SAND2008-3073C

YUCCA MOUNTAIN 2008 PERFORMANCE ASSESSMENT: CONCEPTUAL STRUCTURE AND COMPUTATIONAL ORGANIZATION

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The conceptual structure and computational organization of the 2008 performance assessment (PA) for the proposed high-level radioactive waste repository at Yucca Mountain, Nevada, are described. This analysis was carried out to support the License Application by the U.S. Department of Energy (DOE) to the U.S. Nuclear Regulatory Commission (NRC) for the indicated repository. In particular, the analysis was carried out to establish compliance with the postclosure requirements specified by the NRC in proposed 10 CFR Part 63. The requirements in 10 CFR Part 63 result in a PA that involves three basic entities: (EN1) a characterization of the uncertainty in the occurrence of future events (e.g., igneous events, seismic events) that could affect the performance of the repository; (EN2) models for predicting the physical behavior and evolution of the repository (e.g., systems of ordinary and partial differential equations); and (EN3) a characterization of the uncertainty associated with analysis inputs that have fixed but imprecisely known values (e.g., the appropriate spatially-averaged value for a distribution coefficient). The designators aleatory and epistemic are commonly used for the uncertainties characterized by entities (EN1) and (EN3). The manner in which the preceding entities are defined and organized to produce a complete postclosure PA for the proposed Yucca Mountain repository are described.

I. INTRODUCTION

The appropriate disposal of radioactive waste from military and commercial activities is a challenge of national and international importance. As part of the solution to this challenge, a proposed deep geologic repository for high-level radioactive waste is under development by the U.S. Department of Energy (DOE) at Yucca Mountain (YM), Nevada. The development of the YM repository is the single most important radioactive waste disposal project currently being undertaken in the United States. The following presentation provides a description of the conceptual structure and computational organization of the 2008 performance assessment (PA) for the proposed YM repository.

II. REGULATORY BACKGROUND

As mandated in the Energy Policy Act of 1992 [1], the U.S. Environmental Protection Agency (EPA) is required to promulgate public health and safety standards for radioactive material stored or disposed of in the YM repository; the U.S. Nuclear Regulatory Commission (NRC) is required to incorporate the EPA standards into licensing standards for the YM repository; and the DOE is required to show compliance with the NRC standards. The regulatory requirements for the YM repository that resulted from these mandates have three primary sources: (i) *Public Health and Environmental Protection Standards for Yucca Mountain, NV; Final Rule* (40 CFR Part 197) [2], which has been promulgated by the EPA, (ii) *Disposal of High-Level Radioactive Wastes in a Proposed Geologic Repository at Yucca Mountain, Nevada; Final Rule* (10 CFR Parts 2, 19, 20, etc.) [3], which has been promulgated by the NRC, and (iii) *Yucca Mountain Review Plan; Final Report* (YMRP) [4], which has been published by the NRC to guide assessing compliance with 10 CFR Parts 2, 19, 20, etc. In turn, the DOE is required to carry out a PA for the YM repository that satisfies the requirements specified in the preceding three documents.

The initial promulgations indicated above specified conditions that the Yucca Mountain facility was required to satisfy for the first 10,000 yr after its closure. In a subsequent suit [5], it was ruled that the EPA did not follow guidance in a National Academy of Science (NAS) study [6] as mandated by Congress in the Energy Policy Act of 1992. In particular, it was ruled that the EPA had failed to follow the guidance in the NAS study that the regulatory period for the Yucca Mountain facility should extend over the period of geologic stability at the facility site, which was suggested to be 10^6 yr. As a result, the initial regulation for the YM facility was remanded to the EPA for revision.

In response to this remand, the EPA published 40 CFR Part 197, *Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada; Proposed Rule* [7], which contained proposed revisions to the standards for the Yucca Mountain facility. In turn and in consistency with the EPA's proposed revisions, the NRC published proposed 10 CFR Part 63, *Implementation of a Dose Standard After 10,000 Years* [8]. The EPA's and NRC's proposals in response to the remand left the requirements for the first 10,000 yr after repository closure unchanged. However, new conditions were proposed for the time interval from 10,000 yr to the period of geologic stability.

