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Conceptual Structure of Performance Assessments Conducted for the Waste Isolation Pilot Plant

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ABSTRACT

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PREFACE

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CONCEPTUAL STRUCTURE OF PERFORMANCE ASSESSMENTS CONDUCTED FOR THE WASTE ISOLATION PILOT PLANT

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ABSTRACT

The Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico is being developed by the U.S. Department of Energy as a disposal facility for transuranic waste. In support of this project, Sandia National Laboratories is conducting an ongoing performance assessment (PA) for the WIPP. The ordered triple representation for risk proposed by Kaplan and Garrick is used to provide a clear conceptual structure for this PA. This presentation describes how the preceding representation provides a basis in the WIPP PA for (1) the definition of scenarios and the calculation of scenario probabilities and consequences, (2) the separation of subjective and stochastic uncertainties, (3) the construction of the complementary cumulative distribution functions required in comparisons with the U.S. Environmental Protection Agency's standard for the geologic disposal of radioactive waste (i.e., 40 CFR Part 191, Subpart B), and (4) the performance of uncertainty and sensitivity studies. Results obtained in a preliminary PA for the WIPP completed in December of 1991 are used for illustration.

INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico is being developed by the U.S. Department of Energy as a disposal facility for transuranic waste.[1-3] In support of this project, Sandia National Laboratories is conducting an ongoing performance assessment (PA) for the WIPP.[4,5] At present, a PA is carried out each year to summarize what is known about the WIPP and to provide guidance for future work.[6-8] It is anticipated that these iterative PAs will continue until the WIPP is either licensed for the disposal of transuranic waste or found to be unsuitable for such disposal.

The WIPP is a complex facility, with the result that carrying out a PA is a large undertaking. Successful organization and execution of this undertaking requires a clear conceptual structure for the PA. This presentation provides an overview of the conceptual structure currently used in PAs for the WIPP and illustrates this structure with results from a PA completed in approximately December of 1991.[8-11]

CONCEPTUAL BASIS FOR STRUCTURE OF WIPP PERFORMANCE ASSESSMENT

As proposed by Kaplan and Garrick,[12] the outcome of a PA can be represented by a set R of ordered triples of the form

$$R = (S_i, pS_i, \mathbf{cS}_i), i=1, ..., nS , \tag{1}$$

where S_i is a set of similar occurrences, pS_i is the probability that an occurrence in the set S_i will take place, $\mathbf{cS}_i$ is a vector of consequences associated with S_i, nS is the number of sets selected for consideration, and the sets S_i have no occurrences in common (i.e., the S_i are disjoint sets).

This representation formally decomposes the outcome of a PA into what can happen (the $\mathcal{S}_i$), how likely things are to happen (the pS_i), and the consequences of what can happen (the $\mathbf{cS}_i$). The $\mathcal{S}_i$ are typically referred to as "scenarios" in radioactive waste disposal. Similarly, the pS_i are scenario probabilities, and the vector $\mathbf{cS}_i$ contains environmental releases for individual isotopes, the normalized release defined by the U.S. Environmental Protection Agency (EPA),[13] and possibly other information associated with scenario $\mathcal{S}_i$.

Although the representation in Eq. (1) provides a natural conceptual way to view risk, the set $\mathcal{R}$ by itself can be difficult to examine. For this reason, the risk results in $\mathcal{R}$ are often summarized with complementary cumulative distribution functions (CCDFs), which provide a display of the information contained in the probabilities pS_i and the vectors $\mathbf{cS}_i$. With the assumption that a particular consequence result cS in the vector $\mathbf{cS}$ has been ordered so that $cS_i \le cS_{i+1}$ for $i=1, \ldots, nS-1$, the associated CCDF is shown in Fig. 1. A consequence result of particular interest in performance assessments for radioactive waste disposal is the EPA normalized release to the accessible environment.[13,14] As indicated in Fig. 1, the EPA places a bound on the CCDF for normalized release to the accessible environment.

In practice, the outcome of a PA depends on many imprecisely known variables. These imprecisely known variables can be represented by a vector

$$\mathbf{x} = [x_1, x_2, \ldots, x_{nV}], \tag{2}$$

where each x_j is an imprecisely known input required in the PA and nV is the total number of such inputs. As a result, the set $\mathcal{R}$ is actually a function of $\mathbf{x}$:

$$\mathcal{R}(\mathbf{x}) = [\mathcal{S}_i(\mathbf{x}), pS_i(\mathbf{x}), \mathbf{cS}_i(\mathbf{x})], \; i=1, \ldots, nS(\mathbf{x}) \quad . \tag{3}$$

As $\mathbf{x}$ changes, so will $\mathcal{R}(\mathbf{x})$ and all summary measures that can be derived from $\mathcal{R}(\mathbf{x})$. Thus, rather than a single CCDF for each consequence value contained in $\mathbf{cS}$, there will be a distribution of CCDFs that results from the possible values that $\mathbf{x}$ can take on.

The uncertainty in $\mathbf{x}$ can be characterized by probability distributions

$$D_1, D_2, \ldots, D_{nV}, \tag{4}$$

where D_j is the distribution for the variable x_j contained in $\mathbf{x}$. The definition of these distributions may also be accompanied by the specification of correlations and various restrictions that further define the relations between the x_j. These distributions and other restrictions probabilistically characterize where the appropriate input to use in a PA might fall given that the analysis has been structured so that only one value can be used for each variable.

