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The 1996 Performance Assessment for the **OSTI** Waste Isolation Pilot Plant

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1 Introduction

The Waste Isolation Pilot Plant (WIPP) is under development by the U.S. Department of Energy (DOE) for the geologic disposal of transuranic (TRU) waste that has been generated at government defense installations in the United States. The WIPP is located in an area of low population density in southeastern New Mexico. Waste disposal will take place in excavated chambers in a bedded salt formation approximately 655 m (2150 ft) below the land surface. This presentation describes a performance assessment (PA) carried out at Sandia National Laboratories (SNL) to support the Compliance Certification Application (CCA) made by the DOE to the U.S. Environmental Protection Agency (EPA) in October, 1996, for the certification of the WIPP for the disposal of TRU waste.¹

2 Regulatory Requirements

The conceptual structure of the 1996 WIPP PA ultimately derives from the regulatory requirements imposed on this facility.^{2,3} The following is the central requirement in 40 CFR 191, Subpart B,^{4,5} and the primary determinant of the conceptual structure of the 1996 WIPP PA (p. 38086, Ref. 4):

§ 191.13 Containment requirements: (a) Disposal systems for spent nuclear fuel or high-level or transuranic radioactive wastes shall be designed to provide a reasonable expectation, based upon performance assessments, that cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from all significant processes and events that may affect the disposal system shall: (1) Have a likelihood of less than one chance in 10 of exceeding the quantities calculated according to Table 1 (Appendix A); and (2) Have a likelihood of less than one chance in 1,000 of exceeding ten times the quantities calculated according to Table 1 (Appendix A).

To help clarify the intent of 40 CFR 191, the EPA also published 40 CFR 194.⁶ There, the following elaboration on the intent of 40 CFR 191.13 is given (pp. 5242-5243, Ref. 6):

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§ 194.34 Results of performance assessments. (a) The results of performance assessments shall be assembled into "complementary, cumulative distributions functions" (CCDFs) that represent the probability of exceeding various levels of cumulative release caused by all significant processes and events. (b) Probability distributions for uncertain disposal system parameter values used in performance assessments shall be developed and documented in any compliance application. (c) Computational techniques, which draw random samples from across the entire range of the probability distributions developed pursuant to paragraph (b) of this section, shall be used in generating CCDFs and shall be documented in any compliance application. (d) The number of CCDFs generated shall be large enough such that, at cumulative releases of 1 and 10, the maximum CCDF generated exceeds the 99th percentile of the population of CCDFs with at least a 0.95 probability. (e) Any compliance application shall display the full range of CCDFs generated. (f) Any compliance application shall provide information which demonstrates that there is at least a 95 percent level of statistical confidence that the mean of the population of CCDFs meets the containment requirements of § 191.13 of this chapter.

In addition to the requirements in 40 CFR 191.13(a) and 40 CFR 194.34 just quoted, 40 CFR 191 and 40 CFR 194 contain many additional requirements for the certification of the WIPP for the disposal of TRU waste. However, it is the indicated requirements that determine the overall structure of the 1996 WIPP PA and are the primary focus of this presentation. A complete description of the requirements that are placed on the WIPP and how these requirements are addressed is available in the CCA (pp. XWALK-1 to XWALK-36, Ref. 1).

3 Structure of 1996 WIPP PA

As discussed in earlier presentations,⁷⁻⁹ three basic entities (EN1, EN2, EN3) underlie the results required in 191.13 and 194.34 and ultimately determine the conceptual and computational structure of the 1996 WIPP PA: EN1, a probabilistic characterization of the likelihood of different futures occurring at the WIPP over the next 10,000 yr; EN2, a procedure for estimating the radionuclide releases to the accessible environment associated with each of the possible futures that could occur at the WIPP over the next 10,000 yr; and EN3, a probabilistic characterization of the uncertainty in the parameters used in the definition of EN1 and EN2. Together, EN1 and EN2 give rise to the CCDF specified in 191.13(a), and EN3 corresponds to the distributions indicated in 194.34(b).