The overall structure of the 2008 YM PA derives from the individual protection standard specified by the EPA and the NRC. Specifically, the following standard is specified by the NRC ([8], p. 53319):

§ 63.311 Individual protection standard after permanent closure. (a) DOE must demonstrate, using performance assessment, that there is a reasonable expectation that the reasonably maximally exposed individual receives no more than the following annual dose from releases from the undisturbed Yucca Mountain disposal system: (1) 0.15 mSv (15 mrem) for 10,000 years following disposal; and (2) 3.5 mSv (350 mrem) after 10,000 years, but within the period of geologic stability. (b) DOE's performance assessment must include all potential environmental pathways of radionuclide transport and exposure. (NRC1)

Except for minor differences in wording, the preceding standard is the same as the proposed standard specified by the EPA ([7], p. 49063).

In turn, the NRC proposes the following guidance on implementing the preceding individual protection standard ([8], p. 53319):

§ 63.303 Implementation of Subpart L. (a) Compliance is based upon the arithmetic mean of the projected doses from DOE's performance assessments for the period within 10,000 years after disposal for: (1) § 63.311(a)(1); and (2) §§ 63.321(b)(1) and 63.331, if performance assessment is used to demonstrate compliance with either or both of these sections. (b) Compliance is based upon the median of the projected doses from DOE's performance assessments for the period after 10,000 years of disposal and through the period of geologic stability for: (1) § 63.311(a)(2); and (2) § 63.321(b)(2), if performance assessment is used to demonstrate compliance. (NRC2)

Again, the preceding is the same as the corresponding guidance given by the EPA ([7], p. 49063).

As indicated in (NRC1) and (NRC2), the NRC expects the determination of mean and median dose to the RMEI to be based on a detailed PA. This expectation is further emphasized by the following statement in the YMRP ([4], p. 2.2-1):

Risk-Informed Review Process for Performance Assessment—The performance assessment quantifies repository performance, as a means of demonstrating compliance with the postclosure performance objectives at 10 CFR 63.113. The U.S. Department of Energy performance assessment is a systematic analysis that answers the triplet risk questions: what can happen; how likely is it to happen; and what are the consequences. (NRC3)

For convenience, the preceding questions can be represented by (Q1) "What can happen?", (Q2) "How likely is it to happen?", and (Q3) "What are the consequences if it does happen?". The preceding questions provide the intuitive basis for the Kaplan/Garrick ordered triple representation for risk:

$$(\mathcal{S}_i, p\mathcal{S}_i, \boldsymbol{c}\boldsymbol{\mathcal{S}}_i),\ i = 1, 2, \ldots, n\mathcal{S}, \tag{1}$$

where (i) $\mathcal{S}_i$ is a set of similar occurrences (i.e., an answer to Q1), (ii) $p\mathcal{S}_i$ is the probability of $\mathcal{S}_i$ (i.e., the answer to Q2 corresponding to $\mathcal{S}_i$), and (iii) $\boldsymbol{c}\boldsymbol{\mathcal{S}}_i$ is a vector of consequences associated with $\mathcal{S}_i$ (i.e., the answer to Q3). Further, the $\mathcal{S}_i$ must be disjoint (i.e., $\mathcal{S}_i \cap \mathcal{S}_j = \varnothing$ for $i \neq j$); each $\mathcal{S}_i$ must be sufficiently homogeneous to allow use of a single representative consequence vector $\boldsymbol{c}\boldsymbol{\mathcal{S}}_i$; and $\cup_i \mathcal{S}_i$ must contain all risk significant occurrences for the facility under consideration.

In addition, there is a fourth basic question that underlies the 2008 YM PA and, indeed, all complete PAs: (Q4) " What is the uncertainty in the answers to the initial three questions?". The importance of answering this fourth question is emphasized in a number of statements by the NRC. For example,

For such long-term performance, what is required is reasonable expectation, making allowance for the time period, hazards, and uncertainties involved, that the outcome will conform with the objectives for postclosure performance for the geologic repository. Demonstrating compliance will involve the use of complex predictive models that are supported by limited data from field and laboratory tests, site-specific monitoring, and natural analog studies that may be supplemented with prevalent expert judgment. Compliance demonstrations should not exclude important parameters from assessments and analyses simply because they are difficult to precisely quantify to a high degree of confidence. The performance assessments and analyses should focus upon the full range of defensible and reasonable parameter distributions rather than only upon extreme physical situations and parameter values ([3], p. 55804). (NRC4)

Once again, although the criteria may be written in unqualified terms, the demonstration of compliance must take uncertainties and gaps in knowledge into account so that the Commission can make the specified finding with respect to paragraph (a)(2) of § 63.31 ([3], p. 55804). (NRC5)

Both the preceding statements clearly indicate that a reasonable treatment of uncertainty should be a fundamental part of a PA used to support a licensing application for the Yucca Mountain facility.