Once the distributions in Eq. (4) have been developed, Monte Carlo techniques can be used to determine the uncertainty in $\mathcal{R}(\mathbf{x})$ that results from the uncertainty in $\mathbf{x}$. First, a sample

$$\mathbf{x}_k = [x_{k1}, x_{k2}, \ldots, x_{k,nV}], \; k=1, \ldots, nK, \tag{5}$$

is generated according to the specified distributions and restrictions, where nK is the size of the sample. The PA is then carried out for each sample element $\mathbf{x}_k$, which yields the sequence of risk results

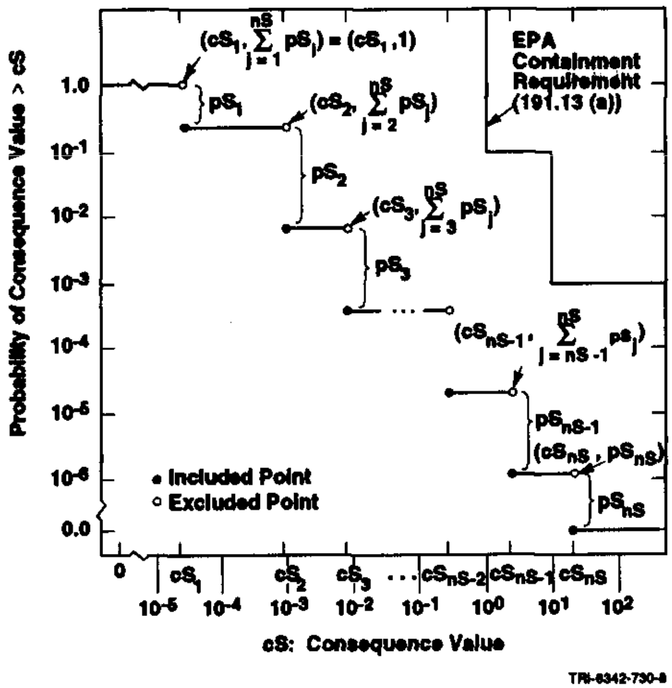

Fig. 1. Estimated CCDF for Consequence Result cS.

$$R(x_k) = [S_i(x_k),\ pS_i(x_k),\ cS_i(x_k)],\ i=1,\ \ldots,\ nS(x_k) \qquad (6)$$

for k=1, ..., nK. Each set $R(x_k)$ is the result of one complete PA carried out with a set of inputs (i.e., x_k) that the review process producing the distributions in Eq. (4) concluded was possible.

In most PAs, CCDFs are the results of greatest interest. For a particular consequence result, a CCDF will be produced for each set $R(x_k)$ shown in Eq. (6). This yields a distribution of CCDFs of the form shown in the left frame of Fig. 2, which can be summarized with mean and percentile curves as shown in the right frame.

An important distinction exists between the uncertainty that gives rise to a single CCDF in Fig. 2 and the uncertainty that gives rise to the distribution of CCDFs in this figure. A single CCDF arises from the fact that a number of different occurrences have a real possibility of taking place. This type of uncertainty is referred to as stochastic variation or uncertainty in this presentation. A distribution of CCDFs arises from the fact that fixed, but unknown, quantities are needed in the estimation of a CCDF. The development of distributions that characterize what the values for these fixed quantities might be leads to a distribution of CCDFs. In essence, a PA can be viewed as a very complex function that estimates a CCDF. Since there is uncertainty in the values of some of the variables operated on by this function, there will also be uncertainty in the dependent variable produced by this function, where this dependent variable is a CCDF.

Both Kaplan and Garrick[12] and a recent report by the International Atomic Energy Agency (IAEA)[15] distinguish between these two types of uncertainty. Specifically, Kaplan and Garrick distinguish between probabilities derived from frequencies and probabilities that characterize degrees of belief. Probabilities derived from frequencies correspond to the

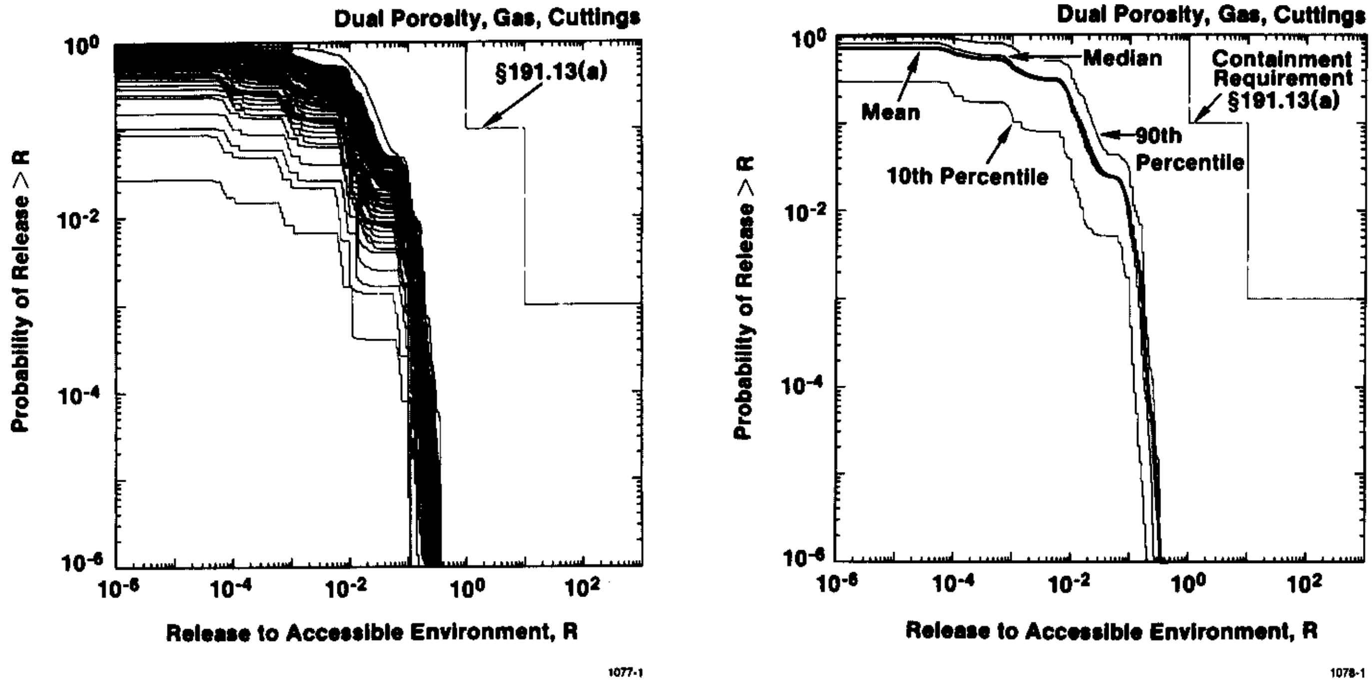

Fig. 2. Distribution of CCDFs for Normalized Release to the Accessible Environment Including Both Cuttings Removal and Groundwater Transport.

