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CHANGES IN DOSE PERFORMANCE MEASURES AS MODELING PROGRESSED FOR THE PREVIOUSLY PROPOSED US REPOSITORY IN VOLCANIC TUFF

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This paper examines changes in dose results as characterization and design of the US tuff disposal system progressed from 1993 to 2008 using two performance measures of dose from Monte Carlo type simulations: the expected dose as a function of time (as required by the US Environmental Protection Agency Standard) and the complementary cumulative distribution function (CCDF) of expected peak doses. Both measures are useful. The mean dose history visually emphasizes the long times prior to release and the long time to reach the peak dose. The expected dose history is greatly enhanced by also displaying the various percentiles (e.g., 5th, 50th, and 95th percentiles) of the range of behavior (as requested by the US Nuclear Regulatory Commission). The CCDF of peak doses readily shows the range of behavior directly (but with a loss of when those peaks occur). The CCDF also provides a convenient summary measure for discerning differences in the behavior of conceptual models and design options.

I. INTRODUCTION

In 2010, the President directed DOE to form the Blue Ribbon Commission on America's Nuclear Future (BRC) to review the current US policy for storage, processing, and disposal of high-level radioactive waste (HLW), commercial spent nuclear fuel (SNF), and SNF managed by DOE (DSNF). In 2012, BRC made several recommendations to Congress and DOE, some of which were "to ensure that future siting efforts are informed by past experience…" and for the US Environmental Protection Agency (EPA) and US Nuclear Regulatory Commission (NRC) to "…work together to define an appropriate process (with opportunity for public input) for developing a generic safety standard for geologic disposal sites."[1, p. 118] Hence, it is an opportune time to examine the current usefulness and potential modifications and alternatives to the standards and regulations governing radioactive waste disposal in a geologic repository.

What follows is an examination of the changes in peak dose as characterization and design of the proposed Yucca Mountain (YM) disposal system progressed from 1993 to 2008 using two performance measures from stochastic simulations: the total expected dose as a function of time and the complementary cumulative distribution function (CCDF) of expected peak doses.

II. ANALYSIS ITERATIONS

The Yucca Mountain Project (YMP) adopted an iterative approach to refine and focus the large-scale risk performance assessments (PAs) on those aspects most pertinent to the policy issue.[2; 3] Five PAs provide historical markers for the discussion. Two early PA iterations to evaluate selection, feasibility, and provide guidance on repository design options are mentioned: (1) PA-93; and (2) PA-95.[4; 5] These two early PAs were followed by three PAs to support major decisions: (3) PA-VA, a viability assessment in 1998, which evaluated undisturbed performance and explored the influence of igneous and seismic events for Congress;[6] (4) PA-SR, a 2000 analysis, which evaluated undisturbed and igneous intrusion scenario classes, to support the 2002 site recommendation;[7] and (5) PA-LA, the 2008 analysis for the license application, which analyzed undisturbed, early failure, igneous intrusion, and seismic scenario classes.[8]

Three additional supportive analyses for the latter two PAs are also mentioned. After completing PA-SR, YMP completed a more realistic analysis of disposal system performance, the Supplemental Science Performance Analysis (SSPA) using more realistic parameter values and models.[9] YMP also completed another analysis, which built upon SSPA. to evaluate performance over 10^6-yr for the environmental impact statement (PA-EIS).[10] Finally, YMP conducted an unqualified performance margin analysis (PMA), somewhat similar to the situation with SSPA and PA-EIS, for the PA-LA licensing analysis.

PA-93 and PA-95 provided rough measures of performance based on regional geologic characterization, data acquired from boreholes from the surface, limited site-specific data, and waste process data. The later three PAs made extensive use of environment-specific laboratory experiments, *in-situ* experiments, and disposal system characterization from the underground.[11, Table 1]

III. SITE-SPECIFIC EPA STANDARD

III.A. Dose Limit

In the *Energy Policy Act of 1992* (EnPA), Congress directed EPA to promulgate site-specific radiation protection standards for a repository at Yucca Mountain. EnPA further specified that "such standards shall prescribe the maximum annual effective dose equivalent to individual members of the public" as the risk indicator.[12; 13] The new EPA standards were to be "based upon and consistent with the findings and recommendations of the National Academy of Sciences (NAS)".