III. CONCEPTUAL STRUCTURE

The requirements in 10 CFR Part 63 result in a PA that involves three basic entities: (EN1) a characterization of the uncertainty in the occurrence of future events (e.g., igneous events, seismic events) that could affect the performance of the repository; (EN2) models for predicting the physical behavior and evolution of the repository (e.g., systems of ordinary and partial differential equations); and (EN3) a characterization of the uncertainty associated with analysis inputs that have fixed but imprecisely known values (e.g., the appropriate spatially-averaged value for a distribution coefficient). The designators aleatory and epistemic are commonly used for the uncertainties characterized by entities (EN1) and (EN3).

In the preceding, aleatory uncertainty is used in the designation of randomness in the possible future conditions that could affect the Yucca Mountain repository. In concept, each possible future at the Yucca Mountain repository can be represented by a vector

$$\mathbf{a} = [a_1, a_2, \ldots, a_{nA}], \quad (2)$$

where each a_i is a specific property of the future $\mathbf{a}$ (e.g., time of a seismic event, size of a seismic event, …). In turn, a subset $\mathcal{S}$ of the set $\mathcal{A}$ of all possible values for $\mathbf{a}$ constitutes what is referred to as a scenario class in the TSPA-LA. As part of the TSPA-LA development, a probabilistic structure is imposed on the set $\mathcal{A}$. Formally, this corresponds to defining a probability space ($\mathcal{A}$, A, p_A) for aleatory uncertainty. Then, A is the set of all possible scenario classes, and p_A is the function that defines scenario class probability (i.e., scenario class $\mathcal{S}$ is an element of A and $p_A(\mathcal{S})$ is the probability of scenario class $\mathcal{S}$). Formally, the probability space ($\mathcal{A}$, A, p_A) provides a characterization of aleatory uncertainty and constitutes the first of the three basic mathematical entities that underlie the determination of expected dose.

Although useful conceptually and notationally, the probability space ($\mathcal{A}$, A, p_A) is never explicitly defined in the TSPA-LA. Rather, the characterization of aleatory uncertainty enters the analysis through the definition of probability distributions for the individual elements of $\mathbf{a}$. Conceptually, the distributions for the elements of $\mathbf{a}$ lead to a distribution for $\mathbf{a}$ and an associated density function $d_A(\mathbf{a})$. The nature of the probability space ($\mathcal{A}$, A, p_A) in the context of the 2008 YM PA is summarized in Table I.

TABLE I. ALEATORY UNCERTAINTY IN THE YM 2008 PA

Individual Futures:

$$\mathbf{a} = [nEW, nED, nII, nIE, nSG, nSF, \mathbf{a}_{EW}, \mathbf{a}_{ED}, \mathbf{a}_{II}, \mathbf{a}_{IE}, \mathbf{a}_{SG}, \mathbf{a}_{SF}]$$

where, for a time interval [*a*, *b*], *nEW* = number of early WP failures, *nED* = number of early DS failures, *nII* = number of igneous intrusive events, *nIE* = number of igneous eruptive events, *nSG* = number of seismic ground motion (GM) events, *nSF* = number of seismic fault displacement (FD) events, $\mathbf{a}_{EW}$ = vector defining the *nEW* early WP failures, $\mathbf{a}_{ED}$ = vector defining the *nED* early DS failures, $\mathbf{a}_{II}$ = vector defining the *nII* igneous intrusive events, $\mathbf{a}_{IE}$ = vector defining the *nIE* igneous eruptive events, $\mathbf{a}_{SG}$ = vector defining the *nSG* seismic ground motion events, and $\mathbf{a}_{SF}$ = vector defining the *nSF* fault displacement events.