probabilities pS_i in Eq. (1), while probabilities that characterize degrees of belief (i.e., subjective probabilities) correspond to the distributions indicated in Eq. (4). The IAEA report distinguishes between what it calls Type A uncertainty and Type B uncertainty. The IAEA report defines Type A uncertainty to be stochastic variation; as such, this uncertainty corresponds to the frequency-based probability of Kaplan and Garrick and the pS_i of Eq. (1). Type B uncertainty is defined to be uncertainty that is due to lack of knowledge about fixed quantities; thus, this uncertainty corresponds to the subjective probability of Kaplan and Garrick and the distributions indicated in Eq. (4). This distinction has also been made by other authors.[14,16-18]

STRUCTURE OF 1991 WIPP PERFORMANCE ASSESSMENT

Scenarios constitute the first element S_i of the ordered triples contained in the set R shown in Eq. (1) and are obtained by subdividing the set

$$S = x: x \text{ a single 10,000-yr history beginning at decommissioning of the WIPP} . \qquad (7)$$

Each 10,000-yr history is complete in the sense that it includes a full specification, including time of occurrence, for everything of importance to PA that happens in this time period. In the terminology of Cranwell et al.,[19] each history would contain a characterization for a specific sequence of "naturally occurring and/or human-induced conditions that represent realistic future states of the repository, geologic systems, and ground-water flow systems that could affect the release and transport of radionuclides from the repository to humans."

The development of scenarios for the 1991 WIPP PA led to a set $\mathcal{S}$ of the form shown in Eq. (7) in which all credible disruptions were due to drilling intrusions [Ref. 8, Ch. 4]. As a result, scenarios were defined to provide a systematic coverage of drilling intrusions. Specifically, scenarios were defined on the basis of (1) number of drilling intrusions, (2) time of the drilling intrusions, (3) whether or not a single waste panel is penetrated by two or more boreholes, of which at least one penetrates a pressurized brine pocket and at least one does not, and (4) the activity level of the waste penetrated by the boreholes.

The construction of scenarios started with the division of the 10,000-yr time period appearing in the EPA regulations into a sequence

$$[t_{i-1}, t_i], \ i = 1, 2, \ldots, nT, \tag{8}$$

of disjoint time intervals. These time intervals lead to scenarios

$$\mathcal{S}(\mathbf{n}) = \{x: x \text{ an element of } \mathcal{S} \text{ for which exactly } n(i) \text{ intrusions occur in time interval } [t_{i-1}, t_i] \text{ for } i=1, 2, \ldots, nT\} \tag{9}$$

and

$$\mathcal{S}(\mathbf{l},\mathbf{n}) = \{x: x \text{ an element of } \mathcal{S}(\mathbf{n}) \text{ for which the } j^{th} \text{ borehole encounters waste of activity level } \ell(j) \text{ for } j=1, 2, \ldots, nBH\}, \tag{10}$$

where

$$\mathbf{n} = [n(1), n(2), \ldots, n(nT)], \ \mathbf{l} = [\ell(1), \ell(2), \ldots, \ell(nBH)], \ nBH = \sum_{i=1}^{nT} n(i). \tag{11}$$

For the 1991 WIPP PA, $nT = 5$, and each time interval $[t_{i-1}, t_i]$ had a length of 2000 yrs. Additional scenarios involving penetrations of pressurized brine pockets were also defined.

Scenarios of the form $\mathcal{S}(\mathbf{l},\mathbf{n})$ were used as the basis for the CCDFs for normalized release to the accessible environment presented in the 1991 WIPP PA (e.g., as shown in Fig. 2). Additional information on the construction of scenarios for the 1991 WIPP PA is available elsewhere [Ref. 9, Ch. 3; Ref. 20].

Probabilities for scenarios were determined under the assumption that the occurrence of boreholes through the repository follows a Poisson process with a rate constant λ [Ref.9, Chs. 2 and 3; Refs. 20, 21]. The probabilities $pS(\mathbf{n})$ and $pS(\mathbf{l},\mathbf{n})$ for the scenarios $\mathcal{S}(\mathbf{n})$ and $\mathcal{S}(\mathbf{l},\mathbf{n})$ are given by

$$pS(\mathbf{n}) = \left\{\prod_{i=1}^{nT}\left[\frac{\lambda^{n(i)}\left(t_i - t_{i-1}\right)^{n(i)}}{n(i)!}\right]\right\} \exp\left[-\lambda\left(t_{nT} - t_0\right)\right] \tag{12}$$

and

$$pS(\mathbf{l},\mathbf{n}) = \left(\prod_{j=1}^{nBH} pL_{\ell(j)}\right) pS(\mathbf{n}), \tag{13}$$

where $\mathbf{n}$, $\mathbf{l}$ and nBH are defined in Eq. (11) and pL_ℓ is the probability that a randomly placed borehole through a waste panel will encounter waste of activity level ℓ. Table 3-2 of Ref. 8 provides an example of probabilities pS(n) calculated as shown in Eq. (12) with $\lambda = 3.28 \times 10^{-4}$ yr^{-1}, which corresponds to the maximum drilling rate suggested for use by the EPA.[13] Related expressions were also developed for the probability of scenarios that involve penetration of pressurized brine pockets [Ref. 9, Chs. 2 and 3; Refs. 20, 21].

As indicated in Fig. 3, the following computer models were used to estimate scenario consequences in the 1991 WIPP PA: CUTTINGS, BRAGFLO, PANEL, SECO2D and STAFF2D. Detailed descriptions of these models and their use in the 1991 WIPP PA are given in Ref. 9. The analyses described in this presentation were performed with gas generation in the repository due to corrosion of steel and microbial degradation of cellulosics and a dual-porosity (i.e., matrix and fracture porosity) radionuclide transport model in the Culebra Dolomite.

