in combination might cause some radioactive release. One of the issues identified during the earliest stage of the Yucca Mountain site investigations was the presence of volcanic cones and intrusion dikes in alluvial basins surrounding Yucca Mountain. Data on the age, number and location of potentially buried igneous intrusions was important in building volcanic framework models that provided the data to conduct a probabilistic volcanic hazard analysis (PVHA). Early on, the US Geological Survey (USGS) found that the silicic volcanic eruptions at Timber Mountain Caldera Complex north of Yucca Mountain, which formed the tuff deposits of Yucca Mountain between 16 and 9.5 Ma had ended in the region and were not a potential hazard [14, Table 2.1; 36; 37] (Fig. A1).

Furthermore, the igneous history of Crater Flat (based on volcanic/hydrologic test hole, VH-1, drilled in 1981) indicated that basaltic volcanism was declining in volume [38; 39, Fig. 1; 40, Fig. 1b] (Fig. 3). However, basaltic volcanism, although rare and diminishing, could not be dismissed because of the presence of 7 Quaternary (< 1.6 Ma) volcanic cinder cones located between 8 and 47 km from the outer boundary of the repository. The consequence of a volcanic eruption and ash deposition was deterministically analyzed in 1982 [41,42], as described in a companion paper [6].

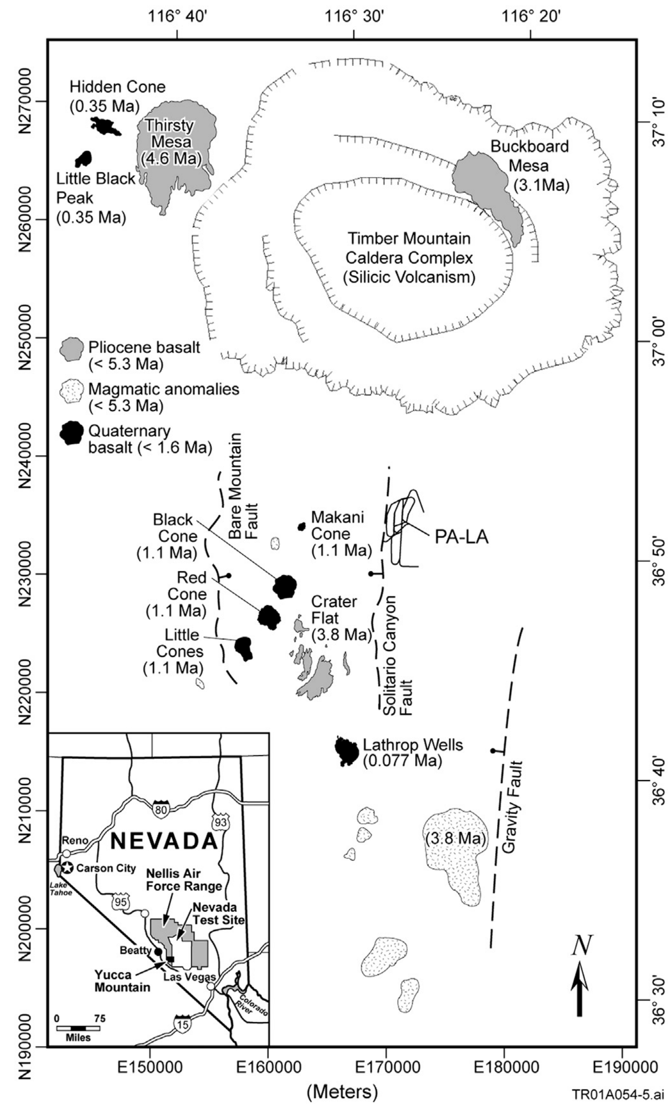

Fig. 3. Location of repository relative to Quaternary and Pliocene igneous activity. Average age of Quaternary igneous activity determined by $^{40}Ar/^{39}Ar$ dating [39, Fig. 1; 40, Fig. 1b; 44].

Yet, basaltic volcanism in any of the existing Quaternary cinder cones would not disrupt the repository; only a new dike extending to the site from an igneous center outside the zone of the current cinder cones could disrupt the repository. The initial estimate of the probability of a new cinder cone forming at a location that could disrupt the repository, was just above the threshold of screening the event into the PA. As suggested in Section 3, much effort in advancing the science underlying this estimate would be undertaken by YMP.

2.2.2. Scenario sequence trees for PA–EA

Screening of processes must usually be coupled with features in a specific location before a screening decision can be made. Because the feature location is unique to the site, the FEP list becomes somewhat specific to the site. The need to couple features and processes was one reason scenario sequences trees were initially formed when examining FEPs in early PAs. Sequence trees that included physical processes and features in addition to basic events were developed in 1981 for a repository in various media at the NTS to promote a qualitative understanding of the issues [11,45]. In 1983, sequence trees specific to a repository sited at Yucca Mountain were constructed [46]. For the deterministic 1984 evaluation, an undisturbed scenario class ($\mathcal{A}_U$) was studied (where the undisturbed scenario class includes expected processes such as gradual corrosion of containers and release of radionuclides to the surrounding host rock and excludes FEPs associated with disruptive events) [11; 14, Chapter 3; 20; 23; 29–32; 45–55].[3]

2.3. Hazards and scenario classes for PA-91, PA-93, and PA-95

2.3.1. Water table rise

USGS identification of nonwelded glass shards in the unsaturated zone (UZ) of well G-4 near the repository [4, Fig. 1] suggested that the water table had never risen to the base of the Topopah Spring Welded (TSw) tuff unit hosting the repository ~60 m above the current water table. Furthermore, USGS simulations of water table rise in 1985 had suggested a maximum water table rise of 130 m in response to doubling of precipitation (e.g., glacial period) [56], which is similar to the elevation of ancient springs in Crater Flat (between 80 and 115 m above the current water table) [57]. However, a dramatic scenario was hypothesized in 1988 by a DOE staff geologist, J.S. Szymanski, who claimed that large veins of calcite in trenches excavated over faults near Yucca Mountain by the USGS in the early 1980s (in particular, Trench 14) [4, Fig. 4] were not caused by meteoric water seeping from the surface, but by groundwater rising hundreds of meters above the water table from earthquakes through "seismic pumping." He further speculated that in the future groundwater could be maintained at these high levels through heat convection from the repository [58]. The draft report made its way to Nevada Governor Bryan who promptly released it. The assertions resulted in an extensive article in the *New York Times* [59] (Fig. A1). Shortly thereafter, Los Alamos National Laboratory (LANL) found that the form of calcite and opal minerals in fractures and faults at Yucca were not typical of deposits from inundation by upwelling water, as hypothesized by Szymanski [60]. In 1990, DOE asked the NAS to study the issue. The next year, USGS studies of U and Sr isotopes contained in the calcite near the repository horizon did not substantiate the hypothesis either [57; 61, p. 551–4; 62]. Also, to evaluate the plausibility of transient seismic pumping, SNL investigated the effects of earthquakes and dike intrusions on water table height using a two-dimensional, finite element flow model that included volumetric strain and displacement [63, p. 11; 64]. Worst-case modeling showed transient changes in water table elevation of <20 m, which was similar to changes observed after large earthquakes. By 1992, a 17-member National Academy of Sciences (NAS) panel unanimously concluded "…there is no evidence to support the assertion by Szymanski that the water table has risen periodically hundreds of meters from deep within the crust" [64].

2.3.2. Human intrusion

Studies in the early 1970s that examined risks from shallow burial of transuranic (TRU) waste and low-level radioactive waste at sites such as at Idaho National Laboratory (INL) or LANL found that human intrusion contributed a significant portion of the calculated consequences [65]. Also a large number of drill holes for mineral exploration and solution mining were discovered at the abandoned Carey salt mine in Lyons, Kansas in 1971, less than a year after it had been tentatively selected for disposal of radioactive waste [1,66]. From this experience, human intrusion was initially considered in the US unlike several international radioactive waste management programs, which began evaluating human intrusion much later or not at all [18].

In the 1985 radiation protection standards (40 CFR 191), EPA specified the human intrusion event as an inadvertent activity during exploratory drilling for minerals [1]. The drilling rate for igneous rock such as volcanic tuff (i.e., 3 boreholes/km^2 repository area/10^4 yr) was an order of magnitude less than recommended for sedimentary rock (as estimated near the Waste Isolation Pilot Plant, WIPP) since igneous rock was less likely to contain economic minerals. A consequence of including human intrusion in the 1985 EPA radiation protection standards is that the guidance may favor disposal in crystalline rock or tuff, if they are used to compare two or more sites (provided site characterization eventually shows that releases from other pathways are less than releases from human intrusion).

2.3.3. Igneous activity

The 1988 Site Characterization Plan (SCP) defined a series of studies of the igneous activity around Yucca Mountain, including analog evaluations, to attempt to refine frequency and consequences. In 1989, LANL reported on a study of the 7 Quaternary basaltic volcanic eruptive centers near the repository. The volcanic centers were similar and typically consisted of a single scoria cone surrounded by small basaltic flows that extend <1 km from the cone. All eruptions were of small volume (<1 km^3 with an average of ~0.1 km^3) with a general decline in the volume of the eruption through time [67]. The frequency of regional igneous activity (λ_{Varea}) was estimated to be ~10^{-6} events/year, based on vent counts and the estimated rate of magma production, with further discussion later in Section 3.2.2 [68].

For PA–EA, USGS and SNL had estimated the age of the Lathrop Wells cinder cone, the youngest of the 7 Quaternary volcanic eruptive centers, between 80 ka and 700 ka, based on K–Ar dating [69]. A SCP study topic was to refine this range. Based on a comparison with morphologic data and analogy with a cinder cone in California, LANL suggested in 1990 that a portion of Lathrop Wells volcanic cone was <20 ka [70]. USGS countered in 1991 that $^{40}Ar/^{39}Ar$ and K–Ar dating that suggested lava flows at Lathrop Wells were between 119 and 141 ka [71,72]. Both ages were younger than the mean 390 ka and near the minimum of the range surmised in 1982.

Because LANL surmised a potentially young age of at least a portion of Lathrop Wells, LANL also hypothesized that volcanic activity in the region was polygenetic as opposed to the usual monogenetic volcanic activity (i.e., multiple episodes at the same igneous center spread over 10^5 years versus several closely spaced events in geologic time, followed by extinction).

2.3.4. Scenario classes for PA-91

In 1988, SCP described 91 FEPs important for scenario development [29; 54, Table 3], based on work a few years before [73], which, in turn, relied on the initial studies for PA-84 [46]. For PA-91, three scenario classes were condensed from the scenario sequences: undisturbed scenario class ($\mathcal{A}_U$); disturbed, igneous intrusion ($\mathcal{A}_V$); and disturbed, inadvertent human intrusion ($\mathcal{A}_H$). The human intrusion scenario was further divided into three subclasses: direct release, indirect release through the tuff aquifer, and indirect release through a deeper carbonate aquifer ($\mathcal{A}_{Hdirect}$, $\mathcal{A}_{Hgwtuff}$, $\mathcal{A}_{Hgwcarb}$). PA-91, following the guidance of 40 CFR 191, calculated the probability of human intrusion based on exploratory drilling for minerals in crystalline rock. For igneous intrusion, only direct release to the surface from a volcanic eruption was evaluated (i.e., the volcanic eruption subclass—$\mathcal{A}_{VE}$). Furthermore, because 40 CFR 191 specified the surface above the repository as

[3] YMP documentation called it the "nominal" scenario class but this name implies it is a common scenario over the long term; however, the disruptive events included in the nominal scenario changed with each PA and by PA–LA the "nominal" scenario was not a common scenario when separated from the seismic scenario class. To track these changes in this historical perspective requires using the more descriptive undisturbed name.

part of the accessible environment, only the entrainment of several packages of waste in the dike and its movement to the surface was evaluated (i.e., under 40 CFR 191, the volcanic eruptive scenario subclass did not necessitate evaluation of eruption into the air and deposition of contaminated ash far downwind from the eruption).

2.3.5. Scenario classes for PA-93

By 1993, YMP had completed FEP sequences for igneous disruption of the repository [47], and was in the process of completing FEP sequences consisting of 136 events for the undisturbed scenario [48]. For PA-93, three scenario classes were condensed from the scenario sequences: $\mathcal{A}_U$; $\mathcal{A}_H$, and igneous disruption. Igneous disruption included both volcanic eruption (using the calculations from PA-91 for $\mathcal{A}_{VE}$) and igneous dike intrusion ($\mathcal{A}_{VI}$). The $\mathcal{A}_{VI}$ consisted of a magmatic dike intersecting the repository, breaching vertically emplaced or in-drift packages (with drift backfill in PA-93), and causing enhanced degradation of containers on either side of the dike from volatiles in the magma, followed by groundwater seepage and release (Table 1).

