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July 31, 2000

U.S. Nuclear Regulatory Commission
ATTN: Mrs. Deborah A. DeMarco
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Subject: Programmatic Review of Two Papers

Dear Mrs. DeMarco:

The enclosed papers, which will be submitted for publication in the Proceedings of the International Conference on Probabilistic Safety Assessment and Management, November 27–December 1, 2000, are being submitted for programmatic review. The titles are:

> "A Performance Assessment Review Tool for the Proposed Radioactive Waste Repository at Yucca Mountain, Nevada, USA" by Sitakanta Mohanty (Center for Nuclear Waste Regulatory Analyses) and Richard B. Codell (U.S. Nuclear Regulatory Commission).
>
> "An Abstracted Model for Assessing the Effect of Seismically Induced Rockfall on the Waste Package Performance for High-Level Radioactive Waste Disposal" by Sui-Min Hsiung and Sitakanta Mohanty (Center for Nuclear Waste Regulatory Analyses).

Please advise me of the results of your programmatic review. Your cooperation in this matter is appreciated.

Sincerely,

Budhi Sagar
Technical Director

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A Performance Assessment Review Tool for the Proposed Radioactive Waste Repository at Yucca Mountain, Nevada, USA

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Keywords: Waste Management, Uncertainty Analysis, Risk Assessment Computer Codes, System Modeling, Nuclear Fuel Cycle

1. INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC), with the assistance of the Center for Nuclear Waste Regulatory Analyses, has developed a Total-system Performance Assessment (TPA) Code [1] to assist in evaluating the performance of the Yucca Mountain (YM) High-Level Waste Repository in Nevada, proposed by the U.S. Department of Energy (DOE). The proposed YM repository would be built in a thick sequence of partially saturated volcanic tuff above the water table. Among the unique challenges of this environment are (1) the transport of radionuclides would take place partially through highly heterogeneous unsaturated rock; (2) the waste packages (WPs) would be generally exposed to oxidizing conditions, and (3) water either infiltrating from the surface or recirculating because of decay heat may drip onto the WPs.

Tools such as the TPA code and embedded techniques for evaluating YM performance are aimed at (1) determining the parameters and key parts of the repository system that have the most influence on repository performance; (2) performing alternative conceptual models studies, especially with bounding models; (3) estimating the relative importance of the physical phenomena that lead to human exposure to radionuclides; and (4) improving NRC staff capabilities in performance assessment and associated license application reviews. This paper presents an overview of the NRC conceptual framework, approach to conducting system-level sensitivity analyses for determining influential parameters, and alternative conceptual model studies to investigate the effect of model uncertainties.

2. COMPUTATIONAL MODELS

The basic conceptual models in the TPA approach that describe the interactions and couplings of the physical and chemical processes can be grouped into the following categories (see Figure 1): (1) precipitation, infiltration, and deep percolation, (2) near-field environment, (3) failure of engineered barrier system (EBS), (4) disruptive events, (5) radionuclide release from the EBS, (6) aqueous-phase radionuclide transport in unsaturated and saturated zones, (7) airborne transport from extrusive volcanism and (8) exposure to the reference biosphere (dose from groundwater and ground surface releases). This paper briefly describes the NRC conceptual models for the YM repository based on the DOE Viability Assessment (VA) design [2]. Since TPA uses Monte Carlo techniques requiring hundreds to thousands of computations (i.e., realizations), all models are highly simplified and abstracted from more complex models.

2.1 Precipitation, infiltration, and deep percolation

The unsaturated zone (UZ) model assumes percolation of meteoric water at the land surface vertically downward through the repository, and ultimately to the water table. The deep percolation flux is calculated from knowledge of present-day percolation at the site, taking into consideration climate changes, elevation, and soil-depth on the mountain. The effects of site-specific soil cover thickness and elevation are used to reflect the spatial variation over each of the subareas of the repository. The temporal and spatial variation of infiltration was developed from paleo-climatic information using detailed process-level analysis [3].

2.2 Near-field environment

The near-field environment model calculates the physical and chemical processes in the near field, which are affected by repository heat and how heat alters the chemistry and hydrology of the rock. The model calculates rock and WP surface temperature, relative humidity, water chemistry, and water reflux. The temperature model considers conduction, thermal radiation, convection and latent heat transfer. Estimates of pH and chloride concentration are calculated externally using a geochemical code [4].

2.3 Failure of EBS

The WP is the major component of the EBS. This model considers WP failure by corrosion of WP, rock-fall, undetected manufacturing defects and disruptive events such as seismicity and igneous intrusion. For the case evaluated (viability assessment), the WP would be constructed of an inner shell of corrosion-resistant nickel alloy and an outer shell of carbon steel. Corrosion of the outer barrier commences when the relative humidity (RH) at the WP surface exceeds a sampled critical value. Corrosion of the inner shell by either pitting or general corrosion is assumed to be possible under conditions of high RH or dripping, once the outer barrier has been penetrated. No radionuclides can escape the WP until it has been penetrated by at least one pit. We assume that there would be a small number, about 0.1 %, of WPs failed at the time of repository closure, as a result of fabrication defects and damage.