Sample Space for Aleatory Uncertainty: $\mathcal{A} = \{\mathbf{a} : \mathbf{a} = [nEW, nED, nII, nIE, nSG, nSF, \mathbf{a}_{EW}, \mathbf{a}_{ED}, \mathbf{a}_{II}, \mathbf{a}_{IE}, \mathbf{a}_{SG}, \mathbf{a}_{SF}]\}$

High-Level Scenario Classes:

Nominal, $\mathcal{A}_N = \{\mathbf{a} : \mathbf{a} \in \mathcal{A} \text{ and } nEW = nED = nII = nIE = nSG = nSF = 0\}$

Early WP failure, $\mathcal{A}_{EW} = \{\mathbf{a} : \mathbf{a} \in \mathcal{A} \text{ and } nEW \geq 1\}$; Early DS failure, $\mathcal{A}_{ED} = \{\mathbf{a} : \mathbf{a} \in \mathcal{A} \text{ and } nED \geq 1\}$

Igneous intrusive, $\mathcal{A}_{II} = \{\mathbf{a} : \mathbf{a} \in \mathcal{A} \text{ and } nII \geq 1\}$; Igneous eruptive, $\mathcal{A}_{IE} = \{\mathbf{a} : \mathbf{a} \in \mathcal{A} \text{ and } nIE \geq 1\}$

Seismic ground motion, $\mathcal{A}_{SG} = \{\mathbf{a} : \mathbf{a} \in \mathcal{A} \text{ and } nSG \geq 1\}$; Seismic fault displacement., $\mathcal{A}_{SF} = \{\mathbf{a} : \mathbf{a} \in \mathcal{A} \text{ and } nSF \geq 1\}$

Scenario Class Probabilities:

$p_A(\mathcal{A}_N)$ = prob of no disruptions of any kind

$p_A(\mathcal{A}_{EW})$ = prob of one or more early WP failures ; $p_A(\mathcal{A}_{ED})$ = prob of one or more early DS failures

$p_A(\mathcal{A}_{II})$ = prob of one or more igneous intrusive events ; $p_A(\mathcal{A}_{IE})$ = prob of one or more igneous eruptive events

$p_A(\mathcal{A}_{SG})$ = prob of one or more seismic GM events; $p_A(\mathcal{A}_{SF})$ = prob of one or more seismic FD events

The second of the three basic mathematical entities that underlie the determination of expected dose is a model that estimates dose to the RMEI. Formally, this model can be represented by the function

$D(\tau|\mathbf{a})$ = dose to RMEI (mrem/yr) at time τ (yr) conditional on the occurrence of the future represented by $\mathbf{a}$. (3)

Technically, $D(\tau|\mathbf{a})$ is the committed 50 yr dose to the RMEI that results from radiation exposure incurred in a single year. In the computational implementation of the TSPA-LA, $D(\tau|\mathbf{a})$ is only on of the results calculated with the GoldSim program for the particular analysis configuration defined for the future $\mathbf{a}$. In practice, many results are calculated for $\mathbf{a}$ in addition to dose to the RMEI. Thus, $D(\tau|\mathbf{a})$ is part of a vector containing at least several thousand elements. For notational convenience, this paper presents the analysis for dose to the RMEI $D(\tau|\mathbf{a})$; however, other TSPA-LA results can be handled in exactly the same manner as described for dose. The general nature of $D(\tau|\mathbf{a})$ is described in several following presentations [9-11].

The third of the three basic mathematical entities that underlie the determination of expected dose. is a probabilistic characterization of epistemic uncertainty. Here, epistemic uncertainty refers to a lack of knowledge with respect to the appropriate value to use for a quantity that is assumed to have constant or fixed value in the context of a specific analysis. Specifically, epistemic uncertainty relates to a vector of the form

$$\begin{aligned}\mathbf{e} &= [\mathbf{e}_A, \mathbf{e}_M] \\ &= [e_{A1}, e_{A2}, \ldots, \cdots e_{A,nAE}, e_{M1}, e_{M2}, \ldots, e_{M,nME}] \\ &= [e_1, e_2, \ldots, e_{nE}],\ nE = nAE + nME,\end{aligned} \quad (4)$$

where

$$\mathbf{e}_A = [e_{A1}, e_{A2}, \ldots, e_{A,nAE}]$$

is a vector of epistemically uncertain quantities used in the characterization of aleatory uncertainty (e.g., a rate term that defines a Poisson process) and

$$\mathbf{e}_M = [e_{M1}, e_{M2}, \ldots, e_{M,nME}]$$

is a vector of epistemically uncertain quantities used in the determination of dose (e.g., a distribution coefficient).