In response to EnPA, NAS made three recommendations in 1995 pertinent to this paper:[13; 14] (1) use a maximum individual risk evaluated from an effective dose; (2) evaluate compliance of the YM disposal system to the time of greatest risk (which is likely within 10^6 yr) while still within the limits imposed by long-term stability of the geologic environment at Yucca Mountain; and (3) avoid specifying criteria on subsystems, since these criteria could potentially result in suboptimal behavior of the overall YM disposal system.

In 2001, EPA promulgated the site-specific radiation protection standards, 40 CFR 197. As the performance measure, the standards specified the expectation (mean) of the peak committed effective dose equivalent (hereafter "dose") over 10^4 years at the controlled area boundary no further south than ~18 km from the repository. The maximum expected dose was to be less than 0.15 mSv/yr. In response to a court ruling, EPA extended the regulatory period to 10^6 years in 2008. The revised rule had a limit of 1 mSv/yr for the period beyond 10^4 years. These limits were applied to PA-LA.

III.B. Treatment of Uncertainty

The NRC regulation 10 CFR 63, which implements EPA's 40 CFR 197, requires inclusion of parameter uncertainty, consideration of model uncertainty, and the technical basis of inclusion or exclusion of features, events, and processes, as part of scenario uncertainty. Evaluation of the expected peak dose implied the use of a stochastic simulation, which was implemented through Monte Carlo techniques for the YM disposal system PAs. If all uncertainty in understanding about current and future behavior of a geologic disposal system could be quantified, they would be represented by a distribution of results (such as cumulative distribution function—CDF or CCDF).

III.C. Implications of dose criterion

Several aspects of the site can be taken into account with a dose criterion. A dose limit allows credit to be taken for dilution of radionuclides along the release pathway. Also, in concept, the DOE operator may select container designs that promote slow, extended release of radionuclides or the operator can size the repository inventory to site conditions.

In addition, a regulatory dose criterion is comparable to individual dose limits in other international radioactive waste programs (provided the regulatory period and features, events, and processes considered are similar). For example, Nuclear Energy Agency (NEA) of Organization for Economic Cooperation and Development (OECD), and International Atomic Energy Agency (IAEA) have recommended a maximum health risk of 10^{-5}/yr [15] or maximum public dose limit of 1 mSv/yr (average background dose at sea level) and average of 0.3 mSv/yr from a disposal facility.[16]

A dose criterion (i.e., rate of release) also has implications related to modeling. Because ambient oxygenated conditions in the UZ might promote, under some conditions, rapid degradation of the waste form and, thus, a rapid release rate in the YM repository, it was important to more precisely model the release rate from the waste package. In turn, the potential high release rate and need for precise modeling indirectly led to the usefulness of a robust waste package with well-defined characteristics, along with other modeling improvements described below.

IV. DOSE MEASURES

IV.A. Progression of modeling and variation of mean dose

The time variation of the expected dose and its maximum at a given time changed for each PA iteration as the modeling of the YM disposal system progressed. This modeling progression is as follows.

PA-93 provided guidance on options for (a) the thermal load, and (b) placement and orientation of the waste package in the floor and drift.[4; 17] Heat loads of either 14 W/m^2 or 28 W/m^2 were evaluated. The proposal to design a hotter repository necessitated the addition of a thermal module to the consequence model.[18] In addition, PA-93 used a 1-D, dual-porosity transport formulation for the unsaturated zone (UZ), based on a single equivalent continuum model (ECM), with flow primarily in the matrix.[19]

By PA-93, YMP had settled on a fairly rapid rate for degradation of SNF within the mostly oxygenated environment of Yucca Mountain. YMP would use a similarly rapid rate for degradation of HLW in PA-VA and thereafter. Other components of the multi-barrier YM disposal system compensated for the high degradation rates (e.g., while the container was structurally intact, the container provided substantial diffusive and advective resistance to flow regardless of the condition of the cladding or rapid waste form degradation).[20] PA-93 evaluated doses from an undisturbed scenario class coupled with an early waste package failure scenario class $\mathcal{A}_{U+EF}$ (i.e., $D^{93}_{U+EF}(t;\mathbf{e}_{U,\ell})$ where $\mathbf{e}_{U,\ell}$ represents the uncertain epistemic parameters for the undisturbed scenario U with 300 stochastic samples ℓ).