2.4 Disruptive events

There are three classes of disruptive events that could lead to radionuclide releases: seismic activity, fault displacement and volcanism. Seismicity can cause the WPs to fail mainly by inducing large rocks to fall into the excavated tunnels on the WPs [5]. Fault displacement could cause failure by shearing of WP. Igneous intrusions can fail WPs in the repository, leading to early release of dissolved contaminants. Extrusive volcanism can fail WPs, and also carry their contents to the surface and into the air.

2.5 Radionuclide release from EBS

The waste form, either uranium dioxide, uranium metal, or glass will degrade in the presence of air and water. Cladding on commercial spent fuel waste is assumed to fail totally or partially at randomly chosen times. Failed cladding is assumed to partially protect the waste form. Commercial spent nuclear fuel (CSNF) constitutes the bulk of the waste. Fuel is assumed to dissolve only in the presence of water, which comes into contact either by immersion (bathtub model), or dripping (flowthrough model). Water must fill the failed WP to an assumed overflow height before radionuclides leave the WP. In the flowthrough model, the fraction of fuel wetted is the same as the fraction immersed in water in the bathtub model, but radionuclides can leave upon WP failure without water filling the WP.

Most of the radionuclides are assumed to be released from the fuel at the rate that the fuel degrades or dissolves in water. Volatile elements (e.g., iodine) are assumed to be partially available as soon as the WP fails. There are several alternative models for CSNF dissolution in

TPA; two are based on assumptions about water chemistry in contact with the waste. Another assumes equilibrium with the uranium mineral schoepite. The dissolution rate also depends on the assumed average surface area of the exposed fuel, fraction of fuel wetted, and flow through the waste package. There is assumed to be one representative WP for each of the 7 subareas of the repository. However, each subarea may be run several times to represent either corrosion failures, premature failures, or disruptive event (e.g., volcanism, seismicity) failures.

Once released from the WP, the radionuclides first pass through the invert (the material under the WPs), which allows for radionuclide decay, diffusion and retardation. If the infiltration rate exceeds the saturated hydraulic conductivity of the invert, then rapid fracture flow is assumed and that leads to the bypass of this model, and the source term goes directly to the unsaturated flow zone (UZ) model.

2.6 Unsaturated and saturated zone flow and transport

Transport through the UZ below the WPs is assumed to be in parallel, one-dimensional flow paths with non-steady, vertical flow. The model allows for advection, longitudinal dispersion, matrix diffusion for fractured-porous media, and radioactive decay. Transport through the saturated zone is assumed to be in four parallel, steady flowing tubes with advection, longitudinal dispersion, matrix diffusion and radioactive decay. Radionuclides travel through several zones characterized as fracture-matrix and porous flow before reaching the assumed points of groundwater use. The one-dimensional stream tubes were derived from an external two-dimensional modeling study of sub-regional flow [6].

2.7 Airborne transport from extrusive volcanism

Doses to the exposed groups associated with extrusive volcanism are calculated by modeling releases of radionuclides in the airborne plume. The volcanism module assumes that magma intercepts WPs, moves upward to the surface, and then ejects the ash and SF mixture to the atmosphere. Three primary factors determine the ash plume transport; (1) power and duration, (2) wind speed and direction (although we considered wind only blowing in the direction of the critical group) and (3) SF particle size. The ash transport model of Suzuki [8] was modified to take into account the ash blanket thickness, leaching and erosion rates and radionuclide decay rates. Doses are strongly influenced by the timing of the event, with early events resulting in larger doses.

2.8 Exposure to the reference biosphere

Two possible exposed groups are evaluated: (1) a farming community of 100 families located 20 km downgradient from the site, and (2) a residential community less than 20 km from the site. The average member of the designated receptor group is assumed to be exposed to radionuclides transported through the groundwater pathway, air pathway, or both. Dose results from ingestion, inhalation, and direct exposure. Both groups are assumed to obtain dose through inhalation and direct exposure to ash-CSNF particles. For the farming community, we assume that all radionuclides released from the repository to the groundwater (except for the fraction decayed) will eventually be taken up in user wells. Doses are based on the amount of radionuclides dissolved in groundwater reaching the wells, mixed into the total quantity of water used by the community. The exposed group is assumed to get the average concentration for this withdrawal. Groundwater dose pathways include typical uses such as drinking water, irrigation, and stock watering. Only drinking water is considered for the residential community. Dose conversion factors (DCFs) are mean values generated through separate pathway calculations using the GENII-S code [7]. There are separate sets of DCFs for present-day and pluvial climates.

