ABSTRACT

The Waste Isolation Pilot Plant (WIPP) is under development by the U.S. Department of Energy (DOE) for the geologic disposal of transuranic waste. The primary regulatory requirements (i.e., 40 CFR 191 and 40 CFR 194) placed on the WIPP by the U.S. Environmental Protection Agency (EPA) involve a complementary cumulative distribution function (CCDF) for normalized radionuclide releases to the accessible environment. The interpretation and use of this CCDF from a decision analysis perspective is discussed and illustrated with results from the 1996 performance assessment for the WIPP, which was carried out to support a compliance certification application by the DOE to the EPA for the WIPP.

I. INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is under development by the U.S. Department of Energy (DOE) for the geologic (i.e., deep underground) disposal of transuranic (TRU) waste. The primary regulatory requirements that must be satisfied by the WIPP is the U.S. Environmental Protection Agency's (EPA's) standard for the geologic disposal of radioactive waste, Environmental Radiation Protection Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes (40 CFR 191). The Waste Isolation Pilot Plant Land Withdrawal Act (LWA) specifies the procedures by which the WIPP's compliance with 40 CFR 191 is to be determined. In particular, the DOE is required to prepare a compliance certification application (CCA), and the EPA is required to determine (and certify, if appropriate) if the WIPP meets the criteria specified in 40 CFR 191.

The required CCA was submitted to the EPA in October 1996, and the EPA issued a proposed certification decision in October 1997. The CCA addresses a large number of regulatory requirements specified in 40 CFR 191 and in the associated guidance Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations; Final Rule (40 CFR 194) (see pp. XWALK-1 to XWALK-36, Ref. 6, for a detailed listing of the requirements in 40 CFR 191 and 40 CFR 194 and how they are addressed in the CCA).

The central requirements in 40 CFR 191 and 40 CFR 194 involve a complementary cumulative distribution function (CCDF) for normalized radionuclide releases from the WIPP to the accessible environment. The primary focus of this presentation is the interpretation and use of this CCDF from a decision analysis perspective.

II. WHAT IS NEEDED FOR A DECISION

The WIPP and other complex entities such as transportation systems, nuclear power plants and manufacturing facilities can undergo a wide variety of disruptions, which in turn have wide ranges of likelihood and consequence. Because of this spectrum of potential occurrences, likelihoods and consequences, the development of an informed decision with respect to a complex system can be viewed, in part, as seeking answers to three questions (Q1, Q2, Q3): Q1, "What occurrences can take place?"; Q2, "How likely are these occurrences?"; and Q3, "What are the consequences of these occurrences?". In the risk assessment community, the consequences indicated in Q3 are typically viewed as being undesirable (e.g., costs incurred, individuals injured, ...); however, in general the consequences can be desirable as well as undesirable. It is hard to envision making a decision with respect to a complex system without seeking answers to these questions.

The fundamental role played by the preceding questions in risk analysis, and more generally in decision
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analysis, was abstracted by Kaplan and Garrick, who defined risk as a set of ordered triples of the form

$$\mathcal{R} = \{(S_i, p_{S_i}, c_{S_i}), \ i = 1, 2, ..., n_S\}, \quad (1)$$

where $S_i$ is a set of similar occurrences, the $S_i$ are disjoint (i.e., $S_i \cap S_j = \emptyset$ for $i \neq j$), the $S_i$ are all inclusive (i.e., $\cup_i S_i$ contains all possible occurrences for the system under study), $p_{S_i}$ is the probability of $S_i$, $c_{S_i}$ is a vector of consequences associated with $S_i$, and $n_S$ is the number of sets into which the potential occurrences are subdivided. The development by Kaplan and Garrick was motivated by a desire to provide a clear conceptual representation for probabilistic risk assessments (PRAs) for nuclear power stations but also applies to analyses for other complex systems.

The individual terms associated with $\mathcal{R}$ (i.e., $S_i$, $p_{S_i}$, $c_{S_i}$) can be examined as separate entities in an attempt to reach an informed decision about a particular system. However, a piecemeal approach of this type does not provide an adequate overall perspective on which to make a decision. Rather, the information associated with $\mathcal{R}$ must be examined in a way that permits a decision to be made on its entirety. The usual way to do this is to summarize the information in $\mathcal{R}$ with CCDFs, with such functions showing the probability of occurrences taking place that will cause specific values of the individual consequences contained in $c_S$ to be exceeded (Fig. 1). In general, there will be one CCDF for each consequence contained in $c_S$. From a risk perspective, such CCDFs are answering the question "How likely is an occurrence to be this bad or worse?", which is usually the question of interest in a risk assessment.