There are too many scenarios (e.g., $S(n)$ and $S(l,n)$) to perform a detailed calculation for each scenario with the models indicated in Fig. 3. For example, 3003 scenarios of the form $S(n)$ are required to reach a cumulative probability of 0.9994 (i.e., all scenarios involving less than or equal to 10 intrusions) with $\lambda = 3.28 \times 10^{-4}$ yr^{-1}. Construction of a CCDF for comparison against the EPA release limits requires the estimation of cumulative probability through at least the 0.999 level. Thus, depending on the value for the rate constant λ in the Poisson model for drilling intrusions, this may require the inclusion of scenarios involving as many as 10 to 12 drilling intrusions, which results in a total of several thousand scenarios. Further, this number does not include the effects of different activity levels in the waste. To obtain results for such a large number of scenarios, it is necessary to plan and implement the overall calculations very carefully. The following describes the approach used in the 1991 WIPP PA.

As indicated in Eq. (8), the 10,000-yr time interval that must be considered in the construction of CCDFs for comparison with the EPA release limits is divided into disjoint subintervals $[t_{i-1}, t_i]$, $i = 1, 2, \ldots, nT$, for the definition of scenarios. The following results were calculated for each of the five 2000 yr time intervals used in the 1991 WIPP PA:

rC_i = EPA normalized release to the surface environment for cuttings removal due to a single borehole in time interval i with the assumption that the waste is homogeneous (i.e., waste of different activity levels is not present), (14)

rC_{ij} = EPA normalized release to the surface environment for cuttings removal due to a single borehole in time interval i that penetrates waste of activity level j, (15)

$rGW1_i$ = EPA normalized release to the accessible environment due to groundwater transport initiated by a single borehole in time interval i, (16)

and

$rGW2_i$ = EPA normalized release to the accessible environment due to groundwater transport initiated by two boreholes in the same waste panel in time interval i, of which one penetrates a pressurized brine pocket and one does not, (17)

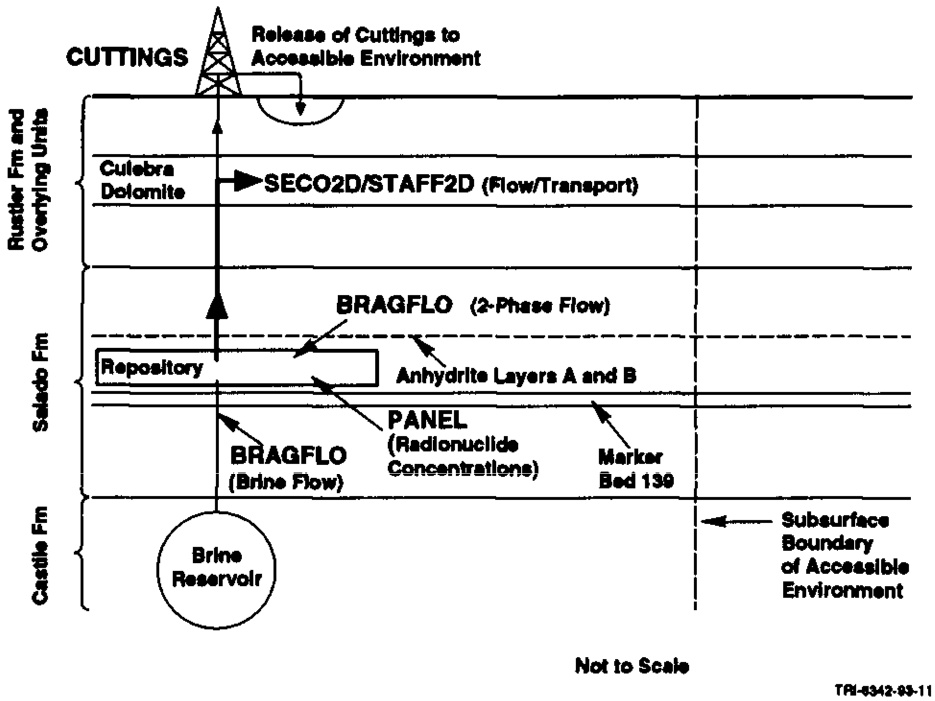

Fig. 3. Models Used in 1991 WIPP PA.

with the assumption that the intrusions occur at the midpoints of the time intervals (i.e., at 1000, 3000, 5000, 7000 and 9000 yrs). For the calculation of $rGW1_i$ and $rGW2_i$, the accessible environment is assumed to begin 5 km from the waste panels.

The cuttings releases rC_1, ..., rC_5 correspond to the cuttings releases for scenarios $S(1,0,0,0,0)$ ... $S(0,0,0,0,1)$ under the assumption that all waste is of the same average activity level. Similarly, the groundwater releases $rGW1_1$, ..., $rGW1_5$ correspond to the groundwater releases for the preceding five scenarios, and $rGW2_1$, ..., $rGW2_5$ correspond to the groundwater releases for scenarios $S^{+-}(2,0,0,0,0)$, ..., $S^{+-}(0,0,0,0,2)$, where $S^{+-}(2,0,0,0,0)$ denotes the scenario in which two drilling intrusion penetrate the same waste panel in the time interval [0, 2000 yr], of which one penetrates a pressurized brine pocket and one does not, and $S^{+-}(0,2,0,0,0)$, ..., $S^{+-}(0,0,0,0,2)$ are defined similarly. In like manner, rC_{1j} corresponds to the cuttings release for scenario $S(j;\ 1,0,0,0,0)$ defined in Eq. (10); rC_{2j} corresponds to the cuttings release for $S(j;\ 0,1,0,0,0)$, and so on.

