IPA PHASE 2 TOTAL SYSTEM CODE AND SCENARIO ANALYSIS

James R. Park
U.S. Nuclear Regulatory Commission
Mail Stop 4H3
Washington, DC 20555
(301) 504-2592

Robert G. Baca
Center for Nuclear Waste Regulatory Analyses
6220 Culebra Road
San Antonio, Texas 78228
(210) 522-3805

Norman A. Eisenberg
U.S. Nuclear Regulatory Commission
Mail Stop 4H3
Washington, DC 20555
(301) 504-2324

Ronald W. Janetzke
Center for Nuclear Waste Regulatory Analyses
6220 Culebra Road
San Antonio, Texas 78228
(210) 522-3318

Budhi Sagar
Center for Nuclear Waste Regulatory Analyses
6220 Culebra Road
San Antonio, Texas 78228
(210) 522-5252

ABSTRACT

The U.S. Nuclear Regulatory Commission (NRC) staff is expanding and improving its independent capability to review performance assessments for a high-level waste (HLW) geologic repository. Two important aspects of a performance assessment are: (1) the scenario analysis and (2) the computation, using a total-system performance assessment code, of the performance measure for the containment requirement, the complementary cumulative distribution function (CCDF) of radionuclide releases to the accessible environment over the 10,000-year period of regulatory interest. This paper discusses the total-system code developed and the scenario analysis performed for the recently completed Iterative Performance Assessment (IPA) Phase 2 analysis, conducted by the NRC and Center for Nuclear Waste Regulatory Analyses (CNWRA) staffs.

I. INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) is expanding and improving its capability to conduct an independent technical review of the U.S. Department of Energy (DOE) pre-licensing and licensing submittals for a high-level waste (HLW) geologic repository. As a means to build this review capability, the NRC staff is expanding and improving its independent capability to conduct performance assessments for an HLW repository. This capability provides a basis for review of DOE's performance assessment activities and for insights into the adequacy of DOE's site characterization activities. The various components that comprise the performance assessment of an HLW repository have been delineated previously[1,2,3]. Two important aspects of the assessment are: (1) the scenario analysis and (2) the computation, using a total-system performance assessment code, of the performance measure for the containment requirement, the complementary cumulative distribution function (CCDF) of radionuclide releases to the accessible environment over the 10,000-year period of regulatory interest. The system code organizes and links the various quantitative components of the analysis, and therefore implements in a concrete fashion the concepts and structure of the assessment methodology. The scenario analysis is intimately linked to the design of the system code and its component modules, since the scenario methodology provides structure to the total system code, with the scenarios identified providing the scope of the consequence modules. This paper discusses the total-system code developed and the scenario analysis performed for the NRC/CNWRA Iterative Performance Assessment (IPA) Phase 2 analysis.

II. IPA PHASE 2 TOTAL SYSTEM CODE

In IPA Phase 1, a simple total-system code was developed to process the data needed to generate a CCDF representative of the performance of an HLW repository.[3] In IPA Phase 2, a more general system model and computer code were developed for this purpose. The principal features of the computer code, designated the Total-System Performance Assessment (TPA) computer code, are outlined and briefly described in this paper. Sagar and Janetzke[4] provide a more complete description of the TPA computer code.

The main objective of the TPA computer code is to provide computational algorithms for estimating compliance with the performance objectives set forth in 10 CFR Part 60. When fully developed, the TPA computer code will permit estimates of overall system performance (10 CFR 60.112) as a function of the specific characteristics of the proposed repository site and design. Within the TPA code, estimates of subsystem performance (10 CFR 60.113) also will be computed, if convenient, in an approximate fashion. Such computations will need to address the complex interactions among the natural and engineered systems, given the possible future states of these systems over the next 10,000 years. The NRC staff expects to use this capability to assist in the review of critical aspects of DOE's demonstrations of compliance with the overall system and subsystem performance objectives of 10 CFR Part 60. As part of iterative performance assessments, the NRC overall system model will be used to help in identifying and understanding the processes and barriers that may have the strongest influences on the isolation of waste.