Given that CCDFs are to be used to summarize the information in $\mathcal{R}$, some criterion is needed on which to base a decision with respect to the acceptability of the probability-consequence results summarized in a CCDF. Typically, less severe consequences are acceptable at higher probabilities than are more severe consequences. The usual construction used to characterize such acceptability is a boundary line (Fig. 1), with a CCDF having an acceptable probability-consequence profile when it falls below the boundary line. The position of the boundary line allows small consequences to be acceptable at higher probabilities than are larger consequences. The boundary line specified by the EPA in 40 CFR 191 for the acceptability of a facility for the geologic disposal of radioactive waste is illustrated in Fig. 1.

If the set $\mathcal{R}$ and its associated elements $S_i$, $p_{S_i}$, and $c_{S_i}$ in Eq. (1) could be unambiguously defined, then a decision with respect to whether or not a system met the requirements imposed by a specific boundary line would be straightforward. In particular, the relevant CCDF (or, CCDFs if appropriate) could be constructed as indicated in Fig. 1, and a decision on acceptability or nonacceptability would be made on the basis of whether or not the CCDF crossed the boundary line. In practice, making a decision is not that simple in any real analysis problem because there is always uncertainty in how $S_i$, $p_{S_i}$, and $c_{S_i}$ should be defined, which in turn leads to uncertainty in where a CCDF is located relative to the boundary line under consideration.

As previously discussed, three basic questions (Q1, Q2, Q3) are present in any analysis for a complex system. However, given the presence of uncertainties of the type indicated in the preceding paragraph, there is also a fourth question (Q4) that underlies any decision with respect to the behavior of a complex system: Q4, "How much
Fig. 2. Different CCDFs resulting from uncertainty in appropriate values to use for $S_t$, $p_S$ and $c_S$.

confidence should be placed in the answers to questions Q1, Q2 and Q3?". Specifically, Q4 is asking how uncertainty in the definitions of $S_t$, $p_S$ and $c_S$ carries over into uncertainty in CCDFs derived from these definitions and hence into uncertainty in the locations of these CCDFs relative to boundary lines on which decisions are to be based (Fig. 2). The essence of making a decision with respect to the acceptability of some system relative to a specified boundary line lies in assessing the implications of multiple possible CCDFs and the level of credibility that should be assigned to these CCDFs.

III. ABSTRACTION OF WHAT IS NEEDED FOR A DECISION

When viewed at a high-level, attempts to answer the four questions (i.e., Q1, Q2, Q3, Q4) indicated in Sect. II lead to analyses that are based on three distinct entities (EN1, EN2, EN3): EN1, a probabilistic characterization of the possible occurrences associated with the system under study; EN2, a procedure for estimating the consequences that result from each of the possible occurrences associated with the system under study; and EN3, a probabilistic characterization of the uncertainty in the parameters used in the definitions of EN1 and EN2. In the context of the original four questions, EN1 provides answers to Q1 and Q2; EN2 provides an answer to Q3; and EN3 provides an answer to Q4.

The entity EN1 derives from an attempt to determine both everything that could potentially occur in the system under study and also the likelihood of different occurrences. The uncertainty that EN1 is attempting to characterize is often referred to as stochastic uncertainty and arises because the system under study can behave in many different ways; alternative designations include aleatory uncertainty, type A uncertainty, irreducible uncertainty, and variability.\(^{13,14}\)

For notational purposes, each possible occurrence can be represented as a vector of the form

$$x_{st} = [x_{st,1}, x_{st,2}, \ldots, x_{st,nP}]$$

where $x_{st,1}, x_{st,2}, \ldots, x_{st,nP}$ is a sequence of properties that defines a particular occurrence, $nP$ is the number of properties required to define an occurrence, and the subscript $st$ is used to denote stochastic. For example, the system under study might be a nuclear power station, with each vector $x_{st}$ representing the defining properties of a particular accident that could occur at that station.