The normalized releases rC_i, rC_{ij} and $rGW1_i$ are used to construct the EPA normalized releases for the scenarios $S(\mathbf{n})$ and $S(\mathbf{l},\mathbf{n})$. For $S(\mathbf{n})$, the normalized release to the accessible environment, $cS(\mathbf{n})$, is approximated by

$$cS(\mathbf{n}) = \sum_{j=1}^{nBH} (rC_{m(j)} + rGW1_{m(j)}), \tag{18}$$

where m(j) designates the time interval in which the j^{th} borehole occurs. The vector

$$\mathbf{m} = [m(1),\ m(2),\ \ldots,\ m(nBH)] \tag{19}$$

is uniquely determined once the vector $\mathbf{n}$ appearing in the definition of $S(\mathbf{n})$ is specified. The definition of $S(\mathbf{n})$ in Eq. (9) contains no information on the activity levels encountered by the individual boreholes, and so $cS(\mathbf{n})$ was constructed with the assumption that all waste is of the same average activity. However, the definition of $S(\mathbf{l},\mathbf{n})$ in Eq. (10) does contain information on activity levels, and the associated normalized release to the accessible environment, $cS(\mathbf{l},\mathbf{n})$, is approximated by

$$cS(\mathbf{l},\mathbf{n}) = \sum_{j=1}^{nBH} \left[rC_{m(j),\ell(j)} + rGW1_{m(j)} \right], \qquad (20)$$

which does incorporate the activity levels encountered by the individual boreholes. Similar approximations are also possible for scenarios that involve penetrations of pressurized brine pockets. These approximation processes are illustrated in Tables 3-4 and 3-5 of Ref. 9.

The scenario probabilities in Eq. (13) and the scenario consequences in Eq. (20) were then used in the construction of CCDFs for normalized release to the accessible environment in the 1991 WIPP PA (i.e., CCDFs of the form appearing in Fig. 2).

EXAMPLE RESULTS FROM 1991 WIPP PERFORMANCE ASSESSMENT

The 1991 WIPP PA considered the effects of 45 imprecisely known variables (i.e., $nV = 45$ in Eq. (2)); a summary of these variables is given in Table 3-1 of Ref 11. As indicated in Eq. (4), a distribution characterizing subjective uncertainty was developed for each of these variables. The impact of this subjective uncertainty was then estimated with use of a Latin hypercube sample[22] of size 60 generated from these variables according to their assigned distributions (i.e., $nK = 60$ in Eq. (5)). A complete PA was conducted for each of these 60 sample elements in the manner described in the preceding section, which lead to the 60 risk representations $R(\mathbf{x}_k)$ in Eq. (6).

The result of greatest interest in PAs for the WIPP is the CCDF for normalized release to the accessible environment that is used in comparisons with the EPA release limits. As shown in the left frame Fig. 2, 60 such CCDFs were obtained in the 1991 WIPP PA (i.e., one CCDF for each of the $nK = 60$ sets $R(\mathbf{x}_k)$ in Eq. (6)). When taken collectively, these 60 CCDFs provide an approximation to the distribution of CCDFs for comparison with the EPA release limits that results from subjective uncertainty. Each CCDF in Fig. 2 is summarizing stochastic uncertainty. As shown in the right frame of Fig. 2, the distribution of CCDFs in the left frame can be summarized with a mean CCDF and selected percentile curves. In past studies, the mean CCDF has often been used for comparisons with the EPA release limits.[14]

As shown in Fig. 1, the CCDFs in Fig. 2 were constructed from the probabilities and normalized releases associated with individual scenarios. In turn, the releases to the accessible environment for the individual scenarios were constructed from a groundwater release component and a cuttings removal component as shown in Eqs. (18) and (20). The subjective uncertainty in the groundwater release component for selected scenarios is shown in the right frame of Fig. 4, where box plots are used to summarize the groundwater releases associated with individual scenarios (i.e., the releases $rGW1_i$ and $rGW2_i$ in Eqs. (16) and (17)). Each box plot summarizes the groundwater release to the accessible environment for a particular scenario (i.e., in the element of the vectors $\mathbf{cS}_i(\mathbf{x}_k)$, k = 1, ..., nK = 60, in Eq. (6) corresponding to groundwater release to the accessible environment for the particular scenario under consideration).

The left frame in Fig. 4 has the same structure as the right frame but is for normalized releases to the Culebra, which are then transported to the accessible environment by groundwater flow to produce the releases summarized in the right frame. As comparison of the two sets of releases shows, a given release to the Culebra produces a substantially smaller release to the accessible environment. Thus, even given the substantial uncertainties present in the analysis, the processes associated with groundwater transport in the Culebra significantly reduce releases to the accessible environment over the 10,000 yr period specified in the EPA regulations.

A summary of the cuttings releases associated with selected scenarios is given in Fig. 5 (i.e., the releases rC_i in Eq. (14)). Again, the individual box plots are summarizing subjective uncertainty. As comparison with the releases to the accessible environment due to groundwater transport in the right frame of Fig. 4 shows, the total release to the accessible environment is dominated by cuttings removal.

The results shown in Eq. (6) create a mapping from analysis inputs (i.e., $\mathbf{x}_k$) to analysis results (i.e., $\mathcal{R}(\mathbf{x}_k)$). This mapping can be explored with sensitivity analysis techniques based on stepwise regression analysis, partial correlation analysis, examination of scatterplots, and possibly other procedures.[23,24] Such analyses are investigating the impact of subjective uncertainty in individual input variables on PA results. As an example, the results of a sensitivity analysis based on stepwise regression analysis with rank-transformed data[25] for scenario $\mathcal{S}^{+-}(2,0,0,0,0)$ is presented in Table I. The importance of the individual variables is indicated by the order in which they enter the regression analysis and by the changes in R^2 values as additional variables enter the regression model.

A regression-based sensitivity analysis for scenario $\mathcal{S}(1,0,0,0,0)$ performed poorly, producing regression models with few independent variables and low R^2 values. Due to the full stratification across the range of each sampled variable produced by Latin hypercube sampling, the examination of scatterplots often facilitates the understanding of such analyses. As shown by the scatterplots in Fig. 6, SALPERM (Salado permeability) acts as a switch, with no releases to the Culebra occurring when SALPERM is less than approximately 5 x 10^{-21} m^2. However, given that a release occurs, the size of this release is controlled by SOLPU (Pu solubility). The effect of SALPERM results from its influence on the time required to fill a waste panel with brine from the Salado Formation.