The preceding entities arise from an attempt to answer three questions (Q1, Q2, Q3) about the WIPP: Q1, "What occurrences could take place at the WIPP over the next 10,000 yr?"; Q2, "How likely are the different occurrences that could take place at the WIPP over the next 10,000 yr?"; Q3, "What are the consequences of the different occurrences that could take place at the WIPP over the next 10,000 yr?"; and one question (Q4) about the WIPP PA: Q4, "How much

confidence should be placed in answers to the first three questions?". In the WIPP PA, EN1 provides answers to Q1 and Q2; EN2 provides an answer to Q3; and EN3 provides an answer to Q4.

Careful definitions of the preceding entities are necessary for the computational implementation of the 1996 WIPP PA. However, the start of a PA for a complex system goes through a preliminary, and often rather ill-defined, phase in which it must be decided what is to be, and hence what is not to be, included in the analysis. It is from this work that the formal definitions of these entities ultimately emerge. For the 1996 WIPP PA, this initial work was carried out in an activity referred to as the identification and screening of features, events and processes (FEPs) (Sect. 6.2, Ref. 1).

The entity EN1 is the formal outcome of the FEPs process for determining what could happen at the WIPP and provides a probabilistic characterization of the likelihood of different futures that could occur at the WIPP over the next 10,000 yr, with the period of 10,000 yr specified in 40 CFR 191. When viewed formally, EN1 is defined by a probability space $(\mathcal{S}_{st}, \mathcal{A}_{st}, p_{st})$, with the sample space $\mathcal{S}_{st}$ given by

$$\mathcal{S}_{st} = \{x_{st}: x_{st} \text{ is a possible 10,000 yr sequence of occurrences at the WIPP}\}. \quad (1)$$

The subscript st refers to stochastic (i.e., aleatory) uncertainty and is used because $(\mathcal{S}_{st}, \mathcal{A}_{st}, p_{st})$ is providing a probabilistic characterization of occurrences that may take place in the future.¹⁰

The FEPs development process for the WIPP identified exploratory drilling for natural resources as the only disruption with sufficient likelihood and consequence for inclusion in the definition of EN1 (App. SCR, Ref. 1). In addition, 40 CFR 194 specifies that the occurrence of mining within the land withdrawal boundary must be included in the analysis. The preceding considerations led to the elements x_{st} of $\mathcal{S}_{st}$ being vectors of the form

$$x_{st} = [\underbrace{t_1, l_1, e_1, b_1, p_1, a_1}_{1^{\text{st}} \text{ intrusion}}, \underbrace{t_2, l_2, e_2, b_2, p_2, a_2}_{2^{\text{nd}} \text{ intrusion}}, \dots, \underbrace{t_n, l_n, e_n, b_n, p_n, a_n}_{n^{\text{th}} \text{ intrusion}}, t_{min}] \quad (2)$$

in the 1996 WIPP PA, where n is the number of drilling intrusions in the vicinity of the WIPP, 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 Formation, 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.

In the development of $(\mathcal{S}_{st}, \mathcal{A}_{st}, p_{st})$, the probabilistic characterization of n , t_i , l_i and e_i derives from the assumption that drilling intrusions occur randomly in time and space (i.e., follow a Poisson process); the probabilistic characterization of b_i derives from assessed properties of brine pockets; the probabilistic characterization

of $\mathbf{a}_i$ derives from the properties of the waste to be emplaced at the WIPP; and the probabilistic characterization of p_i derives from current drilling practices in the sedimentary basin in which the WIPP is located. A vector notation is used for $\mathbf{a}_i$ because a given drilling intrusion can penetrate several different types of waste. Further, the probabilistic characterization for t_{min} follows from guidance in 40 CFR 194 that the occurrence of potash mining should be assumed to occur randomly in time (i.e., follow a Poisson process with a rate constant of $\lambda_m = 10^{-4} \text{ yr}^{-1}$), with all commercially viable potash reserves being extracted at time t_{min} . Additional information on $(\mathcal{S}_{st}, \mathcal{S}_{st}, p_{st})$ is given in Chapt. 3 of Ref. 11.