Epistemic uncertainty results in a set $\mathcal{E}$ of possible values for $\mathbf{e}$. In turn, probability is used to characterize the level of likelihood or credence that can be assigned to various subsets of $\mathcal{E}$. In concept, this leads to a probability space ($\mathcal{E}$, E, p_E) for epistemic uncertainty. Like the probability space ($\mathcal{A}$, A, p_A) for aleatory uncertainty, the probability space ($\mathcal{E}$, E, p_E) for epistemic uncertainty is useful conceptually and notationally but is never explicitly defined in the TSPA-LA. Rather, the characterization of epistemic uncertainty enters the analysis through the definition of probability distributions for the individual elements of $\mathbf{e}$. These distributions serve as mathematical summaries of all available information with respect to where the appropriate values for individual elements of $\mathbf{e}$ are located for use in the TSPA-LA. Conceptually, the distributions for the elements of $\mathbf{e}$ lead to a distribution for $\mathbf{e}$ and an associated density function $d_E(\mathbf{e})$. The nature of the probability space ($\mathcal{E}$, E, p_E) in the context of the 2008 YM PA is summarized in Table II.

TABLE II. EXAMPLES OF THE 392 EPISTEMICALLY UNCERTAIN VARIABLES IN THE YM 2008 PA

ASHDENS - Tephra settled density (kg/m^3). *Distribution:* Truncated normal.. *Range:* 300 to 1500. *Mean:* 1000. *Standard Deviation:* 100.
IGRATE - Frequency of intersection of the repository footprint by a volcanic event (yr^{-1}). *Distribution:* Piecewise uniform. *Range:* 0 to 7.76E-07.
INFIL - Pointer variable for determining infiltration conditions: 10th, 30th, 50th or 90th percentile infiltration scenario (dimensionless). *Distribution:* Discrete. *Range:* 1 to 4.
MICPU239 - Groundwater biosphere dose conversion factor (BDCF) for ^{239}Pu in modern interglacial climate ((Sv/year)/(Bq/m^3)). *Distribution:* Discrete. *Range:* 3.49E-07 to 2.93E-06. *Mean:* 9.55E-07.
SZFISPVO - Flowing interval spacing in fractured volcanic units (m). *Distribution:* Piecewise uniform. *Range:* 1.86 to 80.

IV. EXPECTED DOSE, MEAN DOSE, MEDIAN DOSE

Now that the characterization of epistemic uncertainty has been introduced, the notations used to represent aleatory uncertainty and dose need to be expanded. Because the representation of aleatory uncertainty depends on elements of the vector $\mathbf{e}_A$, each possible value for $\mathbf{e}_A$ could lead to a different probability space ($\mathcal{A}$, A, p_A) for aleatory uncertainty. For notational convenience, this dependence will be indicated by representing the density function associated with aleatory uncertainty by $d_A(\mathbf{a}|\mathbf{e}_A)$. Similarly, the determination of dose depends on elements of the vector $\mathbf{e}_M$, with each possible value for $\mathbf{e}_M$ potentially leading to different dose results. For notational convenience, this dependence will be indicated by representing the dose function by $D(\tau|\mathbf{a}, \mathbf{e}_M)$.

The probability space ($\mathcal{A}$, A, p_A) for aleatory uncertainty characterized by the density function $d_A(\mathbf{a}|\mathbf{e}_A)$, the dose function $D(\tau|\mathbf{a}, \mathbf{e}_M)$, and the probability space ($\mathcal{E}$, E, p_E) for epistemic uncertainty characterized by the density function $d_E(\mathbf{e})$ constitute the three basic parts of the YM PA that come together in the determination of expected dose to the RMEI and the uncertainty in expected dose to the RMEI. Specifically, the expected value for dose at time τ conditional on a specific element $\mathbf{e} = [\mathbf{e}_A, \mathbf{e}_M]$ of $\mathcal{E}$ is given by

$$\begin{aligned}\bar{D}(\tau|\mathbf{e}) &= E_A\left[D(\tau|\mathbf{a}, \mathbf{e}_M)\middle|\mathbf{e}_A\right] \\ &= \int_{\mathcal{A}} D(\tau|\mathbf{a}, \mathbf{e}_M)\, d_A(\mathbf{a}|\mathbf{e}_A)\,\mathrm{d}A,\end{aligned} \quad (5)$$

where $E_A[D(\tau|\mathbf{a}, \mathbf{e}_M)|\mathbf{e}_A]$ denotes expectation over aleatory uncertainty.