When taken collectively, the $x_{st}$ constitute a set $S_{st}$ that contains everything that could occur in the system under study. As such, $S_{st}$ constitutes the answer to Q1. However, answering Q2 requires introducing ideas from probability.

The basic structure on which probability is based is called a probability space and plays a fundamental role in the definitions of both EN1 and EN3. A probability space is a triple of the form $(S, \mathcal{A}, p)$, where $S$ is the collection of everything that could occur in the particular universe under consideration, $\mathcal{A}$ is a suitably-restricted set of subsets of $S$ for which probability is defined, and $p$ is a function that actually defines the probability of the individual subsets of $S$ contained in $\mathcal{A}$ (p. 116, Ref. 15).

In the terminology of probability theory, $S$ is the sample space; the elements of $S$ are elementary events; the elements of $\mathcal{A}$ are events; and the function $p$ is a probability measure.

Answering Q2 involves the definition of a probability space $(S_{st}, \mathcal{A}_{st}, p_{st})$ for stochastic uncertainty. The sample space is the previously introduced set $S_{st}$ of all possible occurrences in the system under study (i.e., the set that provides the answer to Q1). In practice, the definition of $(S_{st}, \mathcal{A}_{st}, p_{st})$ is accomplished by specifying a distribution.
The entity EN2 derives from an attempt to determine the consequences associated with each element $x_{st}$ of $S_{st}$.

In concept, EN2 is simply a function of the form

$$f(x_{st}) = cS(x_{st}),$$

where $cS(x_{st})$ represents the vector of consequences associated with $x_{st}$. In practice, $f(x_{st})$ is the outcome of calculations performed with one or more computer programs, with such programs possibly involving the numerical solution of partial differential equations or other mathematical models used to represent the effects of $x_{st}$ on the system under consideration.

Once EN1 and EN2 are defined, the CCDF in Fig. 1 can be formally defined by an integral involving $(S_{st}, A_{st}, p_{st})$ and $f$ (Fig. 3). Technically, the CCDF in Fig. 1 is an approximation to the CCDF in Fig. 3 obtained with sets $S_1, S_2, \ldots, S_S$ contained in $A_{st}$ subject to the restrictions that $S_{st} = \bigcup_i S_i$ and $S_i \cap S_j = \emptyset$ for $i \neq j$. In practice, $(S_{st}, A_{st}, p_{st})$ and $f$ will be too complex to allow a closed-form evaluation of the integral in Fig. 3, with the result that some type of approximation procedure must be used to obtain the exceedance probabilities $\text{prob}(\text{Conseq} > cS)$ for individual consequence values $cS$. For notational convenience, the integral defining $\text{prob}(\text{Conseq} > cS)$ in Fig. 3 is written with the density function $d_{st}(x_{st})$ associated with $(S_{st}, A_{st}, p_{st})$ and the differential $dV_{st}$ is used because $S_{st}$ will typically be multidimensional.

Given that the CCDF in Fig. 3 will typically be approximated rather than calculated exactly, an issue that should be considered in any decision is the accuracy of this approximation. Clearly, if the approximation is poor, then an inappropriate decision can result even though the information embodied in $(S_{st}, A_{st}, p_{st})$ and $f$ is correct. In general, the procedures used to construct this approximation are analysis specific and so must be addressed on an analysis by analysis basis.

The entity EN3 derives from an attempt to characterize the uncertainty in the definitions of EN1 and EN2 or, more specifically, in the definitions of $(S_{st}, A_{st}, p_{st})$ and $f$. The uncertainty that is being characterized by EN3 is often referred to as subjective uncertainty and arises from an inability on the part of the analysts carrying out a study to unambiguously characterize exact values for all quantities required as input to the study; alternative designations include epistemic uncertainty, type B uncertainty, reducible uncertainty, and state of knowledge uncertainty.\textsuperscript{13,14}

For notational purposes, the uncertain inputs can be represented by a vector of the form

$$x_{su} = [x_{su,1}, x_{su,2}, \ldots, x_{su,nl}],$$

where $x_{su,1}, x_{su,2}, \ldots, x_{su,nl}$ are uncertain inputs, $nl$ is the number of such inputs, and the subscript $su$ is used to denote subjective. In a study of a nuclear power station, some elements of $x_{su}$ might be the frequencies of different initiating events, another element might be the failure strength of the containment and so on, with each of these inputs being imprecisely known but the analysis itself structured to use a single well-defined value for each of them. Put another way, $(S_{st}, A_{st}, p_{st})$ and $f(x_{st})$ are functions $(S_{st}(x_{su}), A_{st}(x_{su}), p_{st}(x_{su}))$ and $f(x_{st}, x_{su})$ of $x_{su}$ with values that change as $x_{su}$ changes.