2.3.6. Undisturbed scenario class for PA-95

Only undisturbed performance was examined in PA-95. Both PA-91 and PA-93 had shown that the releases from $\mathcal{A}_U$ dominated the total releases and so the other two scenario classes, ($\mathcal{A}_H$ and $\mathcal{A}_V$) were omitted, at least for the time being ([15], Section ES). The minor influence of seismic events on the vertically emplaced packages in small boreholes was estimated in a separate analysis but not the influence of seismic events on large horizontally emplaced package directly within the disposal drift [74].

2.4. Hazards and scenario classes examined for PA–VA

2.4.1. Scenario classes for PA–VA

PA–VA analyzed $\mathcal{A}_U$ but also reevaluated the implications of an igneous scenario class, and for the first time, the implication of the seismic scenario class on in-drift disposal (Table 1). Based on the 1995 NAS guidance for the site-specific regulation [1,75], $\mathcal{A}_H$ was treated as a stylized modeling case of one bore hole at 10^4 year allowing a portion of waste from a package to drop to the saturated zone (SZ). The modeling case did not include evaluating a probability for the event. The three igneous disruptive scenario subclasses considered for PA–VA were [16, vol. 3 Section 4.4] (1) a volcanic eruption spewing ash and some radionuclides into the atmosphere and depositing them at the accessible environment 20 km away ($\mathcal{A}_{VE}$) (described as “direct release” scenario in PA–VA), (2) an igneous dike intrusion into repository and disrupting the waste containers (causing an “enhanced source term”) and eventually causing releases after the magma cooled via groundwater percolating through the repository ($\mathcal{A}_{VI}$), and (3) an igneous intrusion dike altering SZ permeability in a zone beyond the repository thereby increasing (or decreasing) radionuclide travel time to the accessible environment ($\mathcal{A}_{Vperm}$). The two seismic scenario subclasses considered in PA–VA were (1) rockfall on a package caused by vibratory ground motion ($\mathcal{A}_{SG}$), and (2) faulting altering SZ permeability ($\mathcal{A}_{SF}$). The same flow model was used to evaluate the influence of (a) faulting in the SZ, and (b) an igneous dike in the SZ. In both cases the permeability in a region near the repository was either increased or decreased and the influence on dose calculated (${}^{max}D_{Vdike} \approx {}^{max}D_{SF}$).

2.4.2. Igneous activity for PA–VA

In 1995, YMP began an effort to formally assess the igneous disruptive hazard using expert elicitation to assess alternative conceptual models for the spatial and temporal patterns of igneous activity in the region, including the eruptive history (i.e., number of eruptive events) [51]. Scientists from LANL, USGS, University of Nevada—Las Vegas (UNLV), and Center for Nuclear Waste Regulatory Analysis (CNWRA—sponsored by NRC) had proposed a number of alternative models that would lead to different estimates of the spatial and temporal frequency of igneous events in the region. In conjunction with the elicitation, LANL summarized past igneous hazard studies [37].

In the PVHA [52,76,77], completed in 1996, 10 experts (selected from 70 nominations) evaluated the data and alternative conceptual models of igneous activity to estimate the annual frequency of an igneous intrusive event (a dike) intersecting the repository and characterize the uncertainty in the hazard estimate. The technical issues most important to the assessing the igneous hazard were (a) the rates of igneous events in the region and (b) the future spatial distribution of igneous events [76]. Characterizing the uncertainty in the igneous rates depended, for example, on estimating the number of buried igneous features in the alluvial basins surrounding Yucca Mountain. Estimates of the future spatial distribution of igneous events involved interpretations of how igneous and structural zones influenced the location of future igneous events. (e.g., the relative significance of a igneous source zone in Crater Flat west of Yucca Mountain versus a zone that included Yucca Mountain because of past activity at Buckboard Mesa—Fig. 3).

Three years later in 1999, LANL and its collaborators used high-resolution $^{40}Ar/^{39}Ar$ measurements of the lava flows and of high-potassium sanidine crystals within lava flows to determine a reliable age for the Lathrop Wells cinder cone of 77 ± 6 ka [78]. These results led to the conclusion that volcanic activity at Lathrop Wells was monogenetic and erupted during a short period of geologic time (months to years).

2.4.3. Seismic activity for PA–VA

In the fall of 1994, YMP began an effort to formally evaluate the seismic hazard also through expert elicitation. Seismic evaluations had been made for conceptual design of the repository in the 1988 SCP and the Exploratory Studies Facility (ESF) design in 1994. However, a more extensive Probabilistic Seismic Hazard Assessment (PSHA) was required for the operational and post-closure aspects of the repository [16, vol. 3, Section 4.4.2.4; 53, Section 1.3]. For PSHA, two expert panels were convened. The first panel consisted of six teams of three experts each in seismicity, tectonics, and geology. Each team estimated the source characteristics of earthquakes (i.e., location, maximum magnitude, and recurrence) and the annual probability for fault displacements. The second panel of seven seismologists estimated vibratory ground motion from normal-faulting earthquakes around the world since few ground-motion records existed at Yucca Mountain [53,79]. The PSHA was completed in the fall of 1998.

2.4.4. Water table rise for PA–VA

The State of Nevada continued to fund several studies of Szymanski's hypothesis on water-table rise through 2006. For example in 1997, a Russian scientist, Dublyansky, argued that calcite mineral crystals in fractures in the ESF formed in a hot environment, which would indirectly support Szymanski hypothesis (unless formed shortly after deposition of the tuff ash flow) [80]. At the time of PA–VA in 1998, the Nuclear Waste Technical Review Board (NWTRB) completed a review of 11 reports submitted by Szymanski including those by Dublyansky and concluded that the reports did not make a credible case that geothermal water flooded Yucca Mountain in the past [17, p. 4–402]. To further substantide these conclusions, NWTRB suggested DOE evaluate the age of the calcite and opal deposits.

Table 1
Underlying features, events, and processes and scenario classes modeled in past performance assessments.

PA	Scenario classes and subclasses retained for modeling	Method to identify FEPs and develop scenarios	FEPs examined
PA–EA (1982 and 1984)	Igneous disruption Volcanic ash eruption ($\mathcal{A}_{VE}$) Nominal (undisturbed) ($\mathcal{A}_{U}$)	SNL sequence approach first described in 1981 [11,45] and updated in 1983 [46].	PA Analyst selection of several FEPs
PA-91	Nominal (undisturbed) ($\mathcal{A}_{U}$) Igneous disruption Dike surface flow ($\mathcal{A}_{VE}$) Human intrusion Direct ($\mathcal{A}_{Hdirct}$) Tuff aquifer ($\mathcal{A}_{Hgwtff}$) Carbonate aquifer ($\mathcal{A}_{Hgwcarb}$)	SNL sequence approach [13, Section 3.1].	PA Analyst selection of several FEPs
PA-93	Nominal Early failure added ($\mathcal{A}_{U+EF}$) Igneous disruption Dike surface flow ($\mathcal{A}_{VE}$) Dike enhances waste package (WP) failure ($\mathcal{A}_{VI}$) Human intrusion ($\mathcal{A}_{H}$)	SNL sequence approach for undisturbed [48] and igneous [14, Chapter 3; 47].	PA Analysts condense several FEP sequences
PA-95	Nominal (undisturbed) ($\mathcal{A}_{U}$)	Based on PA-93.	Based on PA-93
PA–VA (1998)	Nominal Early failure added ($\mathcal{A}_{U+EF}$) Igneous (added to undisturbed) Volcanic ash eruption ($\mathcal{A}_{U+EF+VE}$) Dike enhances WP failure ($\mathcal{A}_{U+EF+VI}$) SZ dike disruption ($\mathcal{A}_{U+EF\ +VDike}$) Seismic (added to undisturbed) Rockfall on WP ($\mathcal{A}_{U+EF\ +SG}$) SZ fault creation (same as SZ dike) Human intrusion[a] ($\mathcal{A}_{H}$) Criticality (added) ($\mathcal{A}_{U+EF+C}$)	SNL sequence approach for undisturbed [48] igneous [47], tectonics [49], criticality [50], and human intrusion[a] Expert elicitation for igneous disruption (PVHA) [51,52] and seismic disruption (PSHA) [53] used in PA–VA and thereafter. Sequences supplemented by NRC/SNL approach using NEA hierarchy and portion of 1261 NEA FEPs [101, Table 10-4].	PA Analysts condense several FEP sequences and use portion of 1261 NEA FEPs
PA–SR (2000)	Nominal Seismic clad damage added ($\mathcal{A}_{U+SGclad}$) Igneous (as increment to undisturbed) Volcanic ash eruption ($\mathcal{A}_{VE}$) Dike enhances WP failure ($\mathcal{A}_{VI}$) Human intrusion[a] ($\mathcal{A}_{H}$)	NRC/SNL approach implemented [29] (as described in 1981 [20] and adapted by WIPP [23]). Used NEA hierarchy and 1261 NEA FEPs and 151 headings [29] 91 SCP FEPs (1980s) [54, vol. 7, Section 8.3.5.13] 201 YMP FEPs (1990s) [47,48] 95 new YMP FEPs added [29,55] 8 added after NRC review	328 primary and 1368 secondary FEPs formally screened
PA–LA (2008)	Undisturbed ($\mathcal{A}_{U}$) Igneous disruption Volcanic ash eruption ($\mathcal{A}_{VE}$) Dike intrusion fails all WP ($\mathcal{A}_{VI}$) Seismic disruption Ground motion damage to WP ($\mathcal{A}_{SG}$) Ground motion damage to DS ($\mathcal{A}_{SD}$) Fault displace damage to WP ($\mathcal{A}_{SF}$) Early EBS failure Early DS failure ($\mathcal{A}_{ED}$) Early WP failure ($\mathcal{A}_{EP}$) Human intrusion[a] ($\mathcal{A}_{H}$)	NRC/SNL approach implemented [30–32] with reclassification via organizing matrix and further review	374 FEPs formally screened (222 excluded; 152 retained)

[a] For PA–VA and thereafter, the probability of the human intrusion scenario class was not evaluated; only consequences of a stylized modeling case as specified by regulation were modeled [1].

2.4.5. Criticality scenario class for PA–VA

The criticality scenario class was considered early in geologic disposal (e.g., it was evaluated for WIPP in 1974 [43,66], listed for consideration by IAEA since 1981 [22], and considered in the YMP container design in 1983 [81]).[4] But events in the 1990s, prompted YMP to make a concerted effort to develop a formal methodology for screening criticality. After the Congressional decision in 1979 to dispose only defense TRU waste at WIPP [82] and the Congressional decision in the NWPA of 1982 [83] to include all DSNF in a commercial repository, disposal of DSNF was anticipated at Yucca Mountain but in the form of HLW. However, in 1992, the United States stopped reprocessing DSNF. This policy decision created a need for direct disposal of DSNF, and exploratory study of DSNF disposal in 1993 identified the criticality event for further study [84, Tables 7-2 and 7-3]. Also in 1993, DOE held discussions on criticality with NRC. Then, in late 1994, Bowman and Venneri at LANL claimed an atomic explosion (i.e., 630 GJ energy release for 108 kg ^{239}Pu) via autocatalytic behavior (positive feedback) from either an initially under-moderated and over-moderated Pu spherical configuration was possible in tuff [85]. Subsequent press articles in 1995 drew public attention to the criticality issue [86; 87; 88, p. 282] (Fig. A1). In 1995, DOE and NRC agreed to interact via a topical report on the criticality methodology (i.e., procedure to be used to evaluate the potential and consequences of the criticality FEP), prior to submitting the license application for construction authorization [91]. The first DOE/NRC Technical Exchange on criticality was held later that year in October.

In 1997, YMP conducted a workshop to discuss a methodology to evaluate the criticality scenario class [89], developed a Master Scenario List of sequences potentially leading to criticality after a container was breached [50], and continued several exploratory calculations [90]. The Master List included 31 sequences: 11 sequences inside the package, 9 sequences in or on the invert of the engineered barrier ("near-field"), and 11 sequences in the geologic barrier ("far-field" critical situations) [50]. The Master List was used, at least in concept, thereafter. The initial sequences were independent of waste form categories and package type, and did not include variations caused by igneous, seismic, or human intrusion disruptions.