In turn, the uncertainty associated with the estimation of $\bar{D}(\tau\,|\,\mathbf{e})$ can be determined from the properties of the probability space ($\mathcal{E}$, E, p_E) for epistemic uncertainty. In particular, the cumulative distribution function (CDF) for $\bar{D}(\tau\,|\,\mathbf{e})$ and the expected value for $\bar{D}(\tau\,|\,\mathbf{e})$ that derive from epistemic uncertainty are given by

$$\begin{aligned}&p_E\left[\bar{D}(\tau|\mathbf{e}) \le D\right] = \int_{\mathcal{E}} \underline{\delta}_D\left[\bar{D}(\tau|\mathbf{e})\right] d_E(\mathbf{e})\,\mathrm{d}E \\ &= \int_{\mathcal{E}} \underline{\delta}_D\left[\int_{\mathcal{A}} D(\tau|\mathbf{a}, \mathbf{e}_M)\, d_A(\mathbf{a}|\mathbf{e}_A)\,\mathrm{d}A\right] d_E(\mathbf{e})\,\mathrm{d}E\end{aligned} \quad (6)$$

and

$$\bar{\bar{D}}(\tau) = E_E\left[\bar{D}(\tau|\mathbf{e})\right] = \int_{\mathcal{E}} \bar{D}(\tau|\mathbf{e})\, d_E(\mathbf{e})\,\mathrm{d}E, \quad (7)$$

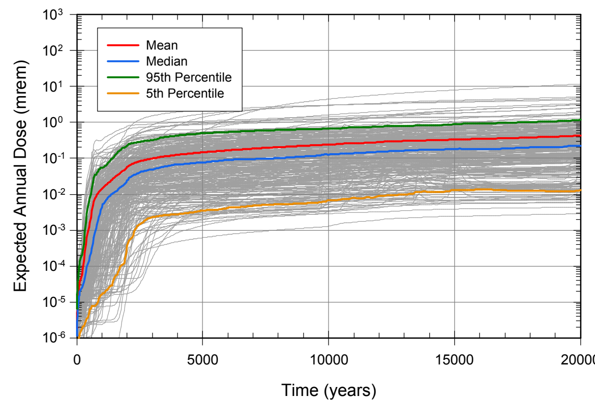
respectively, where

$$\underline{\delta}_D\left[\bar{D}(\tau\,|\,\mathbf{e})\right] = \begin{cases}1 & \text{if } \bar{D}(\tau\,|\,\mathbf{e}) \le D \\ 0 & \text{if } \bar{D}(\tau\,|\,\mathbf{e}) > D\end{cases}$$

and $E_E[\bar{D}(\tau\,|\,\mathbf{e})]$ denotes expectation over epistemic uncertainty.

The individual grey curves in Fig. 1 correspond to expected doses $\bar{D}(\tau\,|\,\mathbf{e})$ as defined in Eq. (5). The totality of the grey curves provides a display of the uncertainty in $\bar{D}(\tau\,|\,\mathbf{e})$ that derives from the uncertainty in $\mathbf{e}$. The red curve in Fig. 1 corresponds to the mean dose $\bar{\bar{D}}(\tau)$ defined in Eq. (7) and used in comparisons with the 10^4 yr standard as specified in Quotes (NRC1) and (NRC2).

FIG. 1 EXPECTED, MEAN AND MEDIAN CURVES FOR DOSE TO THE RMEI.



The value of D for which

$$q = p_E\left[\bar{D}(\tau|\mathbf{e}) \le D\right] = \int_{\mathcal{E}} \underline{\delta}_D\left[\bar{D}(\tau|\mathbf{e})\right] d_E(\mathbf{e})\,\mathrm{d}E \quad (8)$$

defines the q quantile (e.g., q = 0.05, 0.5, 0.95) for the distribution of expected dose over epistemically uncertain analysis inputs. For notational purposes, the value of D corresponding to the q quantile of $\bar{D}(\tau\,|\,\mathbf{e})$ defined in Eq. (8) will be represented by $Q_{E,q}[\bar{D}(\tau\,|\,\mathbf{e})]$. The blue curve in Fig. 1 corresponds to the median dose $Q_{E,0.5}[\bar{D}(\tau\,|\,\mathbf{e})]$ defined in Eq. (7) for q = 0.5 and used in comparisons with the proposed post 10^4 yr standard as specified in Quotes (NRC1) and (NRC2).