A. Description of Work

The complex nature of the various physical processes in the natural system and of the interactions among these processes, and between the engineered and natural systems, requires that a multi-disciplinary approach be taken to performance assessment. Various theories, analyses, and data from the disciplines involved must be integrated into a total-system model. The TPA computer code is designed to simulate the behavior of a geologic repository located in a partially saturated medium, with both the engineered barriers and the natural system accounted for in the program design.

The TPA computer code consists of four basic parts:

(1) a controlling, or "executive," module;
(2) algorithm(s) to sample from statistical distributions;
(3) algorithms to model repository system processes, and consequences associated with potentially disruptive scenarios; and
(4) algorithms to sum the consequences and generate representative performance measures (e.g., CCDFs, individual doses)

Additional algorithms, which compute sensitivities and perform uncertainty analyses, are executed separately. Figure 1 displays schematically the data flow and execution dependencies among the various components of the TPA computer code.

These various algorithms are incorporated into a set of interdependent computational modules, whose individual execution is controlled by the executive module. The

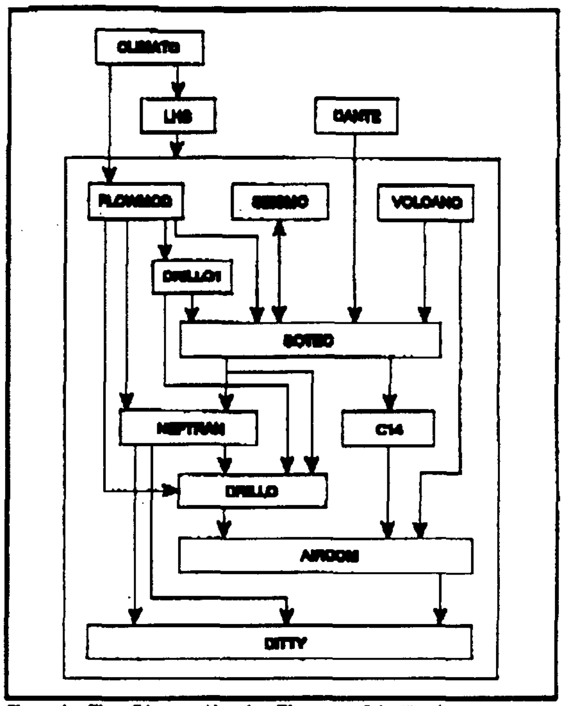

Figure 1. Flow Diagram Showing Elements of the Total-System Performance Assessment (TPA) Computer Code

executive module initiates the consequence modules in the proper sequence to calculate the effects of various scenarios. While the TPA code is running, multiple scenarios can be analyzed via the executive module without further analyst intervention. In addition, the executive module controls data transfer between modules and ensures that appropriate values of input parameters common to two or more consequence modules are passed appropriately.

Algorithms used to model processes occurring in the repository system and the consequences due to disruptive scenarios are incorporated into the consequence modules (see Figure 1). Some of the consequence modules simulate groundwater flow (FLOWMOD), waste package failure and aqueous and gaseous radionuclide release from the engineered barrier system (SOTEC), and transport through the geosphere to the accessible environment (NEFTRAN, C14). Other consequence modules describe the effects of disruptive events and processes (i.e., those associated with volcanic activity (VOLCANO), seismicity (SEISMO), climate change (CLIMATO), and exploratory drilling (DRILLO1, DRILLO2) on the repository. Consequences can be calculated in the form of cumulative radionuclide releases to the accessible environment and as individual or

Park 2

population dose. These modules are designed to be run as part of the overall TPA code, but can be used individually also for special calculations. Because the TPA code is modular, alternative or improved consequence modules can be added, as desired or needed.

Many of the consequence modules required some of their input parameters to be sampled from probabilistic distributions specified by the analyst(s). Latin Hypercube Sampling (LHS)[5] was used to generate, from an input file containing the specifications for these distributions, a vector of parametric values containing the sampled data for each of the input variables. For a given simulation, multiple vectors of parameters can be generated. When each consequence module begins execution as directed, the module searches the LHS output file and selects the necessary variables from the appropriate vector(s), with the aid of a "map" file.

An important consideration in the simulation process is that parameters common to more than one consequence module be specified consistently. Since the design of the TPA code allows consequence modules to be run independently, this consistency is maintained through temporary "global data" files which transmit data from the executive module to the consequence modules. These data files contain parameters in a fixed order, and the corresponding consequence module must follow this order when extracting the parameters from the file. This process is completely automated, not requiring manipulation by the user, and is transparent to the module developer.