The first version of a criticality methodology report was completed in 1998, concurrent with PA–VA, and submitted to NRC for their comments. The methodology envisioned two parts to screening the possibility of criticality [16, vol. 3, Fig. 5-5; 91, Fig. 1-1]. Part 1 was to quantitatively demonstrate the low probability of a criticality (i.e., $\overline{\wp}\{\mathcal{A}_C\} < 10^{-4}$ over 10^4 year). If low probability of the event could not be conclusively demonstrated then Part 2 was to demonstrate the low consequences and, thus, low risk of a criticality. The methodology envisioned dividing the waste into several broad categories and evaluating the potential for criticality for each waste category for each of the 31 sequences of the Master List.

2.4.6. Criticality probability for PA–VA

In response to the Bowman and Venneri claims, the possibility of assembling fissile material into the specific critical configuration (especially the under-moderated situation) and large 108-kg mass of Pu (factor of 2.5 larger mass than in typical CSNF container) was refuted qualitatively by LANL and others based on site characteristics [85,92]. SNL argued that the probability of criticality was $< \sim 10^{-2}$ [93]. The possibility of an explosive consequence was refuted by LANL, who argued that the energy release would be $<$ 42 GJ for 108 kg ^{239}Pu, not 630 GJ [94].

In 1996, a large team at the University of California, Berkeley also concluded probability of assembling enough ^{239}Pu material into a critical concentration in fractures prior to its decay to ^{235}U was very low, based on geologic behavior and simple transport modeling. However as an exercise to bound consequences, they did hypothesize an over-moderated, heterogeneous Pu configuration in a tuff fracture system that through homogenization of the configuration would release substantial energy through autocatalytic behavior (1300 GJ energy release for 254 kg ^{239}Pu in a 2 m sphere with alternating layers of tuff and Pu) [95].

Although not published in the open literature, YMP conducted scoping calculations on several configurations with the potential to go critical in 1996, 1997, and 1998. The calculations were summarized in PA–VA documentation [16, vol. 3]. The simulation of the heterogeneous details of several configurations of fuel inside a container showed that the most critical configuration was when the container was flooded ("bathtub"), internal supports had collapsed, and fuel assemblies were intact and closely packed [96]. Thereafter, this became the worst case or design basis configuration for criticality calculations (not criticality in the fractured tuff of the UZ as hypothesized by Bowman and Venneri).

2.5. NRC work

2.5.1. FEP screening and scenario development for NRC

At the same time DOE was examining the general process of analyzing FEPs with earth scientists in 1976 [21,66] (Fig. A1), NRC funded a group within SNL (separate from YMP or WIPP) to pioneer work on a methodology for assessing the performance of geologic disposal of CSNF and HLW [19]. Part of this development work was the generation of a generic list of 29 FEPs and a procedure to screen FEPs in 1980 [20,97].

At first, NRC requested that the SNL group pursue a scenario development process similar to the Reactor Safety Study [98]. However, the SNL group found that natural processes and a highly coupled geologic disposal system were not readily amenable to event trees since the boundaries in a coupled system and boundaries between process states were more arbitrary than for a fully engineered system. Thus, the number of scenario sequences could become quite large. Hence in 1981, SNL proposed to NRC a procedure that first screened general categories of FEPs (usually initiating event classes such as igneous intrusion $\mathcal{A}_V$ or a seismic events $\mathcal{A}_S$) and then formed combinations of these FEPs with and without its occurrence (e.g., four combinations with $\mathcal{A}_V$ and without $\mathcal{A}_V^-$ and with $\mathcal{A}_S$ and without $\mathcal{A}_S^-$ or $\mathcal{A}_V \mathcal{A}_S$, $\mathcal{A}_V \mathcal{A}_S^-$, $\mathcal{A}_V^- \mathcal{A}_S$, $\mathcal{A}_V^- \mathcal{A}_S^-$) and where the combinations could be readily shown by means of a Latin Square logic diagram to show completeness [20]. Although still possible, the time and order of occurrence of the FEP categories were not typically considered in the formation of the broad scenario classes. Fewer scenario classes were formed and these broad classes appeared more useful for guiding modeling. During modeling, the time and order of occurrence of FEP categories could be considered in developing scenario subclasses (herein called computational scenarios). As a demonstration of the methodology, several FEPs and scenarios from these FEPs were developed that were unique for a repository in the UZ for Yucca Mountain [99]. The NRC/SNL methodology was adapted for use at the WIPP in 1990 [23,66,100].

[4] When we speak of the probability of a criticality, we are usually talking about the probability of *assembling* a critical configuration of fissile mass. The assembly can only occur if several initiating events and several processes occur, where processes are especially important in the far-field. Because both events and process may be important, we describe it more generally as a criticality *scenario class* herein.

2.6. Hazards and scenario classes examined for PA–SR

Because of concerns about scenario development raised by NRC when commenting on the 1988 SCP [19, Section 2.1.5] and because of the success in applying the NRC/SNL methodology at WIPP, YMP adopted the NRC/SNL methodology during the latter phase of PA–VA [101, Section 10.2], but the methodology could not be fully implemented until PA–SR [24,29]. Because the formality of PA–SR greatly increased, the implementation of a new methodology required a major effort to complete for the first time.

2.6.1. FEP development for PA–SR

As more thoroughly described elsewhere [29,30], FEP development for PA–SR started with 1261 FEPs available in a draft version of a database under construction by the Nuclear Energy Agency (NEA) of Organisation for Economic Co-operation and Development (OECD). Five international radioactive waste disposal programs and the NEA had contributed to the list (Canada—281, Sweden—264, United Kingdom—79, Switzerland—245, and WIPP—246, NEA—146).

The list was supplemented by 91 FEPs from SCP [54, vol. 7, Section 8.3.5.13], and 201 FEPs from other YMP reports more specific to disposal of thermally hot SNF in unsaturated, fracture tuff [47,48]. In a series of workshops, YMP investigators and analysts reviewed the initial list of 1553 FEPs and identified 82 additional FEPs (e.g., 40 were identified that were more specific to DSNF [55] and 18 FEPs were identified that were specific to criticality). When subject matter experts began discussing these FEPs in reports, 13 additional FEPs were identified. Finally, meetings and reviews by NRC identified 8 additional FEPs.

For PA–SR, the list of FEPs was grouped according to the hierarchical and numbering scheme of the draft NEA database; however, a criticality heading and an assessment issues category were added for a total of 152 hierarchical headings. The list of 1656 FEPs and 152 hierarchical headings were grouped, combined, and or split to avoid redundancies (e.g., the original 18 criticality FEPs were split into 22 FEPs). To maintain traceability to the source of FEPS, similar FEPs were not removed but rather combined and categorized as either primary, and thereby addressed in the screening process, or secondary, and thus captured by a primary FEP description. Also, 40 of the hierarchical headings were converted to primary FEPs. At the conclusion of the process, the database contained 112 hierarchical headings, 328 primary FEPs for screening, and 1368 related secondary FEPs (Table 1) [29].

For the PA–SR, the rationale to either include or exclude the 328 FEPs in the PA–SR model were developed in 11 reports that corresponded to general modeling areas (e.g., the waste form degradation model dealt with 87 primary FEPs with 256 associated secondary FEPs [102]).

Five scenario classes were formed from those FEPs remaining: $\mathcal{A}_{U+SGclad}$, $\mathcal{A}_{VI}$, $\mathcal{A}_{VE}$, $\mathcal{A}_{H}$, and criticality ($\mathcal{A}_{C}$). The first three classes were retained in the PA–SR, where more details on probability modeling for igneous disruption is discussed in Section 3.5.2. Similar to PA–VA and in accordance with draft EPA and NRC regulations 40 CFR 197 and 10 CFR 63 proposed in 1999 [1], the human intrusion scenario class was treated as a special modeling case and not included with other disruptive scenario classes in evaluating expected dose over time for PA–SR and PA–LA. The nominal scenario class ($\mathcal{A}_{U+SGclad}$) included damage of cladding from a seismic event, but not waste container damage from ground motion/rockfall and fault displacement. Based on regulatory guidance for PA–SR, FEP and scenario class screening focused on the first 10^4 year. Container corrosion was so minor in the first 10^4 year that ground motion was not sufficient to damage an intact container and so seismic damage was screened out based on use of the median hazard curve developed in PSHA. Also, preliminary analysis showed that seismic ground motion would not cause separation or failure of the drip shields in the first 10^4 year because the typical small rock sizes falling during the seismic event pinned the drip shield in place. Furthermore from preliminary analysis, the drip shields could withstand large rockfall sizes and protect the container in the first 10^4 year (normal corrosion failure did not occur until at least 2×10^4 year [103, Figs. 4–184 and 4–183]. Finally, damage from fault displacement was not included based on administrative controls (i.e., it was argued that the requirement to keep containers away from known faults and the low probability of forming new faults with large displacement in intact rock sufficiently reduced the probability of package damage from fault displacement (PSHA estimated only 1 mm displacement at an annual exceedance probability of 10^{-8}).

2.6.2. Water table rise for PA–SR

In response to the 1998 NWTRB request, USGS and UNLV scientists (the latter funded by a DOE cooperative agreement) dated the fluid inclusions and opal and calcite secondary mineral deposits in cavities of the tuff at Yucca Mountain. Q In May 2001, their results were presented to NWTRB and at the IHLRWM Conference (e.g., [104–106] (Fig. A1). USGS noted only 1–40% of cavities and fractures in the UZ at Yucca Mountain had calcite deposits and the calcite deposition was on the floors of cavities and footwalls of fractures whereas deposition in a saturated environment would be on all surfaces and at a higher percentage [17, p. 4–402; 104]. UNLV noted that although some of the secondary minerals had deposited as hot fluids, the deposition had occurred 5 Ma and little had occurred since that time. Also, the secondary mineral deposits were not characteristic of hydrothermal deposition. UNLV and USGS concluded that the hypothesis of hydrothermally upwelling was not valid. Thereafter, YMP and NWTRB considered the issue of seismic pumping resolved [88, p. 304].

2.6.3. Criticality scenario class formation and screening for PA–SR

As noted earlier, the 31 sequences of the Master List were mapped to 22 primary subclasses (although still called FEPs) of the criticality scenario class for PA–SR. Under the 22 primary FEPs were an additional 54 secondary FEPs [29]. Of the 22 primary FEPs, 21 were associated with three locations: 8 inside the container (with 39 secondary), 5 in or on the invert of the engineered barrier (with 10 secondary), and 8 in the geologic barrier (with 5 secondary). One additional FEP dealt with criticality initiated by igneous intrusion into the repository [107].

Only the subclass initiated by igneous intrusion was formally evaluated for PA–SR because container breach by other mechanisms did not occur in the first 10^4 years, as noted in the previous section. SNL argued that igneous activity would not produce conditions conducive to criticality for DSNF [39,108,109]. Also, preliminary criticality calculations of CSNF pellets embedded in basalt did not show a concern [110].

An important aspect of the CSNF analysis was to take credit for the consumption of fissile material and the presence of both actinides and fission products that reduced the reactivity (i.e., burn-up credit, as had been adopted for the package design in 1994 [111]). For PA–SR, an example calculation showed that a bounding, design-basis container loading was subcritical for 93% of existing PWR assemblies [112]. The other 7% of CSNF would require additional neutron absorbers as plates or rods in the container or loading fewer assemblies per container (e.g., 12 assemblies from pressurized water reactors, PWRs [4, Table 4]. The methodology for including burn-up credit was greatly refined for PA–LA [113].

2.7. Hazards and scenario classes examined for PA–LA

2.7.1. Reclassification of FEPs for PA–LA

An NRC review of the FEP list and their screening for the PA–SR identified 20 general comments that included requests for clarifying the screening rationale, improving the technical basis of the screening rationale, adding FEPS, clarifying the FEP description, providing an auditable trail that the FEP list was comprehensive, more description of the FEP process including how the initial lists were generated, how the lists would be improved over time, how consistency in level of detail would be improved, how to improve documentation, and plans for configuration management of the FEP list [30].

One approach adopted in response to NRC comments was to improve the classification scheme for the 328 FEPs used for PA–SR and, thereby, make auditing easier and demonstrate comprehensiveness [30]. Although the intent of the hierarchical classification scheme used in PA–SR was to maintain traceability to the initial NEA database of FEPs, this categorization did not coincide with the pertinent events and process and their association with features of the YM disposal system. Hence, a new classification scheme was developed that categorized the processes into eight areas (hydrologic, chemical, mechanical, thermal, microbiological, radiological, characteristics, and transport) and events into four areas (igneous, seismic, human intrusion, and criticality). Features were categorized according to the engineered system with ten areas (drift, ground support, backfill, seals, drip shield, waste container, cladding, waste form, pallet, invert), and natural system with four areas (disturbed zone, UZ, SZ, and biosphere). The remaining area was the design of the disposal system. After reclassification and adjustments to use a consistent level of detail (such as splitting FEPs to eliminate partial inclusion and exclusion), the number of FEPs increased slightly to 359 in January 2003.