Given that $(S_{st}, A_{st}, p_{st})$ and $f(x_{st})$ change as $x_{su}$ changes, then so will the CCDFs that derive from $(S_{st}, A_{st}, p_{st})$ and $f(x_{st}), f(x_{su})$. For example, the CCDF in Fig. 1 is an approximation to the CCDF in Fig. 3 obtained with sets $S_1, S_2, \ldots, S_S$ contained in $A_{st}$ subject to the restrictions that $S_{st} = \bigcup_i S_i$ and $S_i \cap S_j = \emptyset$ for $i \neq j$. In practice, $(S_{st}, A_{st}, p_{st})$ and $f$ will be too complex to allow a closed-form evaluation of the integral in Fig. 3, with the result that some type of approximation procedure must be used to obtain the exceedance probabilities $\text{prob}(\text{Conseq} > cS)$ for individual consequence values $cS$. For notational convenience, the integral defining $\text{prob}(\text{Conseq} > cS)$ in Fig. 3 is written with the density function $d_{st}(x_{st})$ associated with $(S_{st}, A_{st}, p_{st})$ and the differential $dV_{st}$ is used because $S_{st}$ will typically be multidimensional.

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Given that $(S_{st}, A_{st}, p_{st})$ and $f(x_{st})$ change as $x_{su}$ changes, then so will the CCDFs that derive from $(S_{st}, \ldots, x_{su,nl}]$,}
with the resultant distributions of CCDFs deriving from the uncertainty characterized by \((S_{su}, \mathcal{A}_{su}, P_{su})\). In the context of the KapladGarrick representation in Eq. (1), each CCDF is approximated by an expression of the form

\[
R(X_{su}) = \left\{ S_i(X_{su}), P_i(X_{su}), cS_i(X_{su}), \right\},
\]

where \(i = 1, 2, \ldots, nS(X_{su})\). (6)

with a different CCDF resulting for each value of \(X_{su}\). In the context of the integral representation in Fig. 3, the CCDFs for individual values of \(X_{su}\) are given by

\[
\text{prob(Conseq} > cS) = \int_{S_{st}(X_{su})} \delta_{CS}[f(X_{st}, X_{su})]dS_{st}(X_{st}|X_{su})dV_{st},
\]

where \(\delta_{CS}(f(X_{st}, X_{su})) = 1\) if \(f(X_{st}, X_{su}) > cS\) and \(0\) if \(f(X_{st}, X_{su}) \leq cS\) and \(f\) is represented as a scalar because only one consequence result is considered in the construction of a specific CCDF. As a reminder, the expression in Eq. (6) is just a representation of an approximation procedure for the integral in Eq. (7).

The characterization of subjective uncertainty embodied in \((S_{su}, \mathcal{A}_{su}, P_{su})\) leads to a distribution of exceedance probabilities \(\text{prob(Conseq} > cS)\) for each consequence value \(cS\) on the abscissa in Fig. 2. In particular, an exceedance probability \(\text{prob(Conseq} > cS | X_{su})\) results for each element \(X_{su}\) of \(S_{su}\) and the information contained in \((S_{su}, \mathcal{A}_{su}, P_{su})\) leads to a distribution of \(\text{prob(Conseq} > cS | X_{su})\) for each consequence value \(cS\). One way to represent these distributions is with a three dimensional plot in which \(cS\) and \(\text{prob(Conseq} > cS)\) appear on two axes, and the density function for \(\text{prob(Conseq} > cS | X_{su})\) is represented on the third axis (Fig. 4). In this representation, each density function is conditional on a specific consequence value and derives from the uncertainty in \(X_{su}\).