The next PA-95 also provided guidance on heat loading options for the repository, and floor and in-drift package emplacement options.[4] Furthermore, PA-95 examined the influence of percolation, seepage, and relative humidity on the thermal regime in an expanded thermal-hydrologic module. PA-95 also took the major step of developing a container degradation module (separate from the waste form degradation model) that used a stochastic description of container breach.

For PA-95 and each iteration thereafter, the plot of the expected dose as a function of time for the regulatory duration is available (Fig. 2). Although the thermal load design options (~6 W/m^2 and 20 W/m^2) influenced releases from the engineered barrier system in the first 10^4 yr, the influence of the thermal designs was small on doses at a 5-km boundary of the disposal system (Fig. 2). The hot thermal load dried the repository, yet, the corrosion rates of the container and degradation of the waste form was such that the releases occurred quite early. The bulk of container failures occurred by 10^5 years for either the hot or cool repository. Once the repository cooled, the failure rate was similar for either the hot or cool repository design; hence, the peak doses were similar. PA-95 evaluated doses from only the undisturbed scenario $\mathcal{A}_U$ for 100 samples ℓ of the uncertain epistemic parameters $\mathbf{e}_{U,\ell}$ (i.e., $D_U^{95}(t;\mathbf{e}_{U,\ell})$). The peak expected dose in a hot 20 Wm^2 repository using mean parameters (${}^{\max}D_U^{95}(t;\bar{\mathbf{e}}_U)$) was ~4.9 mSv/yr at 2.9 × 10^5 years (Fig 2).

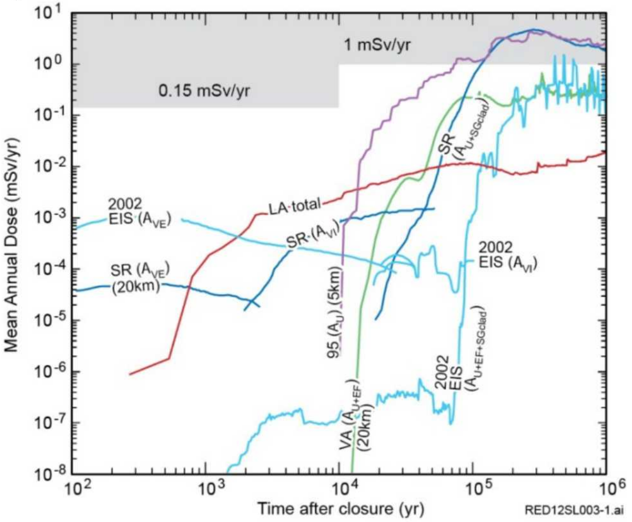


Fig. 2. Calculated dose in past PAs: (1) total mean dose for LA, SR, and 2002 EIS for hot repository (HTOM); (2) undisturbed mean dose for VA; and (3) undisturbed dose using mean parameters for hot repository for 1995.[5, Fig. 9.3-5; 6, Fig. 4-28; 8, Figs. 8.1-2[a; 9, Fig. 4.3-1; 10, Vol 3. Figs. I-12&I-18; 21, Fig. 6]

A major step in modeling complexity occurred in PA-VA. PA-VA was the first to use results of percolation through dual permeability media (both fractures and the matrix) in a 3-D model grid from the surface to the water table.

An important step for incorporating percolation from the surface was to develop an infiltration boundary condition, and, thus, an infiltration module was added in PA-VA.[19] Also, a seepage module was added, which used a detailed, calibrated model of seepage experiments.[19]

With the use of a dose standard,[22] the timing and amount of dilution and dispersion afforded by the geologic barrier was important, and more characterization data become available for the lower UZ and SZ for PA-VA.[23] In addition, a biosphere model was developed to determine individual dose from several exposure pathways in addition to consumption of drinking water for PA-VA.