2.7.2. FEPs review and screening for PA–LA

Between January 2003 and August 2004, the 359 FEPs were then augmented with new FEPs identified in other international programs and internal and external reviews in three different cycles [30]. Potential FEPs were identified but usually found to be already included. At the conclusion of three review cycles, 375 FEPs were identified and the screening rationale developed in ten reports, which corresponded to most of the major modeling components of PA–LA: (1) waste form (e.g., [114]), (2) CSNF cladding, (3) drip shield and waste container, (4) engineered barrier system (EBS), (5) UZ flow and transport, (6) SZ flow and transport, (7) biosphere, (8) disruptive FEPs (e.g., [115]), (9) criticality (e.g., [116]), and (10) system level modeling.

In 2005, YMP continued to update the FEP screening rationale [30]. Although the regulatory period was extended to 10^6 year, EPA stated in the redraft of 10 CFR 197 in 2005 and promulgated in 2008 that the PA was to use FEPs only found important in first 10^4 year except for four FEP categories: general corrosion process, seismic events, igneous events, and climate change events. Furthermore, the analysis on seismic and igneous effects was to be limited to their influence on packages and the analysis on climate change was to be limited to its influence on increased water percolation through the repository horizon [25]. This EPA guidance confirmed the general process that YMP had been following.

In a major effort during the fall of 2007 and winter of 2008, the FEP descriptions and screening rationale was updated to coincide with the design of the 2008 PA–LA (e.g., addition of the transportation, aging, and disposal (TAD) canister for CSNF) [31,32]. Also during this time, the classification scheme for FEPs was changed somewhat. Processes were divided into 7 areas rather than 8 areas used for PA–SR and coupling explicitly included (hydrologic & thermal-hydrologic, chemical & thermal–chemical, mechanical & thermal–mechanical, microbiological, radiological, characteristics, and transport). Features were categorized according to the barriers of the disposal system and corresponding components; hence, the engineered system was divided into 8 areas rather than 10 of PA–SR (disposal drift, backfill/seals, drip shield, waste container, cladding, waste form, pallet, invert) and the natural system was divided into 5 areas rather than 4 (topography/surface soils, upper UZ, UZ below repository, SZ, and biosphere) [31,32].

The FEP list was decreased by one to 374 because a FEP that dealt with magma breaching a bulkhead was no longer applicable with the decision to remove bulkheads between disposal drifts (Table 1). For PA–LA, the screening rationale was collected into one large report rather the ten FEP reports and criticality summary used in 2005 [32]. Of the 374 FEPs, 222 were excluded and 152 were retained [2, Section 2.2].

2.7.3. Scenario development for PA–LA

As in PA–SR, scenario classes were formed from the 152 FEPs retained. Six main scenario class categories were formed in the PA–LA for analysis of the first 10^4 year period: early EBS failure ($\mathcal{A}_E$), seismic disruption ($\mathcal{A}_S$), igneous disruption ($\mathcal{A}_V$), undisturbed ($\mathcal{A}_U$), human intrusion ($\mathcal{A}_H$), and criticality ($\mathcal{A}_C$). Only the first four scenario class categories were analyzed. The criticality scenario class was screened out and the human intrusion scenario class was stylized as specified by regulation [1].

As in PA–SR, the igneous scenario class was divided into two initiating classes, igneous dike intrusion ($\mathcal{A}_{VI}$) and volcanic eruption ($\mathcal{A}_{VE}$) where eruption was dependent upon intrusion. For PA–LA, the early EBS failure scenario class was divided into two event classes[5]: early drip shield failure ($\mathcal{A}_{ED}$), and early container failure ($\mathcal{A}_{EW}$). Possible phenomena that could cause one or two out of the ~11,000 containers to prematurely breach were a fabrication flaw or a stress corrosion crack in the outer closure lid.

The seismic scenario class was divided into three different initiating classes: ground motion that damages waste containers and drip shields ($\mathcal{A}_{SG}$ and $\mathcal{A}_{SD}$), and fault displacement that crimps the waste container ($\mathcal{A}_{SF}$). Ground motion would tend to bounce the packages somewhat and damage the container when striking other packages or at its contact with the pallet. Understandably, the probability of seismic ground motion damaging any one massive container was low but since all ~11,000 containers for PA–LA were potentially affected [5, Table 3], the combined probability of at least one container being damaged was much greater.

The above four scenario classes and their subdivisions were not necessarily mutually exclusive in that, for example, both an early failure event and a seismic event could occur sometime in the future at the repository. Also, not all the event classes were independent in that a seismic event accompanies igneous intrusion. Mutually exclusive sets could have been formed; however, rather than deal with numerous disjoint sets, PA–LA used the four retained scenario classes over 10^6 years and conservatively neglected the small double counting of probability and consequences that occurs because of the overlap of scenarios [2, Section 2.2.1.3.1; 118, Section, 4.7].

[5] In 2001, NRC used a new term, "event class," which was defined as "all possible specific initiating events that are caused by a common natural process (e.g., the event class for seismicity includes the range of credible earthquakes for the Yucca Mountain site)" [117, Section 63.102(j)]. It is convenient to call them event classes here in that the probability was determined solely from the initiating events of the subclasses and not from features or process in the subclass.

2.7.4. Igneous activity for PA–LA

Plans to obtain ground-based magnetic data for identifying and characterizing buried volcanoes were formulated in the mid-1980s, but the work was deferred due to funding limitations and changing programmatic priorities. Although these studies were not conducted as part of formal site characterization activities prior to the conclusion of PA–SR in 2001, a site-wide aeromagnetic survey and drilling program was begun in 2004 in response to a request for additional information from NRC in 2002 [119]. This survey and drilling program resolved remaining questions concerning the location and age of buried igneous centers in the region and provided the basis for an update of the 1996 PVHA, which was completed in 2008 [120]. Hence, analysis of the igneous hazard was one of the first and one of the last scientific studies conducted on YMP.

2.7.5. Water table rise for PA–LA

In the final promulgation of 40 CFR 197 in 2008, EPA required DOE to evaluate the effects of seismic events on water table rise, subject to requirements promulgated by NRC [25]. NRC followed the guidance of the NAS and subsequently suggested that the effects be limited to permanent changes in hydrologic properties of underlying aquifers, such as porosity, and their resulting influence on water table rise that might occur after an earthquake [27, p. 10813 and Section 63.342 (c)(1)(i)]. In response to NRC requests for additional information on the SAR/LA, YMP conducted an evaluation similar to that conducted in 1991, which showed water table rise < 20 m [63, p. 11].

2.7.6. Criticality scenario class for PA–LA

In the 2003 Revision 2 of the topical report on the criticality methodology, YMP changed the manner in which to estimate the probability of criticality [164]. Previous versions of the topical report envisioned simulating the degradation process, the same as modeled in a PA, but then focusing on the hydrologic and geologic processes necessary for assembling fissile material in containers, the EBS, or the natural barrier. The methodology then envisioned developing regression models of these processes (simplified abstractions) to demonstrate that either the configurations were subcritical or to estimate the probability of the configuration occurring through Monte Carlo sampling. However, because PA models were not available at the proper scale, the criticality team would have to develop new models.[6]

Rather than embark on this difficult approach without adequate funding, direct simulation was replaced in Revision 2 with more practical probability event trees. This event tree approach eliminated concerns of NRC related to developing abstracted models through regression analysis for criticality analysis [165, Sections 3.4 & 3.5]. A fortunate outcome was that geochemical modeling, which was greatly enhanced for PA-SR and PA-LA, could be augmented with staff previously used for criticality process modeling. The event tree methodology was implemented in 2004 [166,167]. For SAR/LA in 2008, the general result of the analysis was used to focus the screening on that aspect that had been found to dominate the probability of criticality: the probability of misloading containers with either insufficient neutron absorber or too many CSNF assemblies with insufficient burnup.

Screening the criticality class in the PA–LA was based on 16 criticality FEPs (or computational subclasses) [121]. The critical configurations in the 16 criticality FEPs derive from four environment features *f* (intact supports and fuel inside breached container, degraded supports and/or fuel inside breached container, crushed tuff invert of EBS, and geologic barriers) and four initiating events *e* (early container failure, seismic, igneous, and rockfall). All but the rockfall event correspond to the disruptive scenario classes of the PA–LA. Rockfall caused by seismicity was part of the seismic initiating event. Hence the rockfall initiating event class consisted of rockfall solely caused from thermal and mechanical stress. This type of rockfall was minor and, thus, excluded as an initiating event.

Generally, one may show that either $\overline{D}_j(t)$ or $\overline{\wp}\{\mathcal{A}_j\}$ is sufficiently small to eliminate a scenario class *j* from consideration in the PA (Fig. 2). YMP screened criticality by showing that the probability of criticality outside the container was extremely low [122],[7] and the probability inside a container $\overline{\wp}\{\mathcal{A}_C\} < 10^{-4}$ in 10^4 year for PA–LA [121]. For the PA–LA, the total probability of criticality was expressed as the sum of the probability of criticality for each initiating event *e* and environment feature *f*, and conservatively neglected the double counting from the nonexclusive nature of *e* and *f* since most terms were negligible [2, Section 2.2.1.4.1; 121].

3. Probability modeling in past performance assessments

3.1. Probability modeling of retained disruptive scenario classes

Once a series of FEPs has been selected and scenario classes formed, the PA must evaluate (1) the aleatoric probability of the scenario classes $\wp\{\mathcal{A}_j(\mathbf{e}^p)\}$, and (2) the epistemic probabilities for parameters of the underlying probability models ($\mathbf{e}^p$) and the epistemic probabilities for parameters ($\mathbf{e}^e$) of the exposure consequence models $\mathcal{R}_j(t,\mathbf{x};\ \mathbf{e}^e)$. Only $\wp\{\mathcal{A}_j(\mathbf{e}^p)\}$ and the underlying parameter distribution for $\mathbf{e}^p = \{\lambda_V\}$ are discussed here. The epistemic parameter distributions for the exposure consequence models ($g(\mathbf{e}^e)$) are beyond the scope of this paper.

The primary requirement of a scenario class, besides being of particular interest to a regulator or an analyst, is the ability to calculate the probability of the scenario class, $\wp\{\mathcal{A}_j(\mathbf{e}^p)\}$. For YMP (as for WIPP), models to evaluate the probability of disruptive scenarios (human intrusion, igneous intrusion, and seismic events) (e.g., $\wp\{\mathcal{A}_V(\mathbf{e}^p)\}$) have been based on homogeneous Poisson and binomial processes as presented below.

3.2. Probability modeling for PA–EA

3.2.1. Igneous scenario class probability model

Two probability models are necessary for the igneous disruptive scenario class: a probability model for the igneous intrusion scenario subclass and a probability model for the volcanic eruptive subclass. For PA–EA, only the volcanic eruptive subclass was evaluated; yet in YMP PAs, the probability model for the volcanic eruptive subclass is understandably conditional on the igneous intrusion scenario subclass and so both are discussed here. In general, the probability model for the igneous eruptive scenario subclass was evaluated as

$$\wp\{\mathcal{A}_{VE}(\mathbf{e}^p)\} = \wp\{\mathcal{A}_V(\mathbf{e}^p)\} \bullet \wp\{E_{WPrelease}|E_{WPhit}\} \bullet \wp\{E_{WPhit}|E_{Vvent}\} \bullet \wp\{E_{Vvent}|\mathcal{A}_V\} \quad (1)$$

where $\wp\{\mathcal{A}_V(\mathbf{e}^p)\}$ is the probability of the igneous intrusion scenario subclass, which is the probability of one or more igneous intrusions; $\wp\{E_{WPrelease}|E_{WPhit}\}$ is the probability of a waste release if a package is intersected, $\wp\{E_{WPhit}|E_{Vvent}\}$ is the probability of an

[6] WIPP analysts did develop these models, but because process models were included directly in the WIPP PA, the approach involved the much easier step of developing the models at a different scale rather than developing process models, developing abstractions of these models, and then linking these abstracted models into a stochastic simulation [43,168].

[7] Although WIPP emphasized the probability rationale when excluding the criticality scenario class, WIPP also included low consequence arguments to show the overall risk was very low [43,168].