The sensitivity analyses presented in Table I and Fig. 6 are investigating results associated with individual scenarios. As illustrated by Fig. 7, a sensitivity analysis can also be performed for the distribution of CCDFs in Fig. 2. In particular, Fig. 7 presents plots of standardized rank regression coefficients[25] for the probability of exceeding specified total release values on the abscissa of Fig. 2. In this analysis, the effects of subjective uncertainty on the characterization of stochastic uncertainty is being investigated. The dominant variable is LAMBDA (rate constant in Poisson model for drilling intrusions), with a lesser effect indicated for DBDIAM (drillbit diameter). The effect due to DBDIAM results from the discretization of the waste into a finite number of activity levels (i.e.,

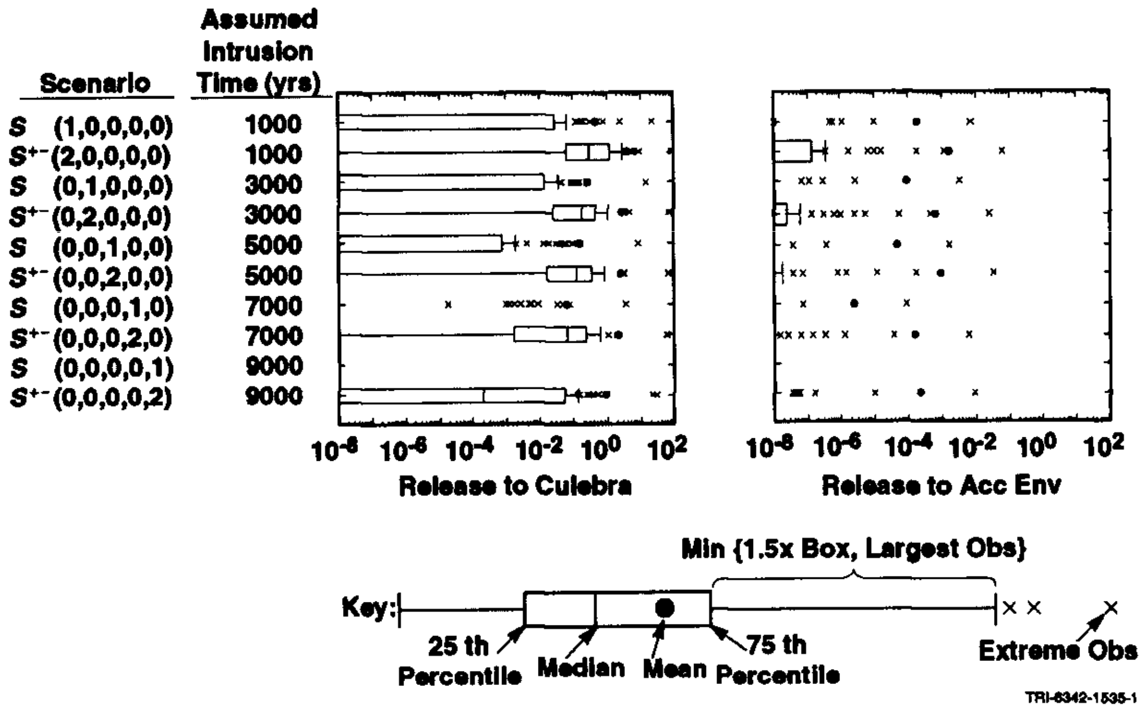

Fig. 4. Total Normalized Release to the Culebra Dolomite and to the Accessible Environment Due to Groundwater Transport.

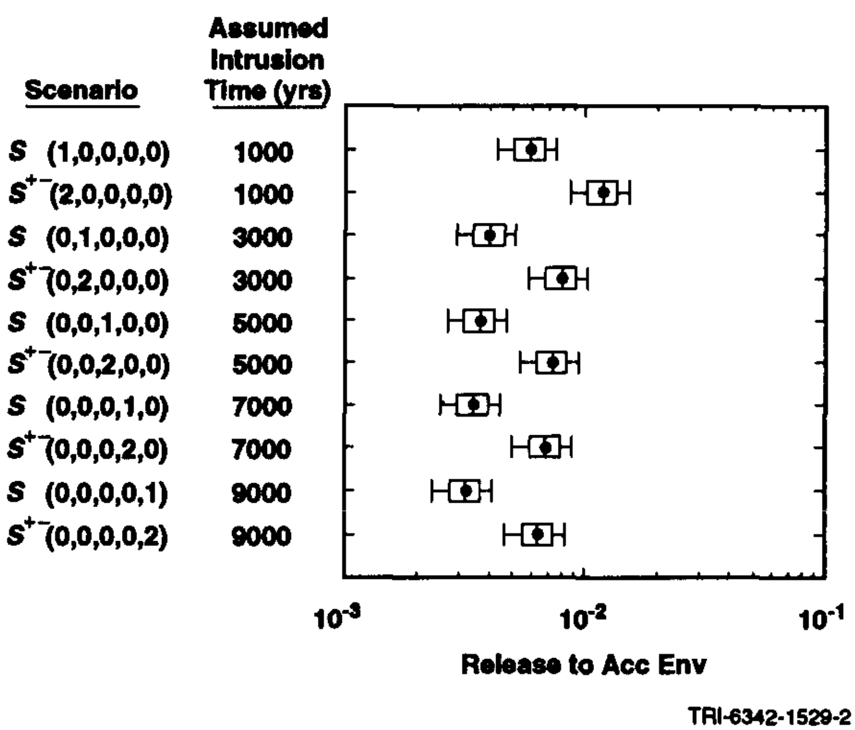

Fig. 5. Total Normalized Release to the Accessible Environment Due to Cuttings Removal from Waste of Average Activity Level.