PA-VA evaluated dose from the undisturbed scenario combined with early failure of the waste package $\mathcal{A}_{U+EF}$ The maximum expected dose ($D_{U+EF}^{VA}(t)$) at wells in Amargosa Valley, 20 km down-gradient from the proposed site for the undisturbed scenario was ~0.4 mSv/yr at ~7.5×10^5 years (Fig. 2).[6, Vol. 3 Fig. 4-26] For the very small doses in the first 10^4 years, technetium (^{99}Tc) and iodine (^{129}I) were the largest contributors.[6, Vol. 3 Fig. 4-29] By 10^5 years, both neptunium (^{237}Np) and ^{99}Tc were the largest contributors. By 10^6 years, ^{237}Np dominated.

The conclusion of site characterization at Yucca Mountain culminated with PA-SR in late 2000 for the site recommendation.[7] Three scenario classes were modeled in PA-SR: volcanic eruption, $\mathcal{A}_{VE}$; igneous dike intrusion, $\mathcal{A}_{VI}$; and undisturbed conditions coupled with CSNF cladding failure from seismic disruption, $\mathcal{A}_{U+SGclad}$. The total dose was thus the sum:

$$D_{total}^{SR}(t;\mathbf{e}) = D_{U+SGclad}^{SR}(t;\mathbf{e}_{U+SGclag})$$
$$+D_{VI}^{SR}(t;\mathbf{e}_{VI}) + D_{VE}^{SR}(t;\mathbf{e}_{VE})$$

However, these three scenario classes dominated the expected doses in three distinct periods. In the first 3×10^3 years, the eruptive dose dominated with a maximum of 4×10^{-5} mSv/yr, primarily from ^{241}Am (i.e., ${}^{\max}\bar{D}_{total}^{SR}(t < 3\times10^3\,\text{yr}) \simeq \bar{D}_{VE}^{SR}(3.5\times10^2\,\text{yr}) = 4\times10^{-5}$ mSv/yr in Fig. 2). For the eruptive dose, the particle size of disrupted waste had been greatly reduced (which caused more dispersion) and a bounding value of the scenario probability was used, which caused the volcanic eruptive ash releases to increase substantially.[17; 24]

Between 3×10^3 and 4×10^4 years, the dose was dominated by releases via a groundwater pathway after an igneous dike had disrupted the repository with maximum peak of ~1.5×10^{-3} mSv/yr from ^{99}Tc, ^{239}Pu, and ^{237}Np (i.e., ${}^{\max}\bar{D}_{total}^{SR}(3\times10^3 < t < 4\times10^4\,\text{yr}) \simeq \bar{D}_{VI}^{SR}(4\times10^4\,\text{yr}) =$ 1.5×10^{-3} mSv/yr in Fig. 2).

Beyond 4×10^4 years, the dose was dominated by releases in the undisturbed scenario after failure of the newly added drip shield and general corrosion of the waste package. The maximum dose was 4.9 mSv/yr at 2.7×10^5 years from ^{237}Np (i.e., ${}^{\max}\bar{D}_{total}^{SR}(t > 4\times10^5\,\text{yr}) \simeq \bar{D}_{U+SGclad}^{SR}(2.7\times10^5\,\text{yr}) = 4.9$ mSv/yr in Fig. 2).

Based on the past tradition in early reactor studies and in concert with the NRC proposed 10 CFR 63, which called for the concept of reasonable assurance,[23] the YMP made extensive use of conservatisms in model choices and parameter assignments in PA-SR. The purposeful conservatism present in PA-SR complicated the understanding of the results;[9] hence, YMP completed SSPA in 2001 using more realistic parameter values and models. The SSPA also included an alternative cooler repository design (i.e., both a high temperature operating mode (HTOM) and low-temperature operating mode (LTOM) were evaluated).[9] In 2002, YMP completed another analysis to evaluate performance over 10^6 years for the environmental impact statement (EIS) for the site suitability recommendation (PA-EIS),[10] which built upon SSPA (Fig. 2).[a]

Based on experiments, container degradation was not temperature or moisture dependent in PA-SR.[20] However, the experiments were at the limits of the measurement technique and so the possible temperature influence was examined further in SSPA and PA-EIS. The general corrosion rate of the Alloy 22 was also reduced, which resulted in a delay in the general breach of the container until at least 8×10^4 such that the dose did not begin to climb substantially until ~7×10^5 years (Fig. 2). The limiting concentration of Np was also greatly reduced (i.e., the bounding function of PA-SR was replaced with a function including uncertainty in Np solubility) such that the maximum total expected dose was 1.5 mSv/yr at 4.8×10^5 years (${}^{\max}\bar{D}_{total}^{EIS}(t) = \bar{D}_{total}^{EIS}(4.8\times10^5\,\text{yr}) =$ 1.5 mSv/yr in Fig. 2).