3.0 UNCERTAINTY AND SENSITIVITY ANALYSES

TPA was usually run in the probabilistic mode, using Latin Hypercube Sampling (LHS) [9]. A total of 246 sampled parameters were sampled and up to 1000 repetitions were made per problem. The LHS runs were used to evaluate the mean doses, and also perform sensitivity analyses of the base case and several alternative conceptual models. The base case model reflects the current repository design and likely parameter ranges for processes affecting repository performance. Key features of the base case are: (1) no cladding protection of SF, (2) dissolution of SF based on current saturated groundwater chemistry, (3) the "bathtub" model for fuel/water contact, (4) no matrix diffusion in the UZ and (5) no volcanism or faulting.

The ultimate output of the TPA code is usually framed in terms of the peak dose to an average member of the critical group. From the set of Monte Carlo realizations for each conceptual model, we evaluated the peak dose in two distinct ways. The first, more conventional way is to take the peak dose calculated for each realization and tabulate it. The average of the ensemble of peak doses is then reported. This procedure is known as the "mean of the peaks." Alternatively, the average dose for the ensemble of all runs was calculated at each time interval. The peak of this average dose was then reported. This procedure is referred to as the "peak of the mean" dose, and is always lower than the mean of the peaks. Currently, the staff has decided that the peak of the mean is a fairer representation of risk because it correctly weighs the range of potential doses to an individual during a single lifetime, and is more in line with the NRC's directive to make regulations risk-informed and performance-based. The peak of the mean dose is specified in NRC's draft rule for the Yucca Mountain repository [10].

3.1 Sensitivity

Several techniques that were used in the sensitivity analysis included regression-based methods, differential analysis, design of experiment-based method, Fourier Amplitude Sensitivity Test method, parameter-tree approach, and student's t-statistics. Parameter sensitivity analyses used peak dose from each realization as the performance measure. However, we used the peak of the mean dose when comparing alternative conceptual models. Staff performed sensitivity analysis on peak dose because the technique had not been developed yet for the sensitivity analysis of the mean dose.

Sensitivity was determined for 10,000 and 50,000 years. For both times, only a few of the 246 parameters were found to be influential for the most likely scenario: (1) areal fraction of the repository wetted by water, (2) a factor that expresses the focussing of flow reaching a WP, (3) the well pumping rate for the critical group, and (4) alluvium matrix sorption coefficients for Tc-99 and I-129. Parameters that were influential for 10,000 years, but not for 50,000 years, are: (1) initially defective fraction of WPs, (2) the fraction of water infiltrating to the repository from the unsaturated zone above the repository that will enter the WP and (3) the areal average mean annual infiltration. The only parameter that was significant for 50,000 years, but not 10,000 years, is the alluvium retardation coefficient for U-234.

The influential parameters were used to identify which of NRC's 14 integrated sub-issues (grouped events and processes or physical phenomena) are important to repository performance. The conclusion on relative importance of the parameters was reached by examining the number of times each of the parameters appeared in the top group identified by the various sensitivity measures. This implies that if a parameter was identified as influential by the majority of the sensitivity analysis methods, the integrated sub-issue associated with that parameter is significant. The majority rule was considered acceptable because no individual sensitivity analysis method was found uniquely superior to other methods. Further investigations are currently underway to determine more suitable methods for handling large parameter sets with multiple correlated parameters sampled over a broad range. A suitable method is yet to be developed for combining sensitivity analysis results from the high consequence low probability scenarios with results from the most likely scenarios.

3.2 Alternative Conceptual Models

Alternative conceptual models included disruptive events such as faulting and volcanism, alternative understanding of the physical processes such as bathtub versus flow-through model of the WP, and different models of fuel dissolution. Figure 2 shows a comparison of some of the alternative conceptual models with the base case model for 10,000 years. This figure shows the large sensitivity of dose to assumptions made in the EBS model.

4.0 CONCLUSIONS

The analyses and results demonstrate only a snapshot of NRC's performance assessment capability that is being continually updated. NRC's models and approach are based on a specific design, simplifying assumptions, and sparse data in certain areas. The performance assessment methodology presented in this paper has aided NRC staff in conducting risk-informed performance-based evaluations by focusing their attention on a limited but significant set of integrated sub-issues and providing specific pre-licensing guidance to DOE on the models and parameters that significantly influence DOE's safety case.

5.0 ACKNOWLEDGMENTS

The work reported here is a summary of using the performance assessment tool developed over several years. The authors acknowledge the contribution of CNWRA and NRC staff members, too numerous to list in this paper. This work was performed on behalf of the NRC Office of Nuclear Material Safety and Safeguards Division of Waste Management under contract No. NRC-02-97-009. This paper is a joint NRC/CNWRA effort and does not necessarily reflect the views or regulatory position of the NRC.