V. COMPUTATIONAL IMPLEMENTATION

Evaluation of expected, mean and median dose as described in the preceding section presents two overarching challenges. First, it is necessary to evaluate integrals over the set $\mathcal{A}$ to obtain expected doses over aleatory uncertainty. Second, it is necessary to evaluate integrals over the set $\mathcal{E}$ to obtain mean and median doses over aleatory and epistemic uncertainty.

Evaluation of integrals over the set $\mathcal{A}$ is considered first. These evaluations are accomplished under the assumption that there are no synergisms between the effects of the disruptions associated with the individual scenario classes that would significantly affect the expected dose $\bar{D}(\tau\,|\,\mathbf{e})$. Thus, dose can be approximated as the sum of the doses attributable to the individual scenario classes:

$$D(\tau|\mathbf{a}, \mathbf{e}) \cong D_N(\tau|\mathbf{e}_M) + \sum_{C \in \mathcal{MC}} D_C(\tau|\mathbf{a}, \mathbf{e}_M) \quad (9)$$

As a result and with the assumption that nominal process releases occur for all scenario classes, $\bar{D}(\tau \mid \mathbf{e})$ can be approximated as indicated in Table III.

TABLE III. DECOMPOSITION OF EXPECTED DOSE $\bar{D}(\tau \mid \mathbf{e})$ INTO EXPECTED DOSES $\bar{D}_C(\tau \mid \mathbf{e})$ FROM INDIVIDUAL SCENARIO CLASSES

$$\begin{aligned}
\bar{D}(\tau|\mathbf{e}) &\cong \int_{\mathcal{A}} \left\{ D_N(\tau|\mathbf{e}_M) + \sum_{C \in \mathcal{MC}} D_C(\tau|\mathbf{a},\mathbf{e}_M) \right\} d_A(\mathbf{a}|\mathbf{e}_A)\,\mathrm{d}A \\
&= D_N(\tau|\mathbf{e}_M) + \sum_{C \in \mathcal{MC}} \int_{\mathcal{A}} D_C(\tau|\mathbf{a},\mathbf{e}_M) d_A(\mathbf{a}|\mathbf{e}_A)\,\mathrm{d}A \\
&= D_N(\tau|\mathbf{e}_M) + \sum_{C \in \mathcal{MC}} \int_{\mathcal{A}_C} D_C(\tau|\mathbf{a},\mathbf{e}_M) d_A(\mathbf{a}|\mathbf{e}_A)\,\mathrm{d}A \\
&= D_N(\tau|\mathbf{e}_M) + \sum_{C \in \mathcal{MC}} \bar{D}_C(\tau|\mathbf{e})
\end{aligned}$$

where $\mathcal{MC} = \{EW, ED, II, IE, SG, SF\}$

Given the decomposition in Table III, $\bar{D}(\tau \mid \mathbf{e})$ can be approximated by (i) approximating $D_N(\tau|\mathbf{e})$ (reduce font of **e**) and individually approximating the integrals defining the expected doses $\bar{D}_C(\tau \mid \mathbf{e})$ as indicated in Table IV and then (ii) adding these approximations to obtain an approximation to $\bar{D}(\tau \mid \mathbf{e})$.

TABLE IV. INTEGRATION PROCEDUES USED TO OBTAIN EXPECTED DOSE $\bar{D}_C(\tau \mid \mathbf{e})$ FOR INDIVIDUAL SCENARIO CLASSES IN THE YM 2008 PA

Nominal Conditions: $D_N(\tau \mid \mathbf{e})$
- Calculated separately for $[0, 2 \times 10^4$ yr]
- Combined with seismic ground motion for $[0, 10^6$ yr]

Early WP and DS Failures: $\bar{D}_{WP}(\tau \mid \mathbf{e})$, $\bar{D}_{DS}(\tau \mid \mathbf{e})$
- Summation of probabilistically weighted results for individual failures