III. IPA PHASE 2 SCENARIO ANALYSIS

In IPA Phase 2, the NRC staff applied the Sandia National Laboratories (SNL) scenario selection procedure[6] to develop scenarios for consideration in the Phase 2 consequence analysis. This methodology, developed by SNL under contract to the NRC, consists of a five-step procedure in which site-specific phenomena considered to be potentially disruptive to HLW isolation are identified, classified, and screened against well-defined criteria. (The term "disruptive" is used in a general sense to indicate conditions other than undisturbed; the exact nature and impact of the change is not implied.) Phenomena remaining following screening are then combined into scenarios, and finally, the resultant scenarios themselves are screened. The methodology has been applied previously by SNL staff[6,7] and by other organizations[8,9] involved in the geologic disposal of high-level radioactive waste.

For the analysis, a "scenario" was defined as any postulated future sequence of events and processes (EPs) which is sufficiently credible to warrant consideration of its projected effect on repository performance. These sequences may involve the occurrence of natural phenomena and/or human-initiated activity. A "scenario class" was defined as a unique combination of processes and/or events without regard to the order in which they occur.

A. Description of Work

1. *Definition of repository system boundaries.* Prior to identification of an initial set of potentially disruptive phenomena for consideration, the boundaries of the repository system were defined. In an approach similar to that taken in the IPA Phase 1 scenario development effort[3], these boundaries were chosen to be largely coincident with those of the accessible environment. For the analysis, the repository system was defined as extending 5 kilometers (3.1 miles) horizontally from the outer perimeter of the proposed repository, and vertically from the land surface to a depth just below the current water table.

Definition of the system boundaries had direct impacts on the identification of an initial set of phenomena (and the scenarios subsequently to be generated) for consideration in the analysis. Phenomena initiated beyond the repository system boundaries were classified as "external" perturbations of the system, even if the effects of the phenomena occurred within the system. For example, fault displacement in the repository was classified as an external event because the tectonic forces responsible for initiating the movement could be considered external to the system. Exploratory drilling was classified as an external event for similar reasons. Phenomena, such as waste canister corrosion, shaft and borehole seal degradation, on the other hand, which would occur within the defined system, were classified as "internal" phenomena. External phenomena were retained for consideration in the scenario analysis, while internal events and processes, including features of the site (e.g., faults), were incorporated into the models and data bases used to describe the system behavior. This approach differs from that proposed by Cranwell *et al.* since they include internal processes and features (e.g., borehole seal degradation, the presence of faults) in their scenario analysis[6].

2. *Identification of potentially disruptive phenomena.* Once the repository system boundaries were defined, an initial non-site specific set of potentially disruptive EPs (naturally-occurring and human-initiated) was compiled from similar lists of those considered: (1) in the IPA Phase 1 scenario analysis[3]; (2) in the SNL work of Cranwell *et al.*[6]; and (3) from the generic list of EPs assembled by the International Atomic Energy Agency

Park 3

(IAEA)[10]. These phenomena are identified in Table 1. This list should not be considered complete nor comprehensive; further work may identify additional site-specific EPs which should warrant, at least, initial consideration within a scenario analysis for the Yucca Mountain site.

It is important to note that the EPs identified were considered as "categories" of events and processes since, implicitly, the entire range in possible manifestations, including location and time of occurrence, is contained under each identified EP. In identifying the EPs at this broad level, the staff considered that the EPA guidance related screening of events and processes based on probability of occurrence could be applied appropriately. This guidance, contained in 40 CFR Part 191[11], allows that performance assessments need not consider categories of events or processes that are estimated to have less than one chance in 10,000 of occurring over 10,000 years. In addition, because categories of EPs were considered, classes of scenarios, rather than explicitly-defined individual scenarios, were produced through this analysis.