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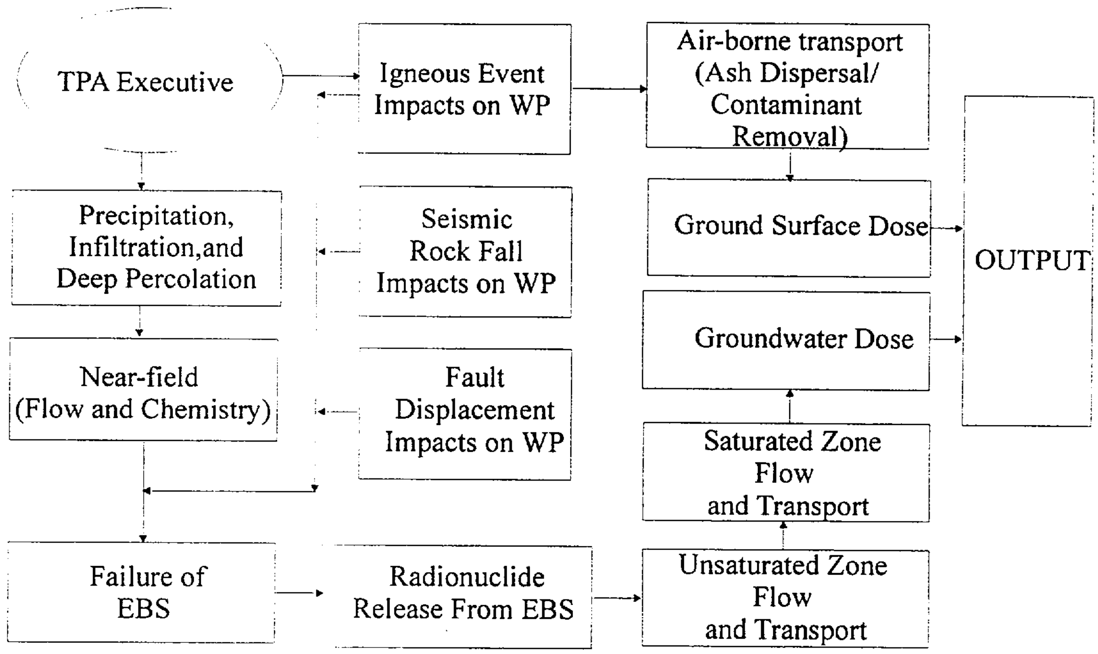

Figure 1. Flow diagram for TPA Version 3.2 code

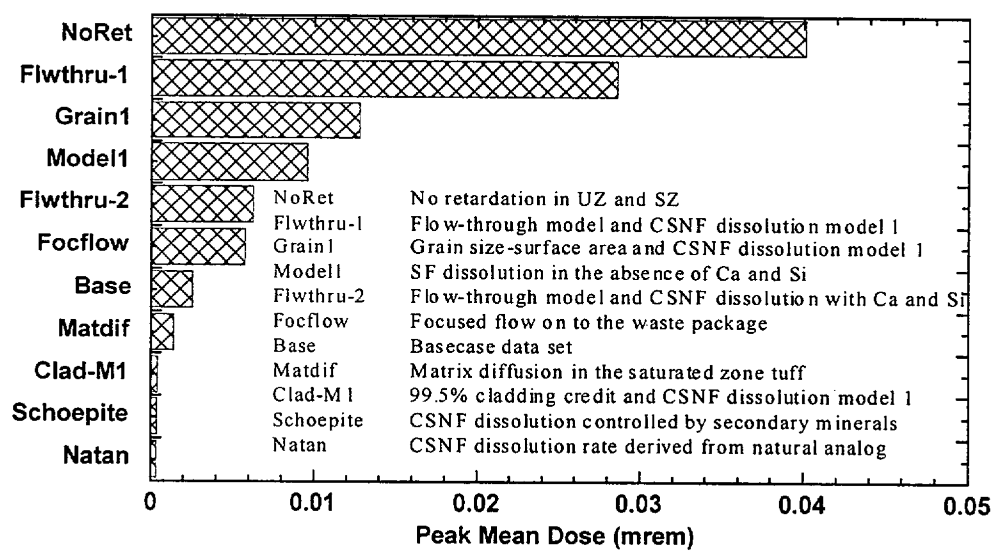

Figure 2. Bar chart showing the effects of alternative conceptual models at 10,000 yr

An Abstracted Model for Assessing the Effect of Seismically Induced Rockfall on the Waste Package Performance for High-level Radioactive Waste Disposal

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Keywords: Seismic Rockfall, Waste Management, Uncertainty Analysis, Performance Assessment

ABSTRACT

Failure of the waste package (WP) from seismically induced rockfall is considered one of the processes that could affect the performance of a repository for high-level radioactive waste disposal. Rockfall could rupture a WP directly from impact or could damage it in a manner that will accelerate corrosion and reduce the intended service life of the WPs. This paper presents the U.S. Nuclear Regulatory Commission's abstracted conceptual model for investigating the consequence of rockfall on WP integrity and demonstrates performance assessment capability using a U.S. Department of Energy repository design concept.

INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) has the responsibility to review the license application for the proposed high-level radioactive waste (HLW) repository site at Yucca Mountain (YM), Nevada, USA. The NRC and the Center for Nuclear Waste Regulatory Analyses (CNWRA) have developed a Total-system Performance Assessment (TPA) code [1] as a review tool that considers events and processes likely to affect the repository and, as a result, public safety. Failure of waste packages (WPs) from seismically induced rockfall is considered one of the processes that could affect repository performance. Rockfall could rupture a WP directly from impact or could damage it in a manner that will accelerate corrosion and reduce the intended service life of the WPs. This paper presents the NRC abstracted model used in the TPA code for independently evaluating the consequence of rockfall on WP integrity and repository performance with respect to model parameter uncertainty.

DESCRIPTION OF THE ABSTRACTION MODEL

The conceptual model for computing the effect of seismicity on WP performance has three basic components: (i) the frequency and magnitude of seismic events, (ii) the quantity of rockfall for each seismic event, and (iii) the effect on the WP. The frequency and magnitude of seismic events are based on a seismic hazard curve that provides accelerations and recurrence frequencies for seismic events during the time period of interest. If a seismic event triggers a rockfall, the volume of rock that falls as a result of a given event is determined by properties related to the thermal-mechanical characteristics of the emplacement rock unit. Although rockfall may rupture the WP by its impact or accelerate corrosion at the location of the impact, only the first aspect is considered in the current model.

Impact Stress and Failure Determination

The abstraction model uses the weight of the rock dislodged from the roof of the emplacement drift to calculate the impact load on the WP. The magnitude of the impact load is assumed to be a function of the size of the falling rock and the distance that the rock falls. The dynamic or impact loads can be approximated based on the principle of conservation of energy using the weights of the freely falling rocks. Assuming that a WP is simply supported at each end, the impact load generated when a rock hits the WP can be approximated using the following relationship [2]

$$P_{dyn} = W\left(1 + \sqrt{1 + \frac{2h}{\Delta_{st}}}\right) \qquad (1)$$

where P_{dyn} is the impact load, W is the weight of the falling rock, h is the falling distance of the rocks hitting the WPs, and Δ_{st} is the maximum combined deformation of the WP and its supports. Δ_{st} is set equal to

$$\Delta_{st} = \frac{W}{k_{wp}} + \frac{W}{2N_p k_b} \qquad (2)$$

where k_{wp} is the stiffness of the WP, N_p is the number of the supports for the WP (2 is used in this case), and k_b is the stiffness of the supports.

Equation (1) assumes (i) a WP can be treated as a simply supported beam or an equivalent spring with a spring constant k_{wp}; (ii) no energy dissipation takes place at the point of impact because of local inelastic deformation of the WP material, (iii) deformation of the WP is directly proportional to the magnitude of the impact, (iv) the rock behaves elastically throughout the impact, and (v) the inertia of the WP may be neglected.

The equivalent static stress, p, resulting from the impact at the point of contact may be approximated by adopting a simple concept of two spheres in contact. Assuming the pressure is distributed over a small circle of contact, and the sphere representing the rock has an infinite radius [3]

$$p = \frac{3}{2\pi}\left(\frac{16P_{dyn}}{9\pi^2}\frac{1}{(C_{wp} + C_{rock})^2 R_{wp}^{\ 2}}\right)^{\frac{1}{3}} \qquad (3)$$

R_{wp} is the radius of the WP, C_{wp} is the material constant for WP, C_{rock} is the material constant for the falling rock, and

$$C_{wp} = \frac{1 - \nu_{wp}^{\ 2}}{\pi E_{wp}} \qquad (4)$$

where E_{wp} is the modulus of elasticity of the lower sphere or WP, ν_{wp} is the Poisson's ratio of the WP,

$$C_{rock} = \frac{1 - \nu_{rock}^{\ 2}}{\pi E_{rock}} \qquad (5)$$

E_{rock} is the modulus of elasticity of the rock, and ν_{rock} is the Poisson's ratio of the rock. In converting impact load to impact stress, all the energy generated during the dynamic impact event is transferred to the WP. If the rock were allowed to break, the effective impact stress to the WP would be smaller because some of the impact energy would be dissipated by the rock fracture mechanisms.

At impact, a WP is considered ruptured if the impact energy is greater than the strain energy necessary to cause the plastic strain of the WP at the point of contact to exceed a predetermined value. This failure criterion is conservative given that only the deformation state at the point of impact is considered for failure, not the entire thickness of the WP wall.