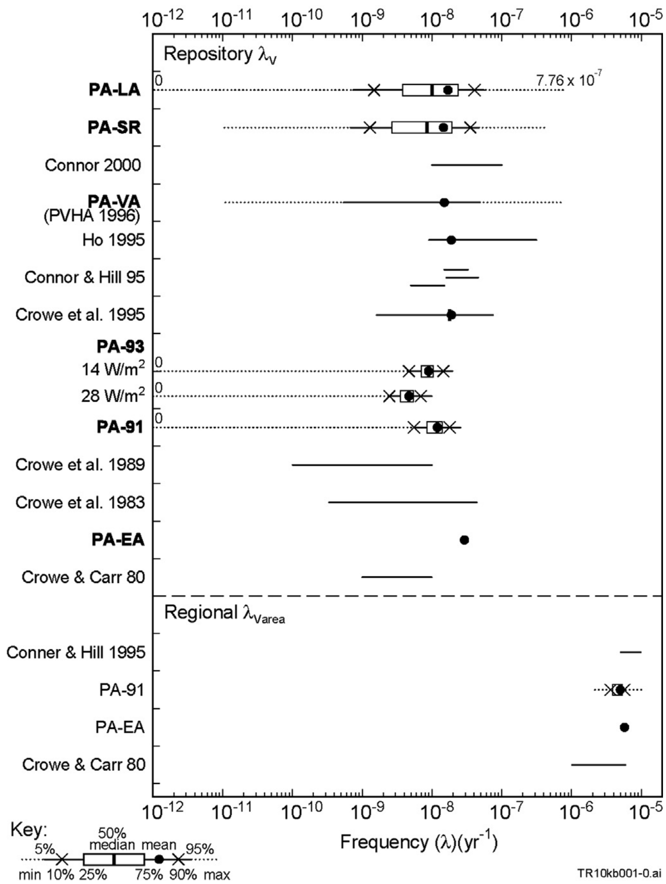

Fig. 4. Estimates of mean frequency of igneous disruption of YM repository have remained fairly constant [13; 14; 37; 40–42; 77, Tables 6-5 & 6-8; 118, Section 6.5.1.1; 124–126; 127, Table 2.2-18].

eruptive vent intersecting a waste package given that a vent is within the repository area; and $\wp\{E_{Vvent}|\mathcal{A}_V\}$ is the probability of an eruptive vent along the intrusion dike that is within the repository area given that a dike has intruded into the repository. For PA–EA, no distinction was made between a dike intrusion and eruptive conduits or vents along a dike and so no estimates were made of $\wp\{E_{WPrelease}|E_{WPhit}\}$, $\wp\{E_{Vvent}|\mathcal{A}_V\}$, and $\wp\{E_{WPhit}|E_{Vvent}\}$.

The probability of an igneous event in the YM repository $\wp\{\mathcal{A}_V(\mathbf{e}^p)\}$ was expressed by the Poisson distribution [13,14]

$$\wp\{\mathcal{A}_{VE}(\mathbf{e}_V^p, \tau^{reg})\} = \frac{(\lambda_V\,\tau^{reg})^{n_V}}{n_V!} e^{-\lambda_V\,\tau^{reg}}, \quad n_V = 0,\ 1, \dots \tag{2}$$

where n_V is the number of igneous intrusion dikes, disrupting the repository in the period of interest (τ^{reg}) (either the 10^4-year regulatory period prior to PA–VA or the 10^6-year regulatory period thereafter) and λ_V is the constant effective frequency of igneous intrusion into the repository. Because of the small value of λ_V, the probability of more than one igneous intrusion over 10^6 year, is also small and, thus

$$\wp\{\mathcal{A}_{VE}(\mathbf{e}_V^p)\} = \wp\{n_V > 0; \lambda_V\,\tau^{reg}\} = 1 - \exp\{-\lambda_V\,\tau^{reg}\} \tag{3}$$

$$\approx \lambda_V\,\tau^{reg} \text{ for small } \lambda_V\,\tau^{reg} \quad \text{(from a Taylor series approximation)} \tag{4}$$

Hence, the focus of the igneous scenario class probability is on the one uncertain parameter ($\mathbf{e}_V^p = \lambda_V$).

3.2.2. Estimates of igneous frequency for PA–EA

Along with an extensive review of igneous activity near Yucca Mountain in 1979 and 1980, LANL and USGS roughly estimated the range in frequency of basaltic volcanism as $10^{-9}\,\mathrm{yr}^{-1} < \lambda_V < 10^{-8}\,\mathrm{yr}^{-1}$, where a volcanic event was defined as the formation of a new igneous center (not multiple vents from the same igneous center) [42].

Two years later, LANL extended the uncertainty range to $3.3\times10^{-10}\,\mathrm{yr}^{-1} < \lambda_V < 4.7\times10^{-8}\,\mathrm{yr}^{-1}$ [123, p. 184–5; 124, p. 6–8] (Fig. 4). This widely cited range used in the 1986 final EA for Yucca Mountain is the product of the frequency of igneous activity in a region ($1\times10^{-6}\,\mathrm{yr}^{-1} < \lambda_{Varea} < 6\times10^{-6}\,\mathrm{yr}^{-1}$) between 25 and 150 km around Yucca Mountain (2000–70,000 km^2) and a reduction factor from a probabilistic model ($\Phi_V(\sim)$). The estimated frequency range of regional igneous activity (λ_{Varea}) did not substantially change over the next several decades. The minimum of the range was determined using the smallest elliptic area including all the Quaternary igneous centers. The maximum was determined using the smallest elliptic area including all nearby igneous centers <4.7 Ma.

For the deterministic draft PA–EA of eruptive volcanism, λ_V was set at a constant value based on an regional frequency λ_{Varea} of $5.6\times10^{-6}\,\mathrm{yr}^{-1}$ in a 2000–km^2 region (A^{Vreg}) near Yucca Mountain and a potential interaction area from a dike of length (L^{dike}) of 4 km intruding into a 47,000-MTHM repository of 2.7 km^2 (A^{rep}) [123, Section 4.3.2]. Hence, conceptually in the draft PA–EA,

$$\lambda_V = \lambda_{Varea} \cdot \Phi_V\{L^{dike}, A^{rep}, A^{Vreg}\} = 2.9\times10^{-8}\mathrm{yr}^{-1} \tag{5}$$

The probability model $\Phi_V(\sim)$ of Eq. (5) reduces the probability of igneous activity at the repository because of the reduced size of repository area relative to the area over which λ_{Varea} is estimated. As pointed out earlier, only a dike extending to the site from an igneous center outside the zone of existing Quaternary cinder cones could disrupt the repository.

3.3. Probability modeling for PA-91 and PA-93

3.3.1. Estimates of igneous frequency between PA–EA and PA-93

In its 1989 report on the 7 Quaternary basaltic igneous centers, LANL estimated the frequency of λ_V between 10^{-10} and $10^{-8}\,\mathrm{year}^{-1}$, based on vent counts and the estimated rate of magma production [68]. By 1992, LANL had concluded that the 1982 regional igneous frequency estimates were still valid [123, pp. 184–5; 128]. LANL also examined structural controls on basaltic volcanism to estimate a mean reduction factor ($\bar{\Phi}_V$ of 0.0028 and a range between 0.0013 and 0.0039 [128,129].

3.3.2. Igneous scenario class probability for PA-91 and PA-93

For PA-91, λ_V was evaluated as the product of distributions for λ_{Varea} and Φ_V, that were both independent of the igneous center locus ($\mathbf{x}$) [13, Section 7.3.1; 130]. The resulting distribution had a mean of $1.08\times10^{-8}\,\mathrm{yr}^{-1}$ [13,14,37,40–42,77,118,124–126] (Fig. 4).

In PA-93, the igneous intrusion scenario subclass ($\mathcal{A}_{VI}$) was evaluated. The λ_{Varea} was defined as for PA-91. However, the repository area had been reduced from 5.6 km^2 to 4.6 km^2 for the cool repository ($\sim$14 W/m^2) and to 2.3 km^2 for the hot repository for PA-93 ([14], Section 17.1); hence, the values for Φ_V, and, thereby, λ_V were reduced proportionally [14, Section 17.1] (Fig. 4). Similar to PA–EA, no distinct was made between a dike intrusion and eruptive conduits or vents along a dike for PA-91 and PA-93 and so again no estimates were made of $\wp\{E_{Vvent}|\mathcal{A}_V\}$ and $\wp\{E_{WPhit}|E_{Vvent}\}$.

3.3.3. Human intrusion probability for PA-91 and PA-93

The initial site characterization reported in the 1986 EA had found no economic minerals at Yucca Mountain. None the less, some exploration had occurred in the area and EPA radiation protection standards 40 CFR 191 required an estimate of releases from inadvertent human intrusion while exploring for minerals.

For PA-91 and PA-93, the probability of human intrusion $\wp\{n_H\}$ was modeled as a Poisson distribution (Eq. (2)) similar to igneous intrusion.[8] It can be shown that the probability of hitting a package given a drilling intrusion $\wp\{n_{WPhit}\}$ is also a Poisson process with an effective frequency of $p_{WPhit}\lambda_H\tau$ where p_{WPhit} is probability of an exploratory drill hole hitting a package. Hence, for PA-91, the probability of the human intrusion scenario (i.e., $n_{WPhit} > 0$) was

$$\wp\{\mathcal{A}_H\} = \wp\{n_{WPhit} > 0\} = 1 - \wp\{n_{WPhit} = 0; p_{WPhit}\lambda_H\tau^{reg}\}$$

$$= 1 - \exp\{-p_{WPhit}\lambda_H\tau^{reg}\} = 0.12 \tag{6}$$

The human intrusion drilling rate λ_H was constant and based on guidance in 40 CFR 191 for a repository in igneous rock which gives an expected number of intrusions of $\lambda_H\tau^{reg}$ or 17 (i.e., an intrusion rate $\lambda_H/A^{rep} = 3$ drill holes/(km^2 repository area 10^4 yr)). The p_{WPhit} for a vertical package was constant and based on the combined areas of the drill bit and package

$$p_{WPhit} = \frac{\pi(r^{WP} + r^{drill})^2}{A^{rep}} N^{WP} = 0.0075 \tag{7}$$

where r^{WP} and r^{drill} are the package and drill bit radius (0.33 m and 0.305 m, respectively), A^{rep} is the repository area (5.6 km^2) [4], and N^{WP} is the number of packages (33,333) [4, Table 3].

The probability of an exploratory drill hole missing a vertical package but extracting tuff around the package that was contaminated from radionuclides required an estimate of the radionuclide release into the host tuff. To be fully consistent with the undisturbed scenario, the area of contamination calculated in the undisturbed scenario should have been used. However, this type of coupling was not attempted in PA-91 and PA-93 (and would not be necessary for the stylized calculations in PA–SR and PA–LA). Rather, the area of contamination was determined by solving for a contaminated radius (r^{cont}), which varied with the time of container failure (τ_H^{fail}) and time of intrusion (τ_H) using a simple diffusion equation for a line source in an infinite volume [13, Fig. 6-5]. For early container failures and late intrusion times, the contaminated radius could exceed the spacing between packages, in which case the area became ellipsoid with the major axis equal to r^{cont} and the minor axis equal to half the package spacing.

PA-93 used the same basic scheme to calculate the probability for the human intrusion scenario as PA-91. However, the variability in the probability was much greater in PA-93 for several reasons. First, 4 design cases were analyzed in PA-93 (2 package types—vertical and in-drift, and 2 heat loads—Q_{option}^{heat} ~hot 28 W/m^2 and cool 14 W/m^2) [14, Section 17.1]. These changes in repository size (A^{rep}) changed the value of λ_H (similar to λ_V).

Second, p_{WPhit} for a direct hit changed because of the difference in cross-sectional areas between the vertical and in-drift package designs. Third, 4 vertical package sizes each with different inventories (HLW, PWR, boiling water reactor—BWR, and hybrid packages [5, Fig. 4] and 3 in-drift packages each with different inventories (HLW, PWR, and BWR [5, Table 3]) were modeled. Finally, the uncertainty in probability was greater in PA-93 because the time of waste container breach was uncertain (τ_H^{fail}) for evaluating the contaminated area around a package [14, Table 16–5].

[8] PA-91 used two human intrusion probability models: one based solely on a binomial process and one based on a Poisson process. Both give similar results and here we describe the model based on the Poisson process.