The entity EN2 is the formal outcome of the FEPs process for determining what physical processes should be modeled at the WIPP and provides a way to estimate radionuclide releases to the accessible environment for the different futures (i.e., elements $\mathbf{x}_{st}$ of $\mathcal{S}_{st}$) that could occur at the WIPP. In the 1996 WIPP PA, estimation of environmental releases corresponds to evaluation of a function f of the form

$$\begin{aligned} f(\mathbf{x}_{st}) = & f_C(\mathbf{x}_{st}) + f_{SP}[\mathbf{x}_{st}, f_B(\mathbf{x}_{st})] + f_{DBR}\{\mathbf{x}_{st}, f_{SP}[\mathbf{x}_{st}, f_B(\mathbf{x}_{st})], f_B(\mathbf{x}_{st})\} \\ & + f_{MB}[\mathbf{x}_{st}, f_B(\mathbf{x}_{st})] + f_{DL}[\mathbf{x}_{st}, f_B(\mathbf{x}_{st})] + f_S[\mathbf{x}_{st}, f_B(\mathbf{x}_{st})] \\ & + f_{S-T}\{\mathbf{x}_{st,0}, f_{S-F}(\mathbf{x}_{st,0}), f_{N-P}[\mathbf{x}_{st}, f_B(\mathbf{x}_{st})]\}, \end{aligned} \quad (3)$$

where $\mathbf{x}_{st}$ ~ particular future under consideration, $\mathbf{x}_{st,0}$ ~ future involving no drilling intrusions but a mining event at the same time t_{min} as in $\mathbf{x}_{st}$, $f_C(\mathbf{x}_{st})$ ~ cuttings and cavings release to accessible environment calculated with the CUTTINGS_S program, $f_B(\mathbf{x}_{st})$ ~ two-phase flow results calculated with the BRAGFLO program, $f_{SP}[\mathbf{x}_{st}, f_B(\mathbf{x}_{st})]$ ~ spallings release to accessible environment calculated with the CUTTINGS_S program, $f_{DBR}\{\mathbf{x}_{st}, f_{SP}[\mathbf{x}_{st}, f_B(\mathbf{x}_{st})], f_B(\mathbf{x}_{st})\}$ ~ direct brine release to accessible environment calculated with the BRAGFLO_DBR program, $f_{MB}[\mathbf{x}_{st}, f_B(\mathbf{x}_{st})]$ ~ release through anhydrite marker beds to accessible environment calculated with the NUTS program, $f_{DL}[\mathbf{x}_{st}, f_B(\mathbf{x}_{st})]$ ~ release through Dewey Lake Red Beds to accessible environment calculated with the NUTS program, $f_S[\mathbf{x}_{st}, f_B(\mathbf{x}_{st})]$ ~ release to land surface due to brine flow up a plugged borehole calculated with the NUTS or PANEL program as appropriate, $f_{S-F}(\mathbf{x}_{st,0})$ ~ Culebra flow field calculated with the SECOFL2D program, $f_{N-P}[\mathbf{x}_{st}, f_B(\mathbf{x}_{st})]$ ~ release to Culebra calculated with the NUTS or PANEL program as appropriate, $f_{S-T}\{\mathbf{x}_{st,0}, f_{S-F}(\mathbf{x}_{st,0}), f_{N-P}[\mathbf{x}_{st}, f_B(\mathbf{x}_{st})]\}$ ~ groundwater transport release through Culebra to accessible environment calculated with the SECOTP2D program. Descriptions of the individual models that comprise f and sources of additional information are given in Chapt. 4 of Ref. 11. Determination of the

CCDF specified in 40 CFR 191.13(a) can be formally represented as the evaluation of an integral involving $(\mathcal{S}_{st}, \mathcal{L}_{st}, p_{st})$ and f (Fig. 1).