At the present time, it is assumed that the WP outer barrier will rupture if the plastic strain at the point of impact exceeds 5 percent. The analysis assumes, nonconservatively, that rockfall occurs on an intact WP (i.e., corrosion of the WP does not reduce WP strength, and cumulative damage caused by consecutive rockfalls is not considered). In addition, the potential loss of material ductility and embrittlement within or near the closure welds is not considered.

Seismic Hazard

The planned emplacement horizon at the proposed YM site is located in a rock unit with fractures. Rockfall in a fractured rock-mass may be induced by (i) inherently unstable rock blocks after excavation, (ii) long-term deterioration of the rock-mass under prolonged thermal load, or (iii) seismically induced ground motion [4]. To investigate seismically induced rockfall, a history was required of seismic events during the time period of interest. For the abstracted model, the history of seismic events, including recurrence times and associated event magnitudes, was generated probabilistically based on an acceleration hazard curve input. In this paper, the curve presented in a U.S. Department of Energy report [5] was used (figure 1). This hazard curve is based on historical information specifically for surface facilities. A common assumption for the YM site is that the seismic acceleration at the repository horizon may be half that of the ground surface. In the abstracted model, half the surface hazard was used as a basecase [1]. Different hazard input can be used in the abstracted model to assess the potential effects of uncertainties related to the seismic hazards.

Rockfall Size

The volume of a falling rock can be calculated from joint spacing: (JS) (width) × JS (length) × vertical dimension. Given the wide range of distribution of JSs for the rock unit at the emplacement horizon, it was convenient to assume that five distinct rock conditions exist. These rock conditions were estimated using available JS information [6] for the rock unit. Because each rock condition represents a range of JS, a normal distribution for the range of the JS was assumed for the corresponding rock condition. Other distribution functions can also be used. The abstraction for the vertical extent of rockfall used information related to the height of the yield zone above the emplacement drift. The height of the yield zone was estimated from dynamic numerical modeling of coupled thermal-mechanical effects. This height was found to be a function of the magnitudes of seismic events. In the abstracted model, the vertical extent of the rockfall is estimated based on a uniform distribution with the JS and the height of the yield zone as the lower and upper bounds of the distribution, respectively. Using the height of the yield zone as an upper limit to estimate rockfall volume was attempted to account for the possibility of multiple rock blocks falling simultaneously such that they behave like a single rock block. It is recognized that the height of the yield zone may not be a good bounding value because rock can fall without the rock yielding. Also, even though rock yielding occurs, rockfall may not extend to the yield zone boundary. Furthermore, the calculation of volume used in the abstracted model effectively assumes that the falling rock represents a rectangular column. In reality, this is seldom the case. A study attempting to relate rockfall characteristics (e.g., size, shape, and multiple blocks) directly to the magnitudes of seismic events is currently ongoing and some limited results are reported [4].

Lateral Area of Rockfall

When a seismic event occurs, it may or may not trigger rockfall in underground excavations. If a rockfall is triggered, it is not expected to take place for the entire excavation. In fact, only a fraction of the rock in an excavation may fall in response to a seismic event because of the inherent variation associated with the rocks. Another fraction of the rock at the same location or different area of the excavation may fall at a later time when a separate seismic event, having the same or greater intensity, occurs. Rockfall could also occur in response to a smaller magnitude event if the rock has been sufficiently weakened by repeated seismic events or long-term degradation. The areas prone to rockfall may be related to event magnitude, fracture orientation, and incident angle of incoming seismic waves. At this time, little information is available to determine a rockfall prone area or the lateral area of rockfall in excavations. Consequently, a conservative continuous function was developed based on judgment for use in the abstracted model. This function, which relates the lateral area (fractional area) of rockfall to the magnitude of seismic ground accelerations, is assumed to be the same under all five rock conditions. In actuality, a seismic event may trigger more rockfall for one rock condition than for another. Intuitively, for a given seismic ground acceleration, a weaker rock condition should experience a relatively larger area of rockfall compared to a stronger rock condition.

RESULTS AND DISCUSSION

Example calculations were performed for the YM using a nominal data set based on the DOE viability assessment design of the engineered barrier system. The overall emplacement of WPs in the repository in this design is as follows. A total of 70,000 metric tons of spent fuel (62,800 MTU) and other HLW are to be emplaced in an area 3,060,000 m^2. The initial inventory of radionuclides is estimated at 200×10^6 Ci. Each WP will contain approximately 9.76 MTU spent fuel, requiring the emplacement of approximately 6,427 WPs. The WPs are emplaced 18 m apart (end-to-end) in a drift, and the drifts themselves are spaced 22 m apart.