Furthermore for SSPA and PA-EIS, early container failure was added to the undisturbed scenario class and caused some dose prior to 10^4 years, but was 2 to 3 orders of magnitude less than doses from volcanic eruption and igneous dike intrusions. Another noticeable change in PA-EIS was the order of magnitude increase in expected dose from the igneous eruption ($\bar{D}_{VE}^{EIS}(t)$). One contributor was the doubling of the conditional probability of igneous eruption given an igneous intrusion.[25] Another contributor was the increase of the inhalation dose during an igneous eruption by a factor of 2.5.[9, Vol. 2 §4.3; 22]

For PA-LA, the potential for container damage from drift degradation and container movement during a seismic event was included, which, in turn, required the addition of seismic damage process codes.[20] In addition for PA-LA, the calculation of the biological dose conversion factors was determined using a new code to conform to the revised method of evaluating dose, as specified by EPA and NRC.

PA-LA evaluated dose as the sum of the dose from six scenario classes: (1) undisturbed combined with seismic ground motion; (2) seismic fault displacement, $\mathcal{A}_{SF}$ (3) volcanic eruption, $\mathcal{A}_{VE}$; (4) igneous dike intrusion, $\mathcal{A}_{VI}$; (5) early waste package failure, $\mathcal{A}_{EW}$; and (6) early drip shield failure above the waste package, $\mathcal{A}_{ED}$

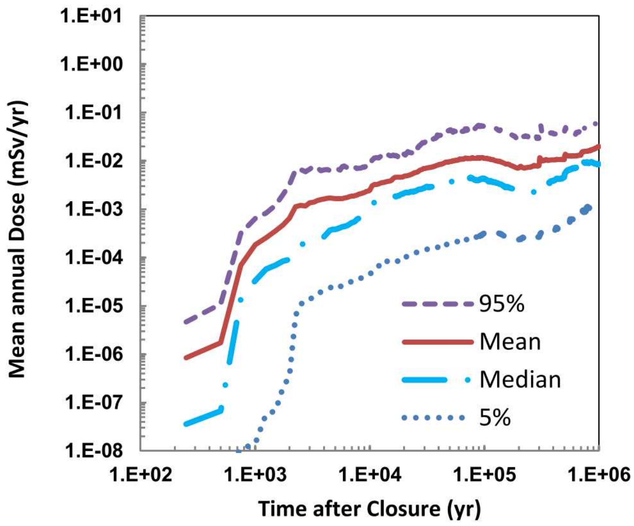
$$D_{total}^{LA}(t;\mathbf{e}) = D_{U+SG}^{LA}(t;\mathbf{e}_{U+SG}) + D_{FD}^{LA}(t;\mathbf{e}_{FD}) + D_{VI}^{LA}(t;\mathbf{e}_{VI})$$
$$+D_{VE}^{LA}(t;\mathbf{e}_{VE}) + D_{EW}^{LA}(t;\mathbf{e}_{EW}) + D_{ED}^{LA}(t;\mathbf{e}_{ED})$$

However, doses from only igneous dike intrusion and the combined undisturbed seismic scenario classes were the primary contributors to the total dose, i.e.,