3. **Event and process screening.** The initial set of EPs was screened against three criteria (lack of physical reasonableness at the site, low probability of occurrence, and insignificant potential consequences). Screening was based on staff judgment, supported by relevant site data, and published scientific and technical analyses. Under these criteria, EPs such as regional uplift and subsidence, sea level change, and meteorite impact were screened from further consideration. Additional EPs were combined with other phenomena when the expected effects of the particular EPs were deemed to be similar. In this way, human-initiated climate control was subsumed into climate change, and weapons testing at the NTS into seismicity. Following this initial screening, six EPs remained:

- Igneous Activity (Extrusive)
- Igneous Activity (Intrusive)
- Faulting
- Seismicity
- Climate Change
- Exploration Drilling

These phenomena were consolidated further due to

Table 1. Initial Set of Potentially Disruptive Events and Processes

Natural Events and Processes	*Human-Initiated Events and Processes*
A. Igneous Activity	A. Climate control (e.g., greenhouse effect)
1. Extrusive	B. War
2. Intrusive	C. Nuclear weapon testing at Nevada Test Site
B. Tectonic Activity	D. Exploration drilling for natural resources
1. Regional Uplift	E. Mining
2. Regional Subsidence	1. Surface-based (open pit)
3. Seismicity	2. Underground shafts and drifts
4. Faulting	F. Large-scale alterations to hydrology (e.g., dams)
C. Climatic Conditions	
1. Current climate — extreme phenomena	
2. Climate change	
D. Other	
1. Sea level change	
2. Tsunamis/seiches	
3. Meteorite impact	

Park 4

consequence modeling constraints, such that the final list of EPs retained for consideration in the IPA Phase 2 scenario analysis consisted of:

- Igneous Activity Affecting the Repository
- Seismicity Affecting the Repository
- Climate Change
- Exploration Drilling

4. Probability of occurrence estimation. Prior to combining the remaining EPs into scenarios, probabilities were estimated for the occurrence of each EP over the coming 10,000 years in the vicinity of the proposed Yucca Mountain site. In estimating the probability of occurrence, the complementary probability of "non-occurrence" also could be derived. The methods used for generating probabilities for each of the EPs are briefly described in the following:

- For "Igneous Activity Affecting the Repository," a non-homogeneous Poisson model, calculated by near-neighbor methods, was used to estimate the likelihood of future volcanic disruption per square kilometer (km) in the Yucca Mountain region. Taking this number, along with an arbitrarily assumed relationship between the likelihood of intrusive versus extrusive events, and a defined region of 12 km × 12 km within which igneous activity was deemed to affect (i.e., intersect) the repository, the probability of activity within the defined region was estimated to be 0.03 over 10,000 years.

- For "Seismicity Affecting the Repository," an attempt was made to relate the level of seismicity necessary to "fail" a waste canister to the degradation of the canister over time. A progressively reduced level of seismic acceleration would be needed as the canister corrodes and the canister strength diminishes. A minimum level of acceleration was determined for a canister "ready" to fail under its own weight. The complement of the probability over 10,000 years of this minimum number (which was approximately equal to zero) was taken to be the probability of the occurrence of the EP. Thus, the probability of "Seismicity Affecting the Repository" was approximately equal to 1.0.

- For "Climate Change," a graph of published interpretations of temperatures and precipitation levels over the previous 45,000 years was generated. From this graph, an arbitrary distinction was made between current climatic ranges of temperature and precipitation and climatic ranges at variance with these ranges (i.e., "Climate Change"). Simple ratios of "Current Climate" and "Climate Change" to the total 45,000 years were calculated, with the "Climate Change" ratio (0.64) used in the analysis as the probability of such change over the next 10,000 years at the site.

- For "Exploration Drilling," the rate of future drilling was taken from the guidance provided in Appendix B of 40 CFR Part 191 for repositories in non-sedimentary rocks. It was further assumed that future exploratory drilling would be distributed randomly in space and time and therefore could be approximated as a Poisson process. As a result, the probability of one or more boreholes being drilled over 10,000 years (i.e., "Exploratory Drilling") within the repository perimeter was nearly 1.0.

5. Combination of phenomena into scenario classes. Following screening, the four EPs were combined to form a set of mutually exclusive scenario classes for potential consideration in the IPA Phase 2 consequence analysis. Figure 2 displays the 16 (2^4) different combinations which are possible, considering both the occurrence and the "non-occurrence" of each of the EPs. "Non-occurrence" should be interpreted to mean "not any occurrence" of the EP over the 10,000-year period of regulatory interest. A scenario class composed of the "non-occurrences" of all four EPs then would be equivalent to an "undisturbed" scenario class. Alternatively, the "completely disturbed" scenario class is the class composed of the occurrences of all four potentially disruptive phenomena within 10,000 years. This does not mean that each of the four EPs transpires concurrently (as this may or may not be physically realistic), but that each phenomenon occurs at some point(s) during the 10,000 years following permanent closure of the repository.