The significance of seismically induced rockfall is investigated in the context of overall repository performance through system level calculations using the TPA code [1]. After determining the WP failure time, the code calculates the aqueous-phase radionuclide releases from failed WPs by considering the dissolution of radionuclides from the spent fuel matrix, advective transport from the WP, and advective and diffusive transport through the invert and the unsaturated zone beneath the repository to the water table. The water in the saturated zone carries the radionuclides downgradient of the repository. A hypothetical receptor group located 20 km downstream of the repository will be exposed to radionuclides from the groundwater pathway when water is withdrawn from wells for consumption.

WP failures may be caused by (i) corrosion and mechanical failures, (ii) disruptive events, and (iii) initially defective failures. Disruptive event failures include the impact of events such as seismicity, fault displacement, and igneous activity. In the case of seismicity, the drift is assumed not to be backfilled for calculating damage to the WP due to rockfall.

The time evolution of seismicity (i.e., the number, time, and magnitude of seismic events) was obtained using the seismic hazard curve in figure 1. The vertical extent of rockfall associated with the different magnitude of seismic events used in the calculation is presented in figure 2. The event type 1 in the figures represents 0.05g of ground acceleration and 0.5g for event type 10. There is a 0.05g difference between the two neighboring event types. The JS information used in the example calculation for computing the rockfall area and volume is presented in figure 3. JS is used to compute volume of rockfall and distribution of JS is used to determine the percent area that has the same JS. The fraction of the area with ground motion for each of the 10 seismic events defined by the seismic hazard curve is presented in figure 4.

The uncertainty in selected parameters for the deterministic mathematical model for rockfall due to seismicity is considered by sampling from probability density functions (PDFs) using the Latin Hypercube Sampling (LHS) technique. The PDFs that represent quantified uncertainty and variability in parameters are closely related to model uncertainty because the PDFs themselves represent assumptions about the system. The rockfall-related model input parameters with mean values and associated PDFs are presented in table 1. The model allows for consideration of uncertainties associated with data presented in figures 2_4.

Monte Carlo realizations (250) were performed using the LHS technique to estimate, with parameter uncertainty, the number of WPs failed by seismically induced rockfall and the consequent dose to a representative individual from a hypothetical critical group. Of the 250 realizations, 22 (i.e., ~9%) showed nonzero WP failures in the first 10^4 yr of the simulation period, which is the proposed regulatory compliance period. WPs failed in the realizations with nonzero seismic failures were 13_33, with failure time 400_35,000 yr (figure 5). Figure 5 shows a cumulative curve with the average (of all realizations) number of WPs failed from rockfall as a function of time. The average number of WPs failed from seismicity (i.e., average of all realizations) is two.

Dose resulting from rockfall-related WP failure as a function of time is shown in figure 6. To emphasize the consequence, figure 6 presents the realization with the largest contribution from seismic failure to dose in 10,000 yr. Negligible difference was observed in the peak expected dose between the basecase with and without the rockfall. In the realization with the largest contribution from rockfall failure, 31 WPs failed in 10,000 yr with 15 at 3,070 yr, 12 at 3,520 yr, and 4 at 8,750 yr. The peak dose for the basecase without seismicity occurred at 7,150 yr.

For the basecase with seismicity, a peak dose value of 3.2 microrem/year occurred at 8,180 yr; a 21% increase in dose. The doses occurring before 10^4 yr are from juvenile and seismic failures. The dominant corrosion failure mode contributes to dose only after 11,000 yr. For the 250 realizations, minimum and maximum peak doses vary five orders of magnitude from about 4×10^{-7} to 0.3 mrem/yr for 10^4 yr and 2×10^{-4} to 50 mrem/yr for 10^5 yr.

The model parameters to which the peak dose is sensitive include Young's modulus of rock and the parameters representing the criterion for WP failure (see table 1).

CONCLUSIONS

An abstracted conceptual model has been developed to investigate the consequence of seismically induced rockfall on WP integrity. The model parameters driving the associated WP failures were also investigated. This model represents the first attempt in the NRC effort to independently evaluate rockfall effects on repository performance.

Based on current knowledge and data, rockfall does not appear to significantly affect overall repository performance. Because of the resistance of the WP to corrosion, however, rockfall related WP failure appears to be the dominant failure mechanism (along with the initially defective failure) contributing to dose during the 10^4 yr compliance period.

The model presented in this paper incorporates considerable intuitive simplification of the process of rockfall related WP failure. The simplification is justifiable if it provides a conservative bound while still demonstrating acceptable repository performance. Detailed calculations are ongoing to relate rockfall characteristics (e.g., size, shape, and multiple blocks) directly to the magnitudes of seismic events. Dynamic finite element analyses of the rock-WP impact event are also being performed to assess the level of conservatism achieved from the simplifying assumptions presently employed in the model abstraction. These finite element analyses are also investigating the effects of potential material ductility loss and embrittlement within and near the closure welds.