Igneous Intrusive Events: $\bar{D}_{II}(\tau \mid \mathbf{e})$
- Quadrature procedure

Igneous Eruptive Events
- Combined Quadrature/Monte Carlo procedure

Seismic Ground Motion Events: $\bar{D}_{SG}(\tau \mid \mathbf{e})$
- Quadrature procedure for $[0, 2 \times 10^4$ yr]
- Monte Carlo procedure for $[0, 10^6$ yr]

Seismic Fault Displacement Events: $\bar{D}_{SF}(\tau \mid \mathbf{e})$
- Quadrature procedure

The mean dose $\bar{\bar{D}}(\tau)$ and the median dose $Q_{E,0.5}[\bar{D}(\tau \mid \mathbf{e})]$ are defined by integrals over the set $\mathcal{E}$ of epistemically uncertain analysis inputs as indicated in Eqs. (7) and (8). In the YM 2008 PA, these integrals are approximated with use of a Latin hypercube sample (LHS)

$$\mathbf{e}_i = [\mathbf{e}_{Ai}, \mathbf{e}_{Mi}],\ i = 1, 2, \ldots, nLHS, \tag{10}$$

generated in consistency with the definition of the probability space $(\mathcal{E}, \mathbb{E}, p_E)$ (i.e., in consistency with the distributions defined for the individual elements of **e**). Then, $\bar{\bar{D}}(\tau)$ and $p_E[\bar{D}(\tau \mid \mathbf{e}) \le D]$ are approximated by

$$\bar{\bar{D}}(\tau) \cong \sum_{i=1}^{nLHS} \bar{D}(\tau|\mathbf{e}_i) / nLHS \tag{11}$$

and

$$p_E\left[\bar{D}(\tau|\mathbf{e}) \le D\right] \cong \sum_{i=1}^{nLHS} \underline{\delta}_D\left[\bar{D}(\tau|\mathbf{e}_i)\right] / nLHS, \tag{12}$$

respectively. Further, this sample can be used in a numerical determination of the quantiles $Q_{E,q}[\bar{D}(\tau \mid \mathbf{e})]$ for $\bar{D}(\tau \mid \mathbf{e})$ defined in Eq. (8). Analogous approximations to mean and median doses over epistemic uncertainty also exist for the individual scenario classes.

VI. SUMMARY

As described, the conceptual and computational structure of the YM 2008 PA is based on three basic entities: (EN1) a characterization of the uncertainty in the occurrence of future events that could affect the performance of the repository (i.e., a probability space $(\mathcal{A}, \mathbb{A}, p_A)$ characterizing aleatory uncertainty), (EN2) models for predicting the physical behavior and evolution of the repository system (i.e., a very complex function $D(\tau|\mathbf{a},$

$\mathbf{e}_M$) that predicts dose to the RMEI and a large number of additional analysis results), and (EN3) a characterization of the uncertainty associated with analysis inputs that have fixed but imprecisely known values (i.e., a probability space ($\mathcal{E}$, E, p_E) characterizing epistemic uncertainty).

This paper summarizes the first presentation in a special session intended to provide an overview on the YM 2008 PA. Following presentations in the session provide summaries of (i) the development and use of the models that collectively constitute the function $D(\tau|\mathbf{a}, \mathbf{e}_M)$ [9-11], (ii) the performance of uncertainty and sensitivity analyses for physical processes based on $D(\tau|\mathbf{a}, \mathbf{e}_M)$ and the characterization of epistemic uncertainty provided by ($\mathcal{E}$, E, p_E) [12], (iii) the performance of uncertainty and sensitivity analyses for expected dose to the RMEI based on the characterization of aleatory uncertainty provided by ($\mathcal{A}$, A, p_A), the function $D(\tau|\mathbf{a}, \mathbf{e}_M)$ and the characterization of epistemic uncertainty provided by ($\mathcal{E}$, E, p_E) [13], and (iv) a summary of the YM 2008 PA in the context of the regulatory requirements specified by the NRC in 10 CFR Part 63 [14].

Additional and more detailed information on the YM 2008 PA is available in a detailed analysis report [15] and in the references cited in this report.

ACKNOWLEDGMENTS

Work performed at Sandia National Laboratories (SNL), which is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Department of Energy's National Nuclear Security Administration under Contract No. DE-AC04-04AL85000. Review at SNL provided by ???? and ????.

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