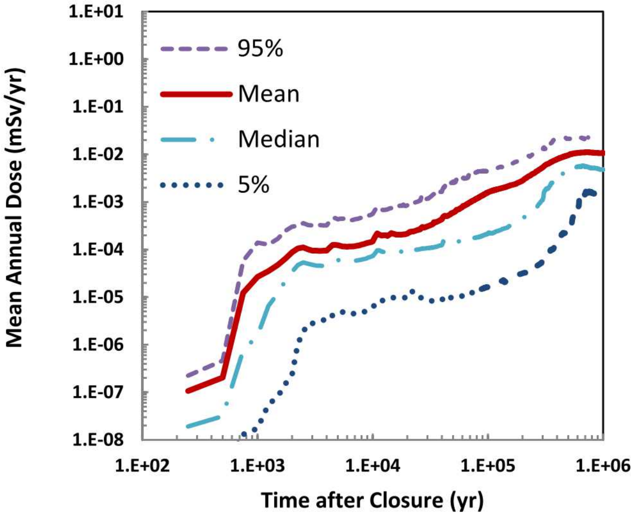
$$D_{total}^{LA}(t;\mathbf{e}) \simeq D_{U+SG}^{LA}(t;\mathbf{e}_{U+SG}) + D_{VI}^{LA}(t;\mathbf{e}_{VI})\,.^{21,\text{ Fig. 8}}$$

A local maximum expected dose of 0.013 mSv/yr occurred at 8×10^4 years, but the absolute maximum expected dose of 0.020 mSv/yr occurred at 10^6 years (i.e., ${}^{\max}\bar{D}_{total}^{LA}(t) = \bar{D}_{total}^{LA}(10^6\,\text{yr})$=0.20 mSv/yr).

Results of risk analysis are often shown as a distribution to answer the question as to how likely it is to be greater than the mean. The distribution about the peak expected dose has a range between 0.001 and 0.083 mSv/yr for the 5th and 95th quantiles, respectively (the quantiles NRC requested in review guidance (Fig. 3a).



(a) PA-LA total dose from all scenarios



(b) PMA total dose

Fig. 3. Range of total dose in individual simulations from propagation of epistemic uncertainty in 392 parameters $\mathbf{e}_\ell$ in stochastic analysis with 300 samples ℓ.[26,Fig. 2]

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[a] By November 2001, NRC had clarified its desire for more realistic analysis by adopting the EPA characterization of reasonable expectation as the standard of proof in the final version of 10 CFR 63 used for PA-LA.[23]

For PMA, more realism in parameter values related to waste package degradation (e.g., reduced seepage, lower general corrosion rates, better water balance inside the waste package, and reduced uncertainties for Np, U, and Pu solubility) reduced the contribution of the combined undisturbed and seismic scenario dose, $D_{U+SG}^{LA}(t;\mathbf{e}_{U+SG})$.[27; 28] The maximum expected peak dose of 1.1×10^{-2} mSv/yr at 7.2×10^{5} yr (Fig. 3b) was solely from igneous intrusion (i.e., $D_{total}^{LA}(t;\mathbf{e}) \simeq D_{VI}^{LA}(t;\mathbf{e}_{VI})$).

The current regulatory period of 10^6 yr adequately captured the majority of the peaks in the PAs (Fig. 2), except possibly for PA-LA (Fig. 3a). As the robustness of the package increased, the peak dose was still climbing at the end of regulatory period in PA-LA (Fig. 3).

IV.B. Distribution of maximum peak doses as modeling progresses

As a dose measure, EPA could have chosen the distribution of expected peak doses (either CDF or CCDF), regardless of the time of occurrence, as the performance measure and defined a limiting distribution, and, thereby, explicitly regulated the dose distribution.[23]

A useful aspect of a CCDF of peak dose is that it shows the probability of the greatest dose exposure during the regulatory period. Furthermore, it is possible to extrapolate somewhat beyond the results of the simulation to examine very low probability exposures.

A general drawback to this approach is that calculated peaks are somewhat sensitive to the model fidelity, such as time steps, or the number of samples used to evaluate the stochastic integrals using Monte Carlo techniques. None the less, the CDF and CCDF provide a convenient method of discerning differences in the behavior of conceptual models and design options. As understanding of the YM disposal system increased, the CDFs and CCDFs of the peak doses generally decreased from those calculated in PA-93 through PA-LA in 2008 (Fig. 4). Specifically, the means and the medians of the CDFs of peak dose decreased to 0.038 and 0.022 mSv/yr, respectively, by PA-LA. Note that the mean of the peaks is twice as large as the maximum expected dose for PA-LA (0.020 mSv/yr at 10^6 yr in Fig. 3a). It is the latter value that is regulated by EPA in 40 CFR 197 and must be less than 1 mSv/yr beyond 10^4 yr.