ACKNOWLEDGMENTS

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Table 1. Parameters used in determining seismic failure of waste packages

Parameter Value	Mean Value	Distribution
Waste package stiffness	1.21×10^{10} Pa m	Constant
Waste package modulus of elasticity	2.07×10^{11} Pa	Constant
Rock modulus of elasticity	3.45×10^{10} Pa	Normal; 2.76×10^{10}, 4.14×10^{10}
Waste package Poisson ratio	2.00×10^{-1}	Constant
Rock Poisson ratio	2.00×10^{-1}	Normal; 0.15, 0.25
Rock falling distance	2.00 m	Constant
Waste package number of support pair	2.00	Constant
Waste package support stiffness	5.50×10^{9} Pa m	Constant
Waste package ultimate strength	4.50×10^{8} N/m^2	Constant
Grain density for Topopah Spring	2.55 g/cm^3	Constant
Waste package yield point	2.00×10^{-3}	Constant
Waste package plastic elongation	2.00×10^{-2}	Constant

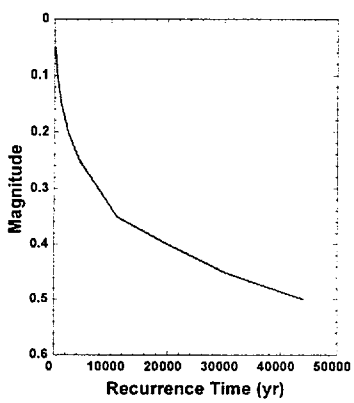

Figure 1. Seismic hazard curve comprises ground acceleration and recurrence times used to determine the time of seismic events

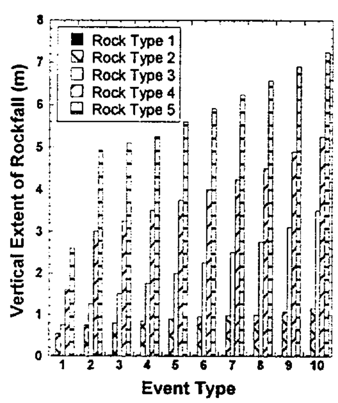

Figure 2. Vertical extent of rockfall associated with the 5 rock types and 10 seismic events defined by the seismic hazard curve

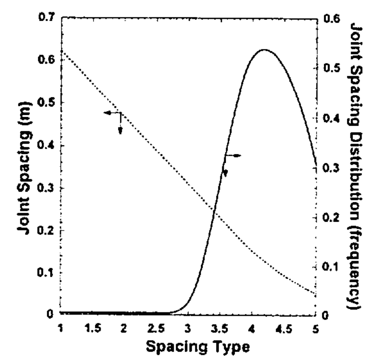

Figure 3. Joint spacing and distribution of the five rock types

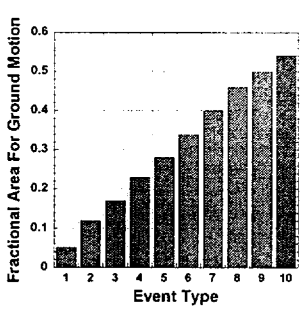

Figure 4. Fraction of the area with ground motion for each of the 10 seismic events defined by the seismic hazard curve

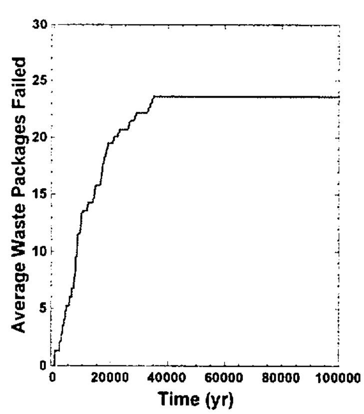

Figure 5. Average number of waste packages failed by seismicity as a function of time

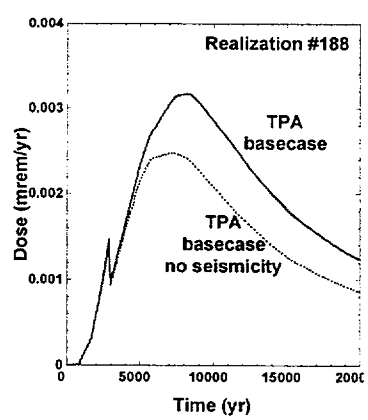

Figure 6. Total effective dose equivalent as a function of time

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REVIEWED BY
Dep. Director ______ 7/31/2000
Element Mgr. ______
Subject Code 709.4

Subject: Programmatic Review of Two Papers

Dear Mrs. DeMarco:

The enclosed papers, which will be submitted for publication in the Proceedings of the International Conference on Probabilistic Safety Assessment and Management, November 27–December 1, 2000, are being submitted for programmatic review. The titles are:

> "A Performance Assessment Review Tool for the Proposed Radioactive Waste Repository at Yucca Mountain, Nevada, USA" by Sitakanta Mohanty (Center for Nuclear Waste Regulatory Analyses) and Richard B. Codell (U.S