3.4. Probability modeling for PA–VA

3.4.1. Igneous scenario class probability for PA–VA

3.4.1.1. Igneous intrusion rate epistemic parameter. In the PVHA completed in 1996 [52,76], the experts treated the regional frequency λ_{Varea} and the reduction factor Φ_V as spatially varying because of geologic structural controls (i.e., $\lambda_{Varea}(\mathbf{x})$ and $\Phi_V(\mathbf{x};\mathbf{e}_V^p(\mathbf{x}))$, where $\mathbf{e}_V^p(\mathbf{x}) = \{\alpha^{dike}(\mathbf{x}), L^{dike}(\mathbf{x}),\ldots\}$; hence

$$\lambda_V = \int_X \lambda_{Varea}(\mathbf{x})\Phi_V(\mathbf{x};\mathbf{e}^p)d\mathbf{x}; \tag{8}$$

Each of the ten experts estimated the frequency of (a) a new igneous center forming and its proximity to the repository based on a decline in frequency as the igneous center, $\mathbf{x}$, moved toward the repository because of structural controls (i.e., $\lambda_{Varea}(\mathbf{x})$), and (b) the probability of a dike extending into the repository ($\Phi_V(\mathbf{x}; \mathbf{e}^p(\mathbf{x}))$ based on a distribution of estimated lengths, $L^{dike}(\mathbf{x})$ and orientations, $\alpha^{dike}(\mathbf{x})$, dependent upon the igneous center, $\mathbf{x}$). The mean for λ_V, estimated from the 10 experts, was 1.5×10^{-8} yr^{-1} with 5th and 95th percentiles of 5×10^{-10} and 5×10^{-7} yr^{-1}, respectively, and a maximum of 10^{-7} yr based on the shape and size of the repository for PVHA (Fig. 4). Although not the exact shape and size of the repository for PA–VA, the estimated distribution of λ_V was used directly in PA–VA for evaluating the probability of igneous intrusion scenario class (i.e., $\overline{\wp}\{\mathcal{A}_V\} = 1.5\times10^{-8} > 10^{-8}$).

In the early 1990s, the State of Nevada supported researchers that examined the applicability of the Poisson model of igneous activity and corresponding frequency. In a series of articles, Ho argued that a power law ($\lambda(t) = \beta/\theta)(t/\theta)^{\beta-1}$) should be used to evaluate λ_{Varea} [126]. Ho estimated λ_V as 1.5×10^{-8} yr^{-1}, 1.09×10^{-8}, 2.83×10^{-8} year, or 3.14×10^{-7} yr^{-1}. Only the latter frequency exceeded the range first proposed by LANL in 1982 (Fig. 4). This value used a $\Phi_V \cong 10^{-1}$. In essence, this value results in using the rates at the more active Lunar Crater (150 km NNE of Yucca Mountain) or the Cima volcanic field in California [37, p. 6–34].

Also in 1995, Conner and Hill estimated, for NRC, an equivalent frequency range of $10^{-8} < \lambda_V < 5\times10^{-8}$ yr^{-1} using three different spatially nonhomogeneous Poisson models (where the inhomogeneity in $\lambda_{Varea}(\mathbf{x})$ was from spatial variability ($\mathbf{x}$), not temporal variability) [125]. The regional rate of igneous activity (λ_{Varea}) was varied between 5×10^{-6} and 10×10^{-6} events/yr (Fig. 4).

3.4.1.2. Conditional probability of eruptive event for PA–VA. In addition to $\wp\{\mathcal{A}_V(\mathbf{e}_V^p)\}$, an estimate of the number of packages potentially disrupted by an eruptive event was made for PA–VA through a direct stochastic simulation by sampling uncertain distributions of the parameters influencing the product $\wp\{E_{WPrelease}|E_{WPhit}\}$, $\wp\{E_{WPhit}|E_{Vvent}\}$ and $\wp\{E_{Vvent}|\mathcal{A}_V\}$ in Eq. (1). The probability of eruptive vents in the repository ($\wp\{E_{Vvent}|\mathcal{A}_V\}$was a function of the spacing of vents along a dike, dike length, and the portion of the dike within the repository area. The probability of an eruptive vent intersecting a drift and packages ($\wp\{E_{WPhit}|E_{Vvent}\}$) was a function of the eruptive vent diameter, spacing of drifts, and spacing of packages. The probability of release from the package was a function of characteristics of particle sizes and ash velocity.

The distributions for dike orientation, length and width, developed by the PVHA expert panel [52,76], were sampled 300 times [101, Section 10.4.2.8]. Seventeen of the 300 simulations (0.057) resulted in some type of release. About 60% of the 300 simulations were eliminated because the sampled location of the volcanic vent along the basaltic dike was outside the repository (i.e., $\wp\{E_{Vvent}|\mathcal{A}_V\} \approx 0.4$) [101, Table 10–17]. Because the median conduit diameter was 50 m (with a range between 15 and 150 m) and the spacing between drifts only 28 m, vents inside the repository usually intersected a waste package (i.e., $\wp\{E_{WPhit}|E_{Vvent}\}\approx 0.92$); hence, $\wp\{E_{WPhit}|E_{Vvent}\}.\bullet\wp\{E_{Vvent}|\mathcal{A}_V\}= 0.37$ [101, Table 10–16d]. The $\wp\{E_{WPrelease}|E_{WPhit}\}$ made up the remaining fraction of ~0.15. After PA–VA, $\wp\{E_{WPrelease}|E_{WPhit}\}$ would be set at 1.

3.4.1.3. Probability of magmatic liquid flow for PA–VA. The second direct effect of an igneous event considered in PA–VA was enhancing the source-term. About 65% (195) of the 300 cases resulted in conditions that caused magmatic disruption of the waste package in-situ and, thereby, enhanced the source-term for a short time. For 35% of the cases, no release was assumed to occur when the sampled water content in the magma was such that the magma might fragment into a pyroclastic flow below the repository.[9]

3.4.2. Seismic scenario class probability for PA–VA

An important result from the PSHA, completed in 1998, was a hazard curve, which expressed the probability of various magnitudes of ground motion. Mean, median, and 15% and 85% hazard curves were developed in terms of peak horizontal (v_{hor}^{peak}) and vertical ground velocity (v_{vert}^{peak}) and an associated probability of v^{peak} being exceeded annually (e.g., $\lambda_\ell^{SG} = {}^{15\%}\mathcal{G}(v_{hor}^{peak})$, ${}^{50\%}\mathcal{G}(v_{hor}^{peak})$, $\overline{\mathcal{G}}\,(v_{hor}^{peak})$, or ${}^{85\%}\mathcal{G}(v_{hor}^{peak})$) [53, Fig. 7–8]. A Poisson probability model was used for modeling the seismic event; therefore, the seismic scenario class probability of one or more events ($\wp\{\mathcal{A}_{SG}\}$) was expressed by Eq. (3) with λ_{SG}. For YMP, v^{peak} values with frequencies of λ_{SG} between 10^{-6} and 10^{-8} yr^{-1} were of most concern, but 10^{-4} yr^{-1} was the *minimum* annual frequency of concern for post-closure seismic events; thus, the probability of at least one seismic event $\wp\{\mathcal{A}_{SG}\}$was 0.63 for the 10^4 year regulatory period and one for the 10^6 year regulatory period [101, Table 10–27]. Hence, unlike igneous intrusion, the probability of at least one seismic event was not a major factor in reducing the expected dose in a practical sense for YMP PAs.

Rather, probability primarily entered into the calculation through the time of the seismic event and the magnitude of the event (expressed here as peak ground velocity, v^{peak}). To elaborate, the time of the seismic event determined the extent of container corrosion while the frequency of occurrence λ_{SG} determined v^{peak}. In turn, the extent of container corrosion and the v^{peak} determined the amount of package damage consequence either via direct physical damage (via rockfall for PA–VA but via additional processes such as package-to-package contact in PA–LA) or as latent damage that enhanced localized corrosion at later times. Because the probability of seismic ground motion causing damage to the package required consideration of the time of the event, it was difficult to implement as a scenario class separate from the undisturbed scenario class. Consequently, PA–VA (and PA–LA) studied the influence of $\mathcal{A}_{SG}$ as part of $\mathcal{A}_U$ (i.e., $\mathcal{A}_{U+SG}$).

The aleatoric parameter time ($\tau_{SG,\ell}\in\mathbf{a}_{SG}$) was expressed as a uniform distribution, consistent with defining a seismic event as a Poisson process ($g(\tau_{SG})$. An uncertain $v_\ell^{peak}$was sampled from a normal distribution constructed from values of σ_{Vpeak} and $\overline{v}^{peak}$ that were derived from the PSHA. An uncertain sampled λ_{SG} was used to define ${}^{50\%}v^{peak}$, which was then assigned to $\overline{v}^{peak}$for the normal distribution (i.e., $\mathcal{G}^{-1}(\lambda_\ell^{SG}) = {}^{50\%}v^{peak} \to \overline{v}^{peak}$). The median curve was assumed to have uncertainty with a standard deviation $\pm\sigma_{Vpeak}$ approximately equal to the bounds of the 15 and 85 percentile hazard curves (${}^{15\%}\mathcal{G}(v_{hor}^{peak})$ and ${}^{85\%}\mathcal{G}(v_{hor}^{peak})$).

3.5. Probability modeling for PA–SR

3.5.1. Igneous activity for PA–SR

In 2000, scientists for NRC argued that the maximum frequency selected by the experts in PVHA was too small; rather, the minimum should be based on igneous activity in the western Great Basin with an area of 8.2×10^4 km^2 which had at least 211 basaltic volcanoes in the last 2 Ma [40]. Consequently, they proposed a frequency range $10^{-8}<\lambda_V<10^{-7}$ yr^{-1} for a homogeneous Poisson model. However, YMP continued to rely upon the extensive 1996 formal expert elicitation (PVHA) [132, Table 8a; 133]. But, the results were adjusted for the PA–SR repository shape [134]. For PA–SR, λ_V was between 7×10^{-10} and 5×10^{-8} yr^{-1} (5th and 95th percentiles) with a mean of 1.5×10^{-8} yr^{-1} [132, Table 8a; 133] (Fig. 4).

3.5.2. Conditional probability of volcanic eruption

For the bounding type of analysis adopted for PA–SR, the probability of an eruptive vent intersecting a package (given that an eruptive vent resided inside the repository and a dike intersected the repository) was 0.36 and, thus, much greater than for PA–VA [133]. Although, the spacing between drifts increased to 81 m in PA–SR; and, thus, greatly reduced the probability of $\wp\{E_{WPhit}|\mathcal{A}_{Vvent}\}$ from the 0.92 value used for PA–VA, the term was not included for PA–SR (i.e., $\wp\{E_{WPhit}|\mathcal{A}_V\}=\wp\{E_{WPhit}|E_{Vvent}\}\bullet\wp\{E_{Vvent}\}|\mathcal{A}_V\}<\wp\{E_{Vvent}|\mathcal{A}_V\}$). For PA–SR, $\wp\{E_{Vvent}|\mathcal{A}_V\}$ was evaluated from geometrical calculations [135; 136, Table 6–113], and for SSPA and PA-EIS, $\wp\{E_{Vvent}|\mathcal{A}_V\}$ was doubled from 0.36 to 0.77 [137, vol. 2, Section 4.3].

3.5.3. Seismic breach of cladding for PA–SR

At Yucca Mountain, 21 earthquakes of magnitude≥6 have occurred within 300 km since 1968 [17,138]. For example, the largest recorded, a 5.4 earthquake, occurred near Little Skull Mountain, ~20 km to the east of Yucca Mountain in June 1992. Although windows broke at the surface 7 km to the north, no damage occurred in 2 tunnels under Little Skull Mountain. This situation is frequently observed in underground tunnels, because the seismic waves travel on the surface. Hence, inclusion of the seismic event was screened out for PA–SR. To elaborate, peak ground velocities (v^{peak}), when sampled from the median hazard curve ${}^{50\%}\mathcal{G}(v^{peak})$ were small enough that package damage from a seismic event was minor. Breach of the less robust CSNF cladding was also infrequent. Only a rarely sampled frequency (λ_{SG}) greater than 1.1×10^{-6} year^{-1} could breach the cladding, where breach was implemented as a simple disruptive event and damage from multiple events did not accumulate, similar to PA–VA.

3.6. Probability modeling for PA–LA

3.6.1. Probability of igneous scenario class in PA–LA

In August 2005, UNLV scientists hypothesized that (1) the Lunar Crater volcanic field in CA may be linked through an anomalously hot mantle source, and (2) buried magnetic anomalies near Yucca Mountain were of Pliocene age, which would cause a 5 fold increase in igneous frequency λ_V [139]. However, by November 2005, LANL scientists were quickly able to dispel these two hypotheses since (1) the composition of magma at Lunar Crater differs substantially from magma at Yucca Mountain; (2) the history of basaltic volcanism near Yucca Mountain is inconsistent with a hot mantle source; and (3) drilling at the buried magnetic anomalies found that they were older than ~9.5 Ma near Yucca Mountain, except for one Pliocene-age cluster

[9] Based on more detailed modeling for PA–LA, magma never fragmented into a pyroclastic flow below the repository, but rather remained a low-viscosity magma [131] (Fig. A1).