IV. APPROXIMATION IN THE FORMATION OF A DECISION

In concept, determination of the density functions in Fig. 4 is based on a double integration problem involving
In practice, the integrals involving both \((S_{st}, J_{pt}, p_{st})\) and \((S_{su}, J_{pt}, p_{su})\) must be approximated with some type of numerical procedure. As previously noted, the Kaplan/Garrick representation in Eq. (1) forms a basis for approximating the integral involving \((s_{su}, d_{psf}, psf)\); another possibility is the use of Monte Carlo procedures. The integral involving \((s_{st}, d_{psu}, psu)\) is often approximated with procedures based on Latin hypercube sampling due to the efficient stratification properties possessed by this technique.

When Latin hypercube sampling or possibly simple random (i.e., Monte Carlo) sampling is used to integrate over \((S_{su}, J_{pt}, p_{su})\), a sample

\[ x_{su,k}, k = 1, 2, ..., nLHS, \tag{9} \]

is drawn from \(S_{su}\) consistent with the definition of \((S_{su}, J_{pt}, p_{su})\), which in practice means consistent with the distributions in Eq. (8) and any associated conditions. Then, a CCDF is constructed for each sample element \(x_{su,k}\); that is, the integral in Eq. (7) is evaluated in some manner for \(x_{su,k}, k = 1, 2, ..., nLHS\). These evaluations produce a distribution of CCDFs of the form indicated in Fig. 2, with one CCDF for each sample element. With both Latin hypercube and simple random sampling, each sample element is given equal weight for purposes of estimating the density functions in Fig. 4. One possibility is simply to present a histogram based on the \(nLHS\) exceedance probabilities obtained for each consequence value \(cS\) (Fig. 5). If desired, smoothing procedures could also be used in conjunction with the results contained in these histograms to produce continuous density functions with the same appearance as those in Fig. 4. A simple and popular approach to summarizing distributions of CCDFs generated by sampling is to plot mean and percentile values above individual consequence values and then to connect means and corresponding percentile values to produce continuous curves (Fig. 6).

Once the effects of subjective uncertainty have been estimated and summarized as indicated in Figs. 5 and 6, answers to all four questions (i.e., Q1, Q2, Q3, Q4) indicated in Sect. II are available. At this point, informed decisions can be made about a system that incorporates both potential consequences and the likelihood of these consequences and also an assessment of the uncertainty present in the estimates of these quantities.

![Fig. 5. Histograms constructed from a sample \(x_{su,k}, k = 1, 2, ..., nLHS\), from \(S_{su}\) that characterize subjective uncertainty in exceedance probabilities \(\text{prob}(\text{Conseq} > cS)\) for individual consequence values \(cS\).](image)

V. THE 1996 WIPP CCA

The performance assessment (PA) carried out in support of the 1996 WIPP CCA was based on a structure of the form described in Sects. II - IV. Regulatory requirements and a detailed screening of features, events and processes (FEPs) (Sect. 6.2, App. SCR, Ref. 6) led to the definition of a probability space \((S_{st}, J_{pt}, p_{st})\) for stochastic uncertainty (i.e., the entity EN1 in Sect. III) in which each element \(x_{st}\) of \(S_{st}\) was a vector of the form

\[
 x_{st} = \left[ t_1, l_1, e_1, b_1, p_1, a_1, t_2, l_2, e_2, b_2, p_2, a_2, ..., \right] \tag{10}
\]

where \(n\) is the number of exploratory drilling intrusions for natural resources (i.e., oil or gas) that occur in the immediate vicinity of the repository, \(t_i\) is the time (yr) of the \(i^{th}\) intrusion, \(l_i\) designates the location of the \(i^{th}\) intrusion, \(e_i\) designates the penetration of an excavated or nonexcavated area by the \(i^{th}\) intrusion, \(b_i\) designates whether or not the \(i^{th}\) intrusion penetrates pressurized brine in the Castile Fm, \(p_i\) designates the plugging procedure used with the \(i^{th}\) intrusion (i.e., continuous plug, two discrete plugs, three discrete plugs), \(a_i\) designates the type of waste penetrated by the \(i^{th}\) intrusion (i.e., no waste, contact-handled (CH) waste, remotely-handled (RH) waste), and \(t_{min}\) is the time at which potash
mining occurs within the land withdrawal boundary (Chapt. 3, Ref. 20). The definition of \( (S_{st}, J_{st}, P_{st}) \) was then completed by assigning a distribution as indicated in Eq. (3) to each element of \( x_{st} \) (Chapt. 3, Ref. 20).