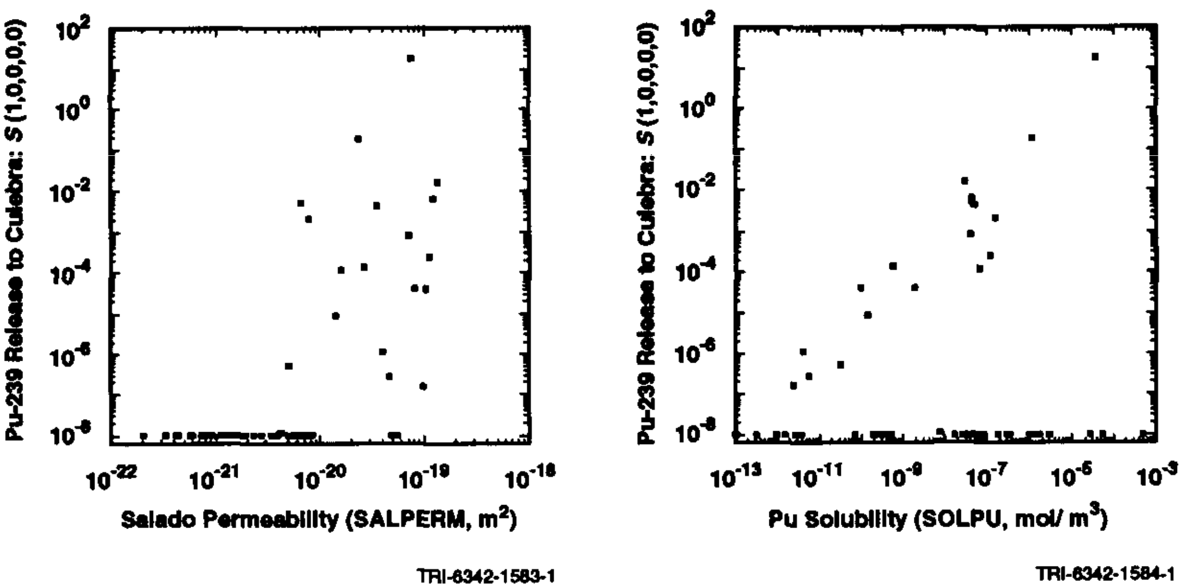

Fig. 6. Scatterplots for Normalized Release of Pu-239 to the Culebra Dolomite for Scenario $S(1,0,0,0,0)$.

radioactivity concentrations in Ci/m^2) for the implementation of cuttings removal and is associated with the appearance of the flattened regions in the CCDFs in Fig. 2.

DISCUSSION

The performance of a complex analysis requires a clear conceptual structure for what is to be done. Such a structure contributes to a logically consistent analysis and provides a framework to guide the actual calculations that must be performed. The ordered triple representation for risk proposed by Kaplan and Garrick is used to provide the conceptual structure for PAs conducted for the WIPP. Use of this structure leads naturally to the many components of a PA, including (1) the development of scenarios, scenario probabilities and scenario consequences, (2) the separation of stochastic and subjective uncertainty, and (3) the construction of CCDFs for comparison with the EPA release limits.

The division of a PA into the determination of scenarios, scenario probabilities and scenario consequences provides a clear identification of the three major parts of a PA. Further, the ordered triple representation does this in a way that provides both a clear link with the theory of probability and perspective on the interpretation of calculations performed in support of a PA. As a reminder, there are actually three entities involved in the definition of probability: (1) a set S, called the sample space, that contains everything that could occur for the particular "universe" under consideration, (2) a suitably restricted set $\mathcal{S}$ of subsets of S, called a Borel or σ-algebra, and (3) a function P defined for elements of $\mathcal{S}$ that actually defines probability. Collectively, the triple $(S,\mathcal{S},p)$ is called a probability space. The scenarios considered in a PA are elements of the set $\mathcal{S}$ and thus are subsets of a sample space. Thus, the logical

TABLE I. STEPWISE REGRESSION ANALYSES WITH RANK-TRANSFORMED DATA FOR EPA RELEASE TO THE CULEBRA DOLOMITE OVER 10,000 YR AND EPA RELEASE AT ONE QUARTER, ONE HALF AND THE FULL DISTANCE TO THE ACCESSIBLE ENVIRONMENT OVER 10,000 YR FOR SCENARIO $s^{+-}(2,0,0,0,0)$.

	Release to Culebra		Release at Quarter Distance		Release at Half Distance		Release at Full Distance	
Step[a]	Variable[b]	R^2[c]	Variable[b]	R^2[c]	Variable[b]	R^2[c]	Variable[b]	R^2[c]
1	BHPERM	0.46 (+)	MKDU	0.26 (-)	MKDU	0.25 (-)	MKDU	0.24 (-)
2	SOLAM	0.57 (+)	CULFRSP	0.40 (+)	CULFRSP	0.43 (+)	CULFRSP	0.44 (+)
3	BPPRES	0.66 (+)	GRCORI	0.46 (-)	GRCORI	0.49 (-)	GRCORI	0.51 (-)
4	SOLPU	0.69 (+)	BHPERM	0.52 (+)	BHPERM	0.55 (+)	SOLNP	0.58 (+)
5	BPSTOR	0.73 (+)	SOLNP	0.58 (+)	FKDPU	0.60 (-)		
6	SOLU	0.76 (+)	FKDPU	0.63 (-)	MKDNP	0.64 (-)		
7			MKDNP	0.68 (-)	SOLNP	0.68 (+)		
8			FKDNP	0.71 (-)				