The entity EN3 is the outcome of the data development effort for the WIPP and provides a probabilistic characterization of the uncertainty in the parameters that underlie the WIPP PA. When viewed formally, EN3 is defined by a probability space $(\mathcal{S}_{su}, \mathcal{L}_{su}, p_{su})$, with the sample space $\mathcal{S}_{su}$ given by

$$\mathcal{S}_{su} = \{\mathbf{x}_{su}: \mathbf{x}_{su} \text{ is possibly the correct vector of parameter values to use in the WIPP PA models}\}. \quad (4)$$

The subscript *su* refers to subjective (i.e., epistemic) uncertainty and is used because $(\mathcal{S}_{su}, \mathcal{L}_{su}, p_{su})$ is providing a probabilistic characterization of where the appropriate inputs to use in the WIPP PA are believed to be located.¹⁰ The vectors $\mathbf{x}_{su}$ in $\mathcal{S}_{su}$ are of the form $\mathbf{x}_{su} = [x_1, x_2, \dots, x_{nV}]$, where each element x_j of $\mathbf{x}_{su}$ is an uncertain input to the 1996 WIPP PA and nV is the number of such inputs (see App. PAR, Ref. 1, and Table 5.2.1, Ref. 11, for a complete listing of the $nV = 57$ elements of $\mathbf{x}_{su}$ and sources of additional information). The uncertainty in $\mathbf{x}_{su}$ is characterized by specifying a distribution $D_j, j = 1, 2, \dots, nV$, for each element x_j of $\mathbf{x}_{su}$. Correlations and other restrictions involving the elements of $\mathbf{x}_{su}$ are also possible. In the 1996 WIPP PA, rank correlations were imposed on three pairs of variables. The distributions $D_j, j = 1, 2, \dots, nV$, and any associated conditions then give rise to the probability space $(\mathcal{S}_{su}, \mathcal{L}_{su}, p_{su})$.

Fig. 1. Definition of CCDF specified in 40 CFR 191, Subpart B as an integral involving the probability space $(\mathcal{S}_{st}, \mathcal{L}_{st}, p_{st})$ for stochastic uncertainty and a function f defined on $\mathcal{S}_{st}$ (Fig. 1, Ref. 7).

4 Results

In the 1996 WIPP PA, the integral that defines the CCDF specified in 40 CFR 191.13(a) (Fig. 1) was approximated with a Monte Carlo procedure based on random sampling of the vectors $\mathbf{x}_{st}$ in Eq. (2) (Sect. 6.6, Ref. 11). The effects of subjective uncertainty were introduced into the analysis by generating a Latin hypercube sample from $\mathcal{S}_{su}$ in consistency with the distributions that define $(\mathcal{S}_{su}, \mathcal{S}_{su}, p_{su})$ and then constructing a CCDF for comparison with the boundary specified in 40 CFR 191.13(a) for each element of this sample (Sects. 6.5, 6.7, Ref. 11). The proximity of the resultant distribution of CCDFs to the specified boundary line then provides an assessment of the "reasonable expectation" of compliance required in 40 CFR 191.13(a).

As indicated by the resultant distribution of CCDFs (Fig. 2), there is a high level of confidence that the requirements in 40 CFR 191.13(a) will be met. In particular, the distribution of CCDFs is substantially removed from the specified boundary line even when the effects of subjective uncertainty are incorporated into the analysis. In addition, the 1996 WIPP PA was designed to implement all the requirements in 40 CFR 194.34 (Chapt. 6, Ref. 11), with the satisfaction of these requirements contributing to the assessed confidence that 40 CFR 191.13(a) is indeed met.

5 Status

Based on the CCA supported by the PA described in this presentation,¹ the EPA has issued a preliminary decision to certify the WIPP for the disposal of TRU waste.¹² At present (April 1998), it appears likely that the WIPP will be in operation by the end of 1998.

Fig. 2. Distribution of CCDFs for total normalized release to accessible environment: (2a) individual CCDFs, and (2b) mean and quantile curves (Fig. 3, Ref. 9).

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