25 km south of Yucca Mountain (Fig. 3). Hence, the anomalies did not substantially influence λ_V [119]. Consequently, λ_V remained similar to PA–SR except for the small adjustment necessary to account for the new repository layout for PA–LA ($\bar{\lambda}_V = 1.7 \times 10^{-8}$ yr^{-1}) [118, Section 6.5.1.1] (Fig. 4).

YMP completed a 4-yr update to the PVHA in 2008 based on the new magnetic surveys that resulted in a small increase in the mean, which was similar to the value first used in 1982 ($\bar{\lambda}_V = 3.1 \times 10^{-8}$ yr^{-1} in 2008 versus 2.9×10^{-8} yr^{-1} in 1982 for the draft PA–EA) [120]. The results of the updated PVHA provided programmatic and regulatory confidence in the results of the 1996 PVHA, which remained the basis for PA–LA.

3.6.2. Conditional probability of volcanic eruption

For PA–LA, the probability of an eruptive vent intersecting a package given that an eruptive vent resided inside the repository and that a dike intersected the repository was 0.083 in Eq. (1) and, thus, similar to PA–VA (i.e., 0.083 versus 0.057) [118, p. 6.5–19] (i.e., $\wp\{E_{WPhit}|\mathcal{A}_V\} = \wp\{E_{WPhit}|E_{Vvent}\} \bullet \wp\{E_{Vvent}|\mathcal{A}_V\} = 0.297 \bullet 0.28 = 0.083$). Similar to PA–SR, $\wp\{E_{Vvent}|\mathcal{A}_V\}$ was evaluated from geometrical calculations [140,141]; however, the underlying eruptive properties were new and $\wp\{E_{Vvent}|\mathcal{A}_V\}$ decreased somewhat [142]. But the major cause of the reduction was the inclusion of $\wp\{E_{WPhit}|\mathcal{A}_{Vvent}\}$.

3.6.3. Probability of seismic scenario class in PA–LA

Based on comments on the PA–SR, PA–LA changed to using the mean hazard curve $\mathcal{G}(v_{hor}^{peak})$ developed by PSHA for evaluating probability and consequences of the seismic scenario class rather than the median hazard curve used in PA–VA and PA–SR (${}^{50\%}\mathcal{G}(v_{hor}^{peak})$). However, while the median curve remained below a bounding value of ~4 m/s for v_{hor}^{peak} (based on physical evidence such as the presence of precariously perched rocks on Yucca Mountain for the past 10^4 to 3×10^4 years [88], p. 294 and intact layers of the structurally weak lithophysal tuff [143]), the mean curve did not (e.g., at $\bar{\lambda}_{SG}$ of 10^{-8} yr^{-1}, $v_{hor}^{peak}$was 10.7 m/s). Thus, the mean curve was scaled such that it was bounded by 4 m/s at $\bar{\lambda}_{SG}$ of 10^{-8} yr^{-1} for PA–LA [144, Fig. 6.4–3]. However, v_{hor}^{peak} values for the bounded mean hazard curve (i.e., $\mathcal{G}^{-1}(\lambda_{\ell}^{SG}) = \bar{v}^{peak}$) were still large enough that seismic damage of packages could not be screened out in PA–LA as in PA–SR. With the use of the larger mean curve, uncertainty in the hazard curve was not considered for PA–LA [145].

Because container corrosion was minimal in the first 10^4 year, YMP separated the seismic scenario class from undisturbed corrosion and evaluated its probability with a Poisson probability model (Eq. (1)). Beyond 10^4 years, package damage was evaluated by coupling the undisturbed and seismic scenario classes as in the study done for PA–VA since the container strength changed over time as it slowly corroded [6].

4. Summary

An important step of the PA methodology is to develop a complete universe of features, events, and processes to consider through either an evaluation during initial screening or as part of the PA modeling. As discussed in the paper and summarized below, the more well-known disruptive events and scenario classes considered for the proposed YM repository included igneous intrusion, human intrusion, seismicity, criticality, and extensive water table rise.

Some of the first site selection tasks for Yucca Mountain identified igneous activity as a potential hazard to the disposal system. The first analysis in 1982 evaluated the consequences and probability of igneous eruptions (Fig. A1). Igneous activity has been evaluated to some extent in all PAs except PA-95. The first estimate of the probability of igneous disruption was established as $\sim 10^{-8}$ in one year and remained at this value through PA–LA in 2008. Hence, the igneous event remained at the threshold of being excluded from the analysis based on the regulatory criterion. In turn, the doses calculated from the igneous event were near the threshold of regulatory interest [146, Fig. 8].

Seismicity was also identified during site identification but the influence on repository performance became much more important after the design evolved to in-drift emplacement of large containers without backfill in PA–VA. The presence of drip shields adopted for PA–SR also enhanced the influence of seismic events somewhat since rockfall did not pin down the packages while the drip shields were intact.

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

A variable water table rise was included in most PAs (between 50 and 120 m for PA-93, between 80 and 120 for PA–VA, and set at 120 m for PA–SR and PA–LA beyond 600 years). However, the 1988 Szymanski hypothesis of a disruptive water table rise whereby earthquakes force water hundreds of meters above the water table ("seismic pumping") was not included. In 1990 DOE asked the NAS to examine Szymanski's hypothesis. In 1992, the NAS concluded that "…there is no evidence to support the assertion by Szymanski…" (Fig. A1).

Human intrusion had been an important source of consequences in shallow land burial, an impetus to search for alternatives to salt disposal, and included in the evaluation of the YM repository when applying 40 CFR 191 in PA-91 and PA-93 [1]. However, the treatment of inadvertent human intrusion event evolved for 40 CFR 197 in that the event was not included in probabilistic dose calculations for PA–SR and PA–LA, consistent with an NAS recommendation [1].

YMP initially constructed scenario sequences that included the timing and order of FEPs identified for a repository in various media at NTS in 1981 and at Yucca Mountain in 1983. Scenario sequences were developed and some general sequences that included the igneous and human disruptive events modeled for PA–EA, PA-91, PA-93, and PA–VA. For PA–SR and PA–LA, the process of constructing scenarios was changed to constructing broad categories of scenarios from combinations of broad categories of FEPs. The order and timing of the FEPs were then part of modeling.

FEP and scenario development is an art in that a practical balance is necessary between the detailed description of a FEP and broad categories that reveal important concepts to facilitate meaningful and practical modeling. The NRC/SNL approach adopted for PA–SR and PA–LA found this practical balance easier than had occurred when developing elaborate scenario sequence trees, which then had to be grouped afterward for modeling. Because of the success of developing scenario classes from combinations of FEP categories at WIPP and YMP, a future repository program in the US would not have to experiment with other procedures.

Iterating an analysis allows for the incorporation of new information from disposal system characterization through continual updating of FEPs. Also, new hypotheses, even dramatic ones such as large water table rise and criticality, can be incorporated. Yet, the relative importance of new information and hypotheses is not always apparent. The strength of the PA process is that new information and hypotheses are placed in context to the overall system performance via a quantitative mathematical model rather than given subjective weights in a qualitative mental model. However, the evaluation of the YM disposal system was very much a public process and, for example, the science writer for the *New York Times* took special interest in water table rise and criticality [59,86]. Because of the wide news coverage of these and other topics, YMP was not always able to use the PA process to allocate resources to new information and hypothesis according to the understanding of the system as a whole. Rather, some issues garnered more public attention and YMP had to spend more money to evaluate some potential hazards than was perhaps warranted. Thus, YMP was not able to fully realize the promise of FEPs in the PA process. Nonetheless, the PA process could identify the significant aspects of these FEPs and, more importantly, ensure that other significant but less publicized FEPs were considered in the PA such that the evaluation of the YM disposal system was not driven by only high profile issues.

Acknowledgments

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Appendix A. Progression of hazard identification

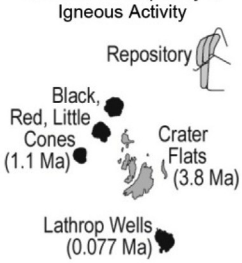
1974 Aug: Draft probabilistic risk assessment for reactors uses fault trees and event trees to synthesize probability of reactor failure [98].

1976 Jul: Energy Research and Development Agency (ERDA), predecessor to Department of Energy (DOE), hosts conference to bring engineers and geologists together to explore modeling events and processes of geologic disposal systems [21]. **Dec:** Nuclear Regulatory Commission (NRC) funds panel of earth scientists to identify events and processes that could disrupt a repository in various media [20].

1977 Human intrusion event significant contributor to consequences for nuclear waste buried in Idaho National Lab (INL), Los Alamos National Lab (LANL), Savannah River Site, and Hanford Reservation, but probability of event difficult to define [65].

1979 US Geological Survey (USGS) study finds silicic volcanic eruptions near Yucca Mt (YM) ended between 7 and 9 Ma [36].

LANL Sets Frequency of Igneous Activity

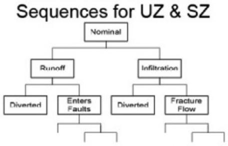


1980 Sandia National Labs (SNL) identifies 29 events and processes for generic repositories and develops a screening method for the NRC [20]. LANL and USGS estimate last basaltic eruption in Crater Flat in Quaternary < 1.6 Ma and estimates frequency (10^{-9} yr^{-1} < λ_V < 10^{-8} yr^{-1}) [42]. **May:** USGS concludes water table at Nevada Test Site (NTS) <61 m above present position during the Pleistocene [147]. **Oct:** DOE's 1980 Generic Environmental Impact Statement (EIS) examines 4 disruptive events for salt, shale, granitic, and basaltic repository: meteorite impact, fault followed by water flow, human exploratory drilling, and solution mining for salt [148, p. 5.73].

1981 International Atomic Energy Agency (IAEA) includes undetected features along with events and processes (FEPs) in performance assessments (PAs) [22]. **Nov:** SNL constructs scenario sequences for generic repository at NTS [45]; method similar to that used in 1979 for Waste Isolation Pilot Plant (WIPP) [149].

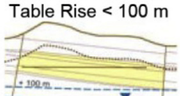
1982 Based on volcanic/hydrologic test hole, VH-1, drilled in 1981, USGS finds basaltic igneous activity declining [38]. K-Ar dating of youngest basaltic Lathrop Wells cinder cone suggests age between 80 and 700 ka [69]. **Apr:** LANL estimates frequency of basaltic activity at 3.3×10^{-10} yr^{-1} < λ_V < 4.7×10^{-8} yr^{-1} [123, pp. 184-185]. For draft PA-EA, SNL sets λ_V to 2.9×10^{-8} yr^{-1}.

SNL Forms Scenario Sequences for UZ & SZ



1983 USGS drills VH-2 to depth of 1200 m to evaluate igneous activity in Crater Flat; 11.3 Ma basalt encountered at 360 m [124, p.6-12]. **Mar:** SNL updates scenario sequences for repository for commercial spent nuclear fuel (CSNF) either in the saturated zone (SZ) of Bullfrog or Tram Fms or in the unsaturated zone (UZ) of Topopah Spring (TSw) or Calico Hills Fms, using combinations of 201 FEPs [46].

USGS Finds Water Table Rise < 100 m



1984 Preservation of nonwelded glass shards in G-4 well suggests that water table never higher than base of TSw.

1985 FEPs and scenarios developed for the site characterization plan (SCP) [73]. USGS uses updated regional flow model to assess effects of doubling infiltration on water table rise (<130 m), flow direction (small), and groundwater flux (factor of 2 to 4) [56].

1986 Seismic hazard at YM estimated for conceptual repository design [53, §1.3.2]. **May:** Final EA of YM uses λ_V of 1.3×10^{-8} as best estimate [150, p. 6-262, 6-387].

Seismic Pumping Proposed

1988 FEPs unique to repository in UZ at YM developed to demonstrate SNL/NRC FEP screening methodology [99]. **Jan:** Based on finding calcite veins in trenches dug over faults around YM, DOE geologist, Szymanski, asserts earthquakes force water hundreds of meter above water table ("seismic pumping") and stay at high levels by heat convection. Szymanski's draft report sent to State of Nevada [58]. **May:** LANL finds that calcite and opal mineral deposits in trenches not from upwelling of water [60]. **Dec:** SCP describes 91 FEPs important for scenario development [54; 151, V7, §8.3.5.13].