SUMMARY OF VARIABLES APPEARING IN REGRESSION ANALYSES

BHPERM	Borehole permeability. Range: 1×10^{-14} to $1 \times 10^{-11} m^2$.
BPPRES	Initial pressure of brine pocket in Castile Formation. Range: 1.1×10^7 to 2.1×10^7 Pa.
BPSTOR	Bulk storativity of brine pocket in Castile Formation. Range: 2×10^{-2} to 2 m^3.
CULFRSP	Fracture spacing in Culebra. Range: 6×10^{-2} to 8 m.
FKDNP	Fracture distribution coefficient for Np in Culebra. Range: 0 to 1×10^3 m^3/kg.
FKDU	Fracture distribution coefficient for U in Culebra. Range: 0 to 1 m^3/kg.
GRCORI	Gas generation rate for corrosion of steel under inundated conditions. Range: 0 to 1.3×10^{-8} mol/m^2 surface area steel•s.
MKDNP	Matrix distribution coefficient for Np in Culebra. Range: 0 to 1×10^2 m^3/kg.
MKDU	Matrix distribution coefficient for U in Culebra. Range: 0 to 1 m^3/kg.
SOLAM	Solubility of Am^{+3} in brine. Range: 5×10^{-14} to 1.4 mol/ℓ.
SOLNP	Solubility of Np in brine. Range: 3×10^{-16} to 2×10^{-5} mol/ℓ for Np^{+4} and 3×10^{-11} to 1.2×10^{-2} mol/ℓ for Np^{+5}.
SOLPU	Solubility of Pu in brine. Range: 2×10^{-16} to 4×10^{-6} mol/ℓ for Pu^{+4} and 2.5×10^{-17} to 5.5×10^{-4} mol/ℓ for Pu^{+5}.
SOLU	Solubility of U in brine. Range: 1×10^{-15} to 5×10^{-2} mol/ℓ for U^{+4} and 1×10^{-7} to 1 mol/ℓ for U^{+6}.

[a] Steps in stepwise regression analysis.
[b] Variable selected at each step in regression analysis.
[c] R^2 value at each step with sign of regression coefficient in parentheses.

starting point in scenario development is the determination of the sample space S. Then, the actual scenarios used in a PA (i.e., the S_i in Eq. (1)) are subsets of this sample space. There is no unique way to develop these scenarios and the level of detail used in the definition of scenarios will depend on the needs and constraints associated with a particular analysis. However, scenarios will always be subsets of the sample space and thus scenario probabilities (i.e., the pS_i in Eq. (1)) are defined for subsets of the sample space. Similarly, consequence results (i.e., the cS_i in Eq. (1)) are calculated as one outcome to be used as the result associated with every element of a set (i.e., the elements of the set or scenario S_i in Eq. (1)).

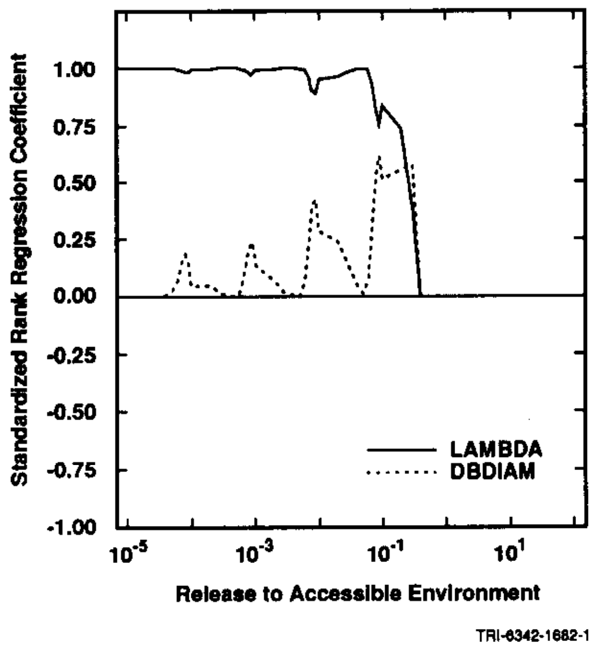

Fig. 7. Standardized Rank Regression Coefficients for Exceedance Probabilities Associated with Individual CCDFs in Fig. 2 for Normalized Release to the Accessible Environment.

The separation of stochastic and subjective uncertainty is very important in a PA for a complex system. Without this separation, it is difficult to assess the meaning of probabilistic statements coming out of the assessment (i.e., do these statements represent different possibilities that have a real potential of occurring, a degree of belief with respect to different alternatives, or some combination of the preceding). The probabilities pS_i appearing in Eq. (1) represent stochastic uncertainty. As indicated Eqs. (2), (3) and (4), subjective uncertainty enters the PA due to analyst uncertainty with respect to how to formulate the risk representation in Eq. (1). What is referred to as uncertainty and sensitivity analysis is typically an attempt to assess the impact of subjective uncertainty. Uncertainty and sensitivity analysis play an important role in a PA by both indicating how much confidence should be placed in the results and where efforts can be invested most productively to improve this confidence.

With respect to stochastic and subjective uncertainty, there are actually two probability spaces: A probability space ($\mathcal{S}_{st}$, $\mathcal{S}_{st}$, p_{st}) for stochastic uncertainty and a probability space ($\mathcal{S}_{su}$, $\mathcal{S}_{su}$, p_{su}) for subjective uncertainty. A PA typically uses a different experimental design to cover each space. The division of the space $\mathcal{S}_{st}$ associated with stochastic uncertainty into the scenarios $\mathcal{S}_i$ in Eq. (1) is a form of importance sampling. The scenarios $\mathcal{S}_i$ are the strata in this design and the scenario probabilities pS_i are the strata probabilities. Importance sampling is often used to assure the inclusion of potentially important, but low probability, events in an analysis. The sample space $\mathcal{S}_{su}$ associated with subjective uncertainty is covered with a design based on random or Latin hypercube sampling. This design is used to assure the full coverage of the range of each variable and is often used when either there is not enough information to plan an analysis based on importance sampling or the presence of a large number of potential dependent variables makes the use of importance sampling impractical. Due to the large number of independent and dependent variables, classical experiment designs (e.g., factorial, fractional factorial, ...) are typically not very useful for covering $\mathcal{S}_{su}$.

The primary focus of the EPA standard for the geologic disposal of radioactive waste[13] is a CCDF for normalized radionuclide release to the accessible environment that is required to fall below the bound indicated in Fig. 1. This CCDF is displaying the effect of stochastic uncertainty and is constructed from the probabilities pS_i and the vectors $\mathbf{cS}_i$ in Eq. (1). Further, as illustrated in Fig. 2, the presence of subjective uncertainty leads to a distribution of such CCDFs. Upon first encounter, many individuals feel that this standard is novel. However, the EPA standard is actually an example of the Farmer limit line approach to specifying acceptable risk[26] and is conceptually equivalent to the large release safety goal proposed by the U.S. Nuclear Regulatory Commission for nuclear reactors.[27,28]

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