The FEPs screening process also led to the identification of processes and associated models for use in the estimation of consequences (i.e., normalized radionuclide releases to the accessible environment in the context of the EPA regulations\(^3,4,7\) for elements \( x_{st} \) of \( S_{st} \) (i.e., the entity EN2 in Sect. III). Symbolically, this estimation process can be represented by

\[
f(x_{st}) = f_C(x_{st}) + f_{SP}[x_{st}, f_B(x_{st})] + f_{DBR}[x_{st}, f_{SP}[x_{st}, f_B(x_{st})], f_B(x_{st})] + f_{MB}[x_{st}, f_B(x_{st})] + f_{DL}[x_{st}, f_B(x_{st})] + f_{S-T}[x_{st}, f_{S-F}[x_{st}, 0], f_{N-P}[x_{st}, f_B(x_{st})]],
\]

where \( f(x_{st}) \) is normalized radionuclide release to the accessible environment associated with \( x_{st} \) and, in general, many additional consequences, \( x_{st} \) are particular future under consideration, \( x_{st,0} \) is future involving no drilling intrusions but a mining event at the same time \( t_{min} \) as in \( x_{st} \), \( f_C(x_{st}) \) is cuttings and cavings release to accessible environment for \( x_{st} \) calculated with CUTTINGS.S, \( f_B(x_{st}) \) is results calculated for \( x_{st} \) with BRAGFLO (in practice, \( f_B(x_{st}) \) is a vector containing a large amount of information including time-dependent pressures and saturations for gas and brine), \( f_{SP}[x_{st}, f_B(x_{st})] \) is spallings release to accessible environment for \( x_{st} \) calculated with the spallings model contained in CUTTINGS.S, \( f_{DBR}[x_{st}, f_{SP}[x_{st}, f_B(x_{st})], f_B(x_{st})] \) is direct brine release to accessible environment for \( x_{st} \) calculated with a modified version of BRAGFLO designated BRAGFLO_DBR, \( f_{MB}[x_{st}, f_B(x_{st})] \) release through anhydrite marker beds to accessible environment for \( x_{st} \) calculated with NUTS, \( f_{DL}[x_{st}, f_B(x_{st})] \) release through Dewey Lake Red Beds to accessible environment for \( x_{st} \) calculated with NUTS, \( f_{S-T}[x_{st}, f_{S-F}[x_{st}, 0], f_{N-P}[x_{st}, f_B(x_{st})]] \) release to surface due to brine flow up a plugged borehole for \( x_{st} \) calculated with NUTS or PANEL as appropriate, \( f_{S-F}[x_{st}, 0] \) flow field calculated for \( x_{st,0} \) with SECOFL2D, \( f_{N-P}[x_{st}, f_B(x_{st})] \) release to Culebra for \( x_{st} \) calculated with NUTS or PANEL as appropriate, \( f_{S-T}[x_{st,0}, f_{S-F}[x_{st,0}, 0], f_{N-P}[x_{st}, f_B(x_{st})]] \) ground-water transport release through Culebra to accessible environment calculated with SECOTP2D (\( x_{st,0} \) is used as
an argument to $f_{S-T}$ because drilling intrusions are assumed to cause no perturbations to the flow field in the Culebra, and the actual models and computer programs in use are described elsewhere (Chapt. 4, Ref. 20). Most of the indicated models involve the numerical solution of partial differential equations used to represent fluid flow, material deformation, and radionuclide transport.

Finally, a probability space $(\Omega, \mathcal{F}, \mathbb{P})$ characterizing subjective uncertainty was defined (i.e., the entity EN3 in Sect. III). The elements $x_{st}$ of $\Omega$ were vectors of the form appearing in Eq. (5) (Table 1), with the definition of $(S_{st}, J_{st}, p_{st})$ being completed by assigning a distribution as indicated in Eq. (8) to each element of $x_{st}$ (Chapt. 5, Ref. 20). With the definition of $S_{st}$ the function $f$ in Eq. (11) has the form $f(x_{st}, x_{su})$.