1989 Feb: LANL reports on evidence from 7 Quaternary basaltic igneous centers located between 8 and 47 km from the repository. All eruptions were of small volume (< 1 km^3) and decline in volume over time [67]. **Jul:** Szymanski report released to public [152]. **Aug:** Internal DOE review concludes Szymanski assertion without basis [17, p. 4-397].

1990 DOE asks National Academy of Sciences (NAS) to examine Szymanski assertion [64]. **May:** Nevada argues that local patterns of volcanic activity should not be used and suggests that reduction factor for igneous disruption of repository (Φ_V) should be 0.1 rather than 0.0028 proposed by LANL [153]. **Jun:** Based on morphologic data and analogy with a cinder cone in California, LANL suggests that portion of Lathrop Wells cinder cone is < 20 ka [70]. **Nov:** Press reports on Szymanski hypothesis [59].

USGS & LANL disagree on age of Lathrop Wells

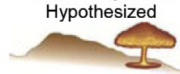
1991 SNL finds changes in water table <20 m from earthquakes and dike intrusions [63, p 11]. USGS finds that U and Sr nuclides in caliche at repository level not from water far below repository [61, pp. 551-554]. **Apr:** ^{40}Ar/^{39}Ar and K-Ar dating by USGS suggest lava flows at Lathrop Wells are between 119 and 141 ka [72]. **Dec:** External DOE majority report concludes Szymanski assertion without basis [17, p. 4-397].

NAS Finds No Evidence for Seismic Pumping

1992 As part of NRC IPA-1, NRC studies effect of increased recharge from climate change and igneous/seismic events on water table rise [154]. Igneous/seismic activity modeled by changing SZ permeability; climatic changes modeled with recharge. Water table rises small for igneous/seismic events; water table rises by 45 and 87 m in response to increasing recharge by a factor of 10 and 20, respectively [154, pp. 6 1 to 6 5]. NAS 17 member panel unanimously concludes "…there is no evidence to support the assertion by Szymanski…" [64]. **May:** LANL continues to evaluate structural controls on basaltic volcanism and estimates a range for reduction factor: 0.0013 < Φ_V < 0.0039 [128]. **Jun:** 5.4 magnitude earthquake, largest recorded at YM, occurs beneath Little Skull Mt ~20 km to the east [138]. Waste table surges only 0.3 m. **Jul:** Two disruptive scenarios are considered in PA-91: volcanism and human intrusion [13, §7.3.1].

1993 SNL completes scenario sequences for igneous activity near YM [47].

Atomic Explosion Hypothesized



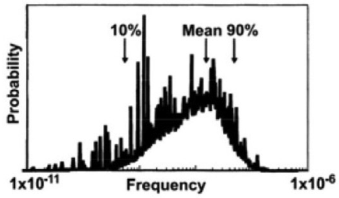
1994 Aug: Planning begins on probabilistic seismic hazard assessment (PSHA) for pre- and post-closure periods. Also, seismic analysis for exploratory studies facility (ESF) tunnel completed [53, §1]. **Dec:** Bowman and Venneri of LANL circulate paper speculating that an atomic explosion could occur at YM [85].

Criticality & Explosion Refuted

1995 Mar: In report requested by Congress in 1992, NAS suggests human intrusion not be part of PA, but rather a modeling case, which does not include probability [75]. Press reports on Bowman and Venneri's claim [87]. Others at LANL refute the possibility of assembling fissile material [92]. **Apr:** SNL estimates consequences of seismic event for vertically emplaced packages [74]. YMP starts expert elicitation for PSHA. **May:** YMP starts expert elicitation in probabilistic volcanic hazard assessment (PVHA) to estimate λ_V by resolving (a) rate of igneous events in region, (b) location of active igneous zone, and (c) best probability model [51]. In conjunction with PVHA, LANL summarizes igneous studies [37]. **Jun:** Using alternative conceptual probability models, Conner and Hill [125] and Ho [126] estimate, for the NRC, a frequency of igneous disruption of 10^{-8} < λ_V < 5×10^{-8} yr^{-1} and 9×10^{-9} < λ_V < 2×10^{-7} yr^{-1}, respectively. **Nov:** SNL completes scenarios sequences for undisturbed scenario modeled in PA-95 [48].

Fig. A1. Identification of hazards and scenarios for Yucca Mountain disposal system [147–167].

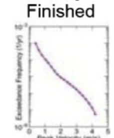
Igneous Hazard Study Completed



1996 SNL completes scenario sequences for influence of tectonic process near YM [48]. Ten experts complete PVHA [76], resulting in a range and mean for λ_V: $5\times10^{-10} < 10^{-8}$ yr^{-1} $< 5\times10^{-7}$ yr^{-1}. **May:** Bowman and Venneri paper published along with papers refuting the possibility of criticality [92]. LANL reports on small energy release from autocatalytic criticality in homogenous system with instantaneous water removal [94]. SNL argues probability of criticality $<\sim10^{-2}$ and consequence small since far less fissions would occur than are already represented in repository [93]. **Sep:** Berkeley concludes very low probability of criticality, but hypothesis possible consequence for Pu in UZ in a heterogeneous system with slow water removal [95]. **Oct:** YMP completes study showing low probability and consequences of criticality from CSNF in the repository once closed for several configurations after a container breach on Master Scenario List [90].

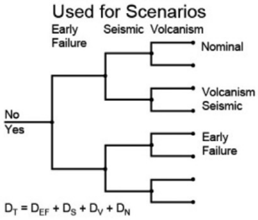
1997 Mar: YMP conducts workshop to discuss a methodology to evaluate the criticality scenario class [89]. **Sep:** YMP publishes summary of criticality probability and consequences [90].

Seismic Hazard Study Finished



1998 Feb: In NRC funded study, researchers report that, based on GPS data, the earth's crust is deforming 51 nanostrains/yr near YM vs. average of 12 nanostrains/yr in Basin and Range, which suggests either a large earthquake or igneous activity could occur in the future [155]. **Jul:** Based on tests funded by Nevada, Russian scientist, Dublyansky, argues that calcite crystals in fractures of ESF formed in hot water [156]. Nuclear Waste Technical Review Board (NWTRB) completes review of 11 reports submitted by Szymanski including those by Dublyansky and concludes reports do not make credible case that geothermal water flooded YM in the past [17, p. 4-402]. **Aug:** SZ Expert Panel concludes Szymanski assertion without basis [17, p. 4-397]. **Sept:** PSHA is completed (effort stopped in FY97 because funds lacking). PSHA produces hazard curves in terms of peak ground velocity (PGV) and an associated probability of PGV being exceeded annually [79]. **Nov:** YMP completes criticality topical report that envisions two parts [91]: Part 1 is to show low probability of criticality. If low probability cannot be shown, then Part 2 is to show low consequences of criticality. An important aspect is "burn-up credit" for consumption of fissile material and production of neutron absorbing fission products and actinides that reduce fuel reactivity as proposed in 1994. **Dec:** PA-VA analyzes undisturbed scenario class and evaluates influence of (a) seismic rock fall on package and fault altering SZ permeability; and (b) igneous eruption, igneous dike enhancing source term, and igneous dike altering SZ permeability [16, Vol. 3, §4.4].

SNL/NRC Method Used for Scenarios



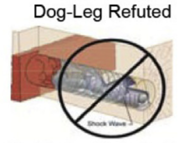
1999 USGS reports deformation near YM over long term is at Basin and Range average and propose discrepancy with 1998 NRC work caused by relaxation from 1992 Skull Mt earthquake [157]. USGS conducts magnetic survey ~30 anomalies found around YM [158]. **Jan:** LANL resolves age of Lathrop Wells at 77 ka from $^{40}Ar/^{39}Ar$ dating [78]. **Apr:** University of Nevada at Las Vegas (UNLV) begins study on timing of fluid inclusions in tuff to answer claims by Szymanski [159]. **Jul:** YMP transitions to SNL/NRC methodology for FEP development [101, §10.2].SNL completes preliminary database with 310 primary FEPs (including preliminary screening rationale) and 1476 related secondary FEPs for review in workshops between Dec and April 2000.

2000 INL completes 4 studies examining the feasibility of critical conditions for 11 DSNF types on the Master Scenario List for criticality (e.g., [160]). **Jan:** NRC scientists estimate frequency of igneous disruption at YM ($10^{-8} < \lambda_V < 10^{-7}$ yr^{-1}) [40]. **May:** INL publishes 40 FEPs related to DOE SNF [55]. **Jun:** SNL finalizes database of FEPs containing 323 primary FEPs (including compiled screening arguments from reports supporting PA-SR) and 1368 related secondary FEPs from various sources [29]. FEP screening arguments for PA-SR developed in 11 reports completed during the year. NRC issues a safety evaluation report (SER) on DOE's planned approach for screening criticality. The NRC identified 28 issues that need to be resolved for LA such as [161] (1) develop a criticality limit that includes bias and uncertainty; (2) develop approach for burn-up credit that includes test validation; (3) validate models that estimate fissile migration external to the package; (4) include more processes for waste degradation; (5) develop consequence analysis. **Oct:** Criticality screened out from PA-SR (e.g., [39; 108-110; 112]. **Nov:** In PA-SR, only undisturbed and igneous scenario classes included; damage to container from seismic scenario screened out; however, damage to cladding included [17].

2001 Feb: Process leading to 328 primary and 1368 secondary FEP list documented [29]. **May:** At NWTRB meeting and HLW International conference, USGS [162] and UNLV scientists [159] summarize findings that calcite formed by water dripping from the surface as YM cooled and not from thermal water that rose up in recent geologic time. Also, boreholes at paleosprings indicate only a 17 to 30-m rise in the water table during last 2 pluvial cycles [104]. Dublyanski presents opposing opinion [105]. **Sep:** YMP updates the criticality topical report that adopts a fault tree/event tree approach [103].

2002 Jun: 4.4 magnitude earthquake occurs in Rock Valley ~30 km east of YM. **Aug:** Scientists for NRC, propose "dog-leg" scenario in which igneous dike runs down drifts and disrupts large numbers of packages before continuing assent to surface. NRC also supports concept of container failure by shock wave from dike bursting into drift [163].

Shock Wave & Dog-Leg Refuted



2003 Expert panel finds, based on numerical modeling, that both NRC "dog-leg" scenario and PA-VA and PA-SR hypothesis of pyroclastic flow and shock wave are not plausible [131].

2004 Feb: In response to NRC request in 2002, YMP conducts new aerial magnetic survey of magnetic anomalies west, east, and south of YM (in Crater Flat, Jackass Flats, and Amargosa Desert, respectively—865 km^2) to resolve remaining questions on igneous history and direct future drilling [119].

2005 Aug: SNL publishes revised FEP database; 375 FEPs are listed. In response to internal comments and NRC (e.g., eliminate secondary FEPs), a new hierarchical system is developed that consists of 8 processes, 4 disruptive events (igneous, seismic, criticality, human intrusion) acting on 10 features of the engineered barrier system (EBS), 3 features of the natural barrier, the system as a whole, and the biosphere. Original 328 FEPs are not changed much, but some FEPs are split if they are included for one feature but excluded for another feature [30]. FEP screening arguments are contained in 10 reports. UNLV scientists hypothesize (1) buried magnetic anomalies near YM are of Pliocene age, which would cause 5 fold increase in igneous rate, and (2) volcanoes near YM may be linked to more active Lunar Crater, CA volcanic field 150 km to the NNE [139]. **Nov:** YMP dispels hypothesis of UNLV scientists: Drilling at 7 magnetic anomalies found 4 basalt masses, 3 were Miocene age basalt (>9.5 Ma), youngest 3.8 Ma; also, no feeder dikes cut across existing faults parallel to YM. Thus, no impact to igneous activity rate. Also, composition of magma at Lunar Crater differs from composition at YM and, thus unrelated [88, p. 292; 119].

2008 Mar: In major effort, FEP screening arguments updated and compiled into one report [32]. PA-LA considers 152 of the 374 FEPs in 4 scenario classes: (a) undisturbed, (b) EBS early failure with container and drip shield subclasses, (c) seismic with ground motion and fault displacement subclasses, and (d) igneous with eruption and intrusion subclasses. Also, FEP list decreased by one to 374 since drift bulkheads removed and cannot influence magma path. Criticality scenario class screened out based on low probability rationale for 16 subclasses [2]. **Sep:** After 4 yr, update to PVHA completed using new aeromagnetic surveys: mean of igneous occurrence confirms results of 1996 PVHA ($\lambda_V = 3\times10^{-8}$ vs. 1.7×10^{-8} yr^{-1}) [120]; also, mean similar to draft PA-EA estimate ($\lambda_V = 3.1\times10^{-8}$ vs. 2.9×10^{-8} yr^{-1}).

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Fig. A1. (continued)

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