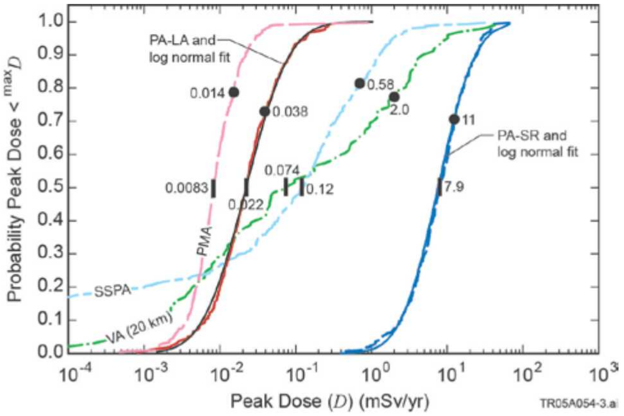
Until PA-LA, the peaks from the individual simulations based on the sampled uncertain epistemic parameters $\mathbf{e}_{U,\ell}$ were dominated by doses from the undisturbed scenario class, that is , $D_{total} \simeq$

$$^{\max}D_{U+EF}^{93}(t;\mathbf{e}_{U+EF,\ell}),$$
$$^{\max}D_{U}^{95}(t;\mathbf{e}_{U,\ell}) ,$$
$$^{\max}D_{U+EF}^{VA}(t;\mathbf{e}_{U+EF,\ell}) \text{, or}$$
$$^{\max}\overline{D}_{U+SGclad}^{SR}(t > 4\times10^{5}\,\text{yr};\mathbf{e}_{U+SGclad,\ell})$$

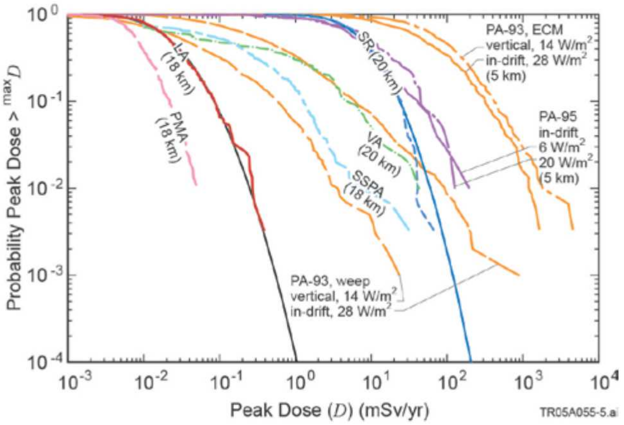
By PA-LA, however, rare disruptive events such as seismicity and volcanism were the primary cause of releases. That is, for PA-LA, both the volcanic intrusion scenario class and the combined undisturbed scenario class with seismic disruption contributed to the total dose:

$$D_{total}^{LA} \simeq {}^{\max}D_{U+SG}^{LA}(t;\mathbf{e}_{U+SG,\ell}) + {}^{\max}D_{VI}^{LA}(t;\mathbf{e}_{VI,\ell}) .$$

To elaborate, coincident with the general decrease in peak doses, was the general increase in the contribution to dose from disruptive events, such as seismic damage and especially igneous disruption. Yet, igneous disruption remained at the threshold of being eliminated from the analysis, based on the regulatory screening criterion of 10^{-8}/yr.[23; 25] Consequently, a major component of the expected individual doses was near the threshold of regulatory interest and represented a point, after lengthy study, where sufficient knowledge of the YM disposal system had been obtained to go forward with licensing.



(a) Semi-logarithmic CDF



(b) Logarithmic CCDF

Fig. 4. The CDFs and CCDFs of expected peak doses at accessible environment boundary (5 km boundary in early PAs and 18 km boundary in later PAs) generally decreased from PA-93, PA-95, viability assessment (VA), site recommendation (PA-SR), supplemental science with hot repository option (SSPA), license application (PA-LA), and performance margin analysis (PMA).[4, Figs. 14-21 & 15-42; 5, Figs. 9.3-33 & 9.3-34; 6, Vol 3 Fig. 4-26; 8, Figs. 8.1-2[a; 21, Fig.3]

For disruptive events, the dose is multiplied (conditioned) by the probability of these rare disruptive events and so expected peak dose from any one simulation ℓ is shown, not the unconditioned peak dose.