In addition, the EPs were assumed to be mutually independent. Therefore, the probability of occurrence for each respective scenario class was equal to the product of the probabilities of its constituent EPs. The scenario classes and their attendant probabilities are shown in Figure 3.

6. Scenario class screening. Cranwell *et al.*[4] suggest that scenarios may be screened against three criteria similar to those recommended for screening of potentially disruptive phenomena. However, for this analysis, no scenario classes were screened.

IV. CONCLUSIONS

The NRC's TPA code, developed in the IPA Phase 2 exercise, represents a significant improvement over the

Park 5

		$\underline{V}$		V	
		$\underline{D}$	D	$\underline{D}$	D
$\underline{C}$	$\underline{S}$	$\underline{C}\,\underline{S}\,\underline{D}\,\underline{V}$	$\underline{C}\,\underline{S}\,D\,\underline{V}$	$\underline{C}\,\underline{S}\,\underline{D}\,V$	$\underline{C}\,\underline{S}\,D\,V$
	S	$\underline{C}\,S\,\underline{D}\,\underline{V}$	$\underline{C}\,S\,D\,\underline{V}$	$\underline{C}\,S\,\underline{D}\,V$	$\underline{C}\,S\,D\,V$
C	$\underline{S}$	$C\,\underline{S}\,\underline{D}\,\underline{V}$	$C\,\underline{S}\,D\,\underline{V}$	$C\,\underline{S}\,\underline{D}\,V$	$C\,\underline{S}\,D\,V$
	S	$C\,S\,\underline{D}\,\underline{V}$	$C\,S\,D\,\underline{V}$	$C\,S\,\underline{D}\,V$	$C\,S\,D\,V$

$\underline{C}$ - No climate change
C - Climate change

$\underline{S}$ - No seismic activity affecting the repository
S - Seismic activity affecting the repository

$\underline{D}$ - No human intrusion via exploratory drilling
D - Human intrusion via exploratory drilling

$\underline{V}$ - No igneous activity affecting the repository
V - Igneous activity affecting the repository

Figure 2. Combination of Events and Processes into Scenario Classes

		$P(\underline{V}) \approx 0.97$		$P(V) \approx 0.03$		SUM (approximate)
		$P(\underline{D}) \approx 2.3 \times 10^{-7}$	$P(D) \approx 1.0$	$P(\underline{D}) \approx 2.3 \times 10^{-7}$	$P(D) \approx 1.0$	
$P(\underline{C}) \approx 0.356$	$P(\underline{S}) \approx 0.0$	0.0	0.0	0.0	0.0	0.0
	$P(S) \approx 1.0$	7.9×10^{-8}	0.35	2.5×10^{-9}	0.01	0.36
$P(C) \approx 0.644$	$P(\underline{S}) \approx 0.0$	0.0	0.0	0.0	0.0	0.0
	$P(S) \approx 1.0$	1.4×10^{-7}	0.62	4.4×10^{-9}	0.02	0.64
SUM (approximate)		2.2×10^{-7}	0.97	6.9×10^{-9}	0.03	1.0

$P(\underline{C})$ - Probability of no climate change
$P(C)$ - Probability of climate change

$P(\underline{S})$ - Probability of no seismic activity affecting the repository
$P(S)$ - Probability of seismic activity affecting the repository

$P(\underline{D})$ - Probability of no human intrusion via exploratory drilling
$P(D)$ - Probability of human intrusion via exploratory drilling

$P(\underline{V})$ - Probability of no igneous activity affecting the repository
$P(V)$ - Probability of igneous activity affecting the repository

Figure 3. IPA Phase 2 Scenario Classes and Probabilities

02-09-94 10:26 AM FROM NRC White Flint P13? P11

system code employed in Phase 1. Some of the key improvements are: (1) introduction of an executive module, which controls the sequence of execution of various consequence modules and data transfer among the modules; (2) incorporation of a more detailed source term module for both liquid and gaseous components; (3) addition of seismicity and volcanism consequence modules;and (4) addition of a dose-to-man module. The TPA code development is part of the NRC's on-going effort to develop the capability and tools for reviewing DOE's assessments of repository performance. The TPA code is expected to play an important role in assessing key technical uncertainties in total-system performance assessment, particularly those associated with data, parameters, conceptual models, and future system states (i.e., scenarios).