Table 1 Four Examples of the $nl = 57$ Uncertain Input Variables (i.e., elements $x_{n,l}$ of $x_{su}$) Considered in the 1996 WIPP PA (see App. PAR, Ref. 6, and Table 5.2.1, Ref. 20, for a complete listing of the elements of $x_{su}$ and sources of additional information)

| WGRMICI: Gas generation rate due to microbial degradation of cellulose under inundated conditions. Used in BRAGFLO. Range: $3.17 \times 10^{-10}$ to $9.51 \times 10^{-9}$ mol/kg-cellulosics. Distribution: Uniform. |
| BHPRM: Borehole permeability. Used in BRAGFLO. Range: $1 \times 10^{-14}$ to $1 \times 10^{-11}$ m². Distribution: Loguniform |
| WTAUFAIL: Shear strength of waste. Used in CUTTINGS_S. Range: 0.05 to 10 Pa. Distribution: Uniform. |
| CKDPU3: Distribution coefficient for plutonium in the +3 oxidation state in the Culebra Dolomite. Used in SECOTP2D. Range: 0.02 to 0.5 m³/kg. Distribution: Uniform. |

Once $(S_{st}, J_{st}, p_{st}), (S_{su}, J_{su}, p_{su})$ and $f(x_{st}, x_{su})$ were defined, procedures of the type discussed in Sects. III and IV were used to estimate CCDFs for comparison with the boundary line specified in 40 CFR 191 and illustrated in Figs. 1-6. Specifically, a Latin hypercube sample (LHS) of size $nLHS = 300$ was generated from $S_{st}$ as discussed in conjunction with Eq. (9); Monte Carlo procedures using a sample of size 10,000 for $S_{st}$ (Chapt. 6, 9, 10, 11, 12, 13, Ref. 20) were used to evaluate the integral in Eq. (7) for each LHS element and thus obtain CCDFs for normalized release to the accessible environment (Fig. 7a); and the resultant distribution of CCDFs was summarized with mean and percentile curves as described in conjunction with Fig. 6 (Fig. 7b).

To satisfy certain requirements in 40 CFR 194 related to assessing the robustness of results obtained in the PA, the indicated LHS of size 300 was actually generated as three individual samples (i.e., replicates R1, R2, R3) of size 100 each (Sects. 6.4, 6.5, Ref. 20). In the Monte Carlo evaluation of the integral in Eq. (7), the mechanistic models that underlie the function $f$ in Eq. (11) were evaluated for a relatively small number of futures (i.e., elements $x_{st}$ of $S_{st}$) and these evaluations were then used in conjunction with various algebraic and interpolation procedures to evaluate the large number (i.e., 10,000) of futures used in the Monte Carlo integration (Chapts. 9, 10, 11, 12, 13, Ref. 20).

From a decision analysis perspective, the goal of the 1996 WIPP PA was to determine if the WIPP met the requirements imposed by 40 CFR 191 and 40 CFR 194, of which the central requirement was that the CCDF for normalized release to the accessible environment fall below a specified boundary line. As discussed, this can be viewed as attempting to answer four distinct questions (i.e., Q1, Q2, Q3, Q4 in Sect. II) and results in an analysis that is based on three distinct entities (i.e., EN1, EN2, EN3 in Sect. III). The resultant CCDFs and associated uncertainty assessment (Fig. 7) indicate a high level of confidence that the WIPP meets the requirements imposed on it with respect to normalized radionuclide releases to the accessible environment. As a result of this and other related analysis results, the EPA has determined that the WIPP meets the conditions imposed by 40 CFR 191 and 40 CFR 194 and has issued a preliminary decision to certify the WIPP for the disposal of TRU waste.7
Total Normalized Releases: R1
100 Observations, 10000 Futures/Observation

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Total Normalized Releases: R1, R2, R3
300 Observations, 10000 Futures/Observation

Frame 7b

Fig. 7. Distribution of CCDFs for normalized release to the accessible environment over 10,000 yr: (7a) 100 CCDFs for replicate R1, and (7b) mean and percentile curves obtained from all 300 CCDFs for replicates R1, R2 and R3.

REFERENCES