The change in expected peak doses between PA-93 and PA-VA partially represents the difference in knowledge based on limited data from surface boreholes versus knowledge based on data obtained *in-situ* such that the conceptual model uncertainty could be reduced. However, the site-specific data were not immediately available and understanding continued to increase between PA-VA and PA-LA. Furthermore, some of the reasons for this general decrease in peak dose can be found in the design and modeling changes to the waste package. For example, the inner handling canister for CSNF reduced the susceptibility of CSNF containers to seismic damage.

The use of a CDF or CCDF of peaks more readily shows the effects of uncertainty in model calculations over the range of peak times between 10^4 and 10^6 years. Although there was a general decrease in peak dose between iterations, the change in the spread of the results (i.e. uncertainty) was not consistently reduced (Fig. 4). For example, PA-SR purposely added a conservative bias of uncertainty. This conservative bias was greatly reduced for the more realistic SSPA analysis and resulted in a spread in the doses similar to PA-VA.

Throughout the PA iterations, most parameters that explained the spread in results were related to the geologic barrier.[21, Table 2; 27; 28, Table 1] Although conceptual model uncertainty was reduced in the geologic barrier, the uncertainty in parameters values remained substantial. In addition, parameters related to the corrosion resistant waste container, a major feature in later PAs, had a strong influence on both the absolute value and variability of dose.[27; 28, Table 1]

The times of the peak dose ranged from 3250 to 10^6 years in PA-LA. The distribution was skewed toward 10^6 years and flatter than a lognormal distribution. Also, the median time of the peak (6.2×10^5 years) was somewhat greater than the mean (5.5×10^5 years) (Fig. 5).

As noted earlier, PMA greatly reduced releases and thereby doses from seismic disruption and general corrosion of the waste package such that doses occurred primarily because of igneous intrusion. [17; 21] The times of the peaks in the PMA had a somewhat narrower range: 2.5×10^5 to 10^6 years. Also, the time of peaks were clustered together, because one release phenomenon dominated (groundwater releases after igneous intrusion), The time of the peaks were also somewhat later and reasonably approximated by a log-normal distribution, with a mean and median of 6.5×10^5 and 6.6×10^5 years, respectively (Fig. 5).

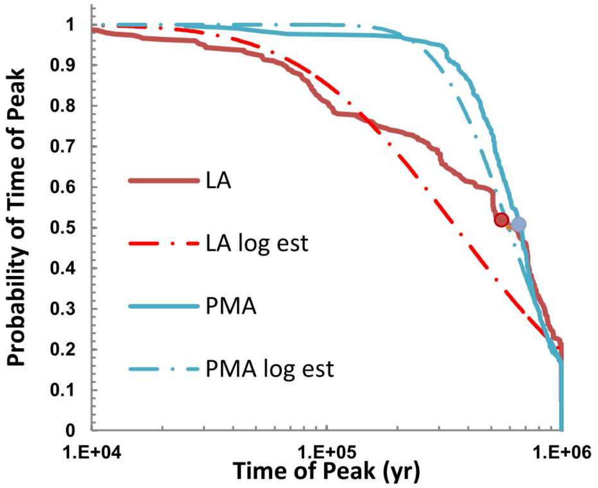


Fig. 5. Distribution of the time of expected peak dose in individual simulations for PA-LA and PMA.

V. INSIGHT

In general, both the expected total dose as a function of time (Fig. 2) and the CCDF of peak doses (Fig. 4) are useful as performance measures of dose. However, the usefulness of expected total dose is greatly enhanced by also displaying the dose history of the individual simulations and the various quantiles (e.g., 5th, 50th, and 95th quantiles) to show the range of behavior (Fig. 3), as requested by NRC review guidance for 10 CFR 63.

A CCDF of peak doses provides a convenient summary measure for discerning differences in the behavior of conceptual models and design options (Fig. 4). In addition, a CCDF of peak dose more readily shows the range of uncertainty in peak dose and the probability that the peak dose will be exceeded. However, the CCDF does not show when those peaks occur unless the distribution of time of peaks is also displayed (Fig. 5).

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