In applying the SNL scenario selection procedure, the authors found it to form an adequate basis for the development of scenario classes for the IPA Phase 2 analysis. Definition of repository system boundaries affected directly the number and types of phenomena identified for consideration in the analysis, and thus the form of the scenarios (i.e., scenario classes) developed. Through this analysis, 16 scenario classes, with associated probabilities, were formed for potential treatment in the IPA Phase 2 consequence analysis.

DISCLAIMER

The views expressed in this paper are the sole opinions of the authors, and do not represent an official position of the U.S. Nuclear Regulatory Commission. Furthermore, the results presented here are for illustration purposes only. They were based largely on preliminary models and limited data, and should not be interpreted as conclusions regarding the adequacy of the proposed repository at Yucca Mountain, Nevada.

REFERENCES

1. U.S. Nuclear Regulatory Commission, "Performance Assessment for High-Level Waste Repositories," Appendix H to Risk Assessment: A Survey of Characteristics, Application, and Methods Used by Federal Agencies for Engineered Systems, submitted to The Federal Coordinating Council for Science, Engineering and Technology Ad Hoc Working Group on *Risk Assessment* (1992).

2. S. Coplan, N. Eisenberg, and J. Randall, "Performance Assessment at the NRC: Current Issues and Recent Progress," *Proceedings of the First Annual International High Level Radioactive Waste Management Conference*, April 8-12, 1990, Las Vegas, Nevada, vol.1, p. 353, (1990).

3. R. Codell, *et al.*, *Initial Demonstration of the NRC's Capability to Conduct a Performance Assessment for a High-Level Waste Repository*, Washington, D.C., U.S. Nuclear Regulatory Commission, NUREG-1327 (1992).

4. B. Sagar, and R.W. Janetzke, *Total-System Performance Assessment (TPA) Computer Code: Description of Executive Module, Version 2.0 - Iterative Performance Assessment, Phase 2*, CNWRA 93-017, San Antonio, TX: Center for Nuclear Waste Regulatory Analyses (1993).

5. R.L. Iman and M.J. Shortencarier, *A FORTRAN 77 Program and User's Guide for the Generation of Latin Hypercube and Random Samples for Use in Computer Models*, Washington, D.C., U.S. Nuclear Regulatory Commission, NUREG/CR-3624 (1984).

6. R.M. Cranwell, *et al.*, *Risk Methodology for Geologic Disposal of Radioactive Waste: Scenario Selection Procedure*, Washington, D.C., U.S. Nuclear Regulatory Commission, NUREG/CR-1667 (1990).

7. R.L. Hunter, *Preliminary Scenarios for the Release of Radioactive Waste From a Hypothetical Repository in Basalt of the Columbia Plateau*, Washington, D.C., U.S. Nuclear Regulatory Commission, NUREG/CR-3353 (1983).

8. J. Andersson, *et al.*, *The Joint SKI/SKB Scenario Development Project*, SKI Technical Report 89:14, Swedish Nuclear Power Inspectorate, Stockholm, Sweden (1989).

9. M.E. Stephens, and B.W. Goodwin, "Systematic Scenario Analysis for the Post-Closure Assessment of the Canadian Concept for Nuclear Waste Disposal," *Proceedings of the International Symposium Safety Assessment of Radioactive Waste*, OECD/NEA, Paris, France (1989).

10. International Atomic Energy Agency, Safety Assessment for the Underground Disposal of Radioactive Wastes, Safety Series No. 56, Int. Atomic Energy Agency, Vienna, Austria (1981).

11. U.S. Environmental Protection Agency, "Environmental Standards for the Management of Spent Nuclear Fuel, High-Level and Transuranic Wastes [Final Rule]," *Federal Register*, vol. 50, no. 182, September 19, 1985, pp. 38066 - 38089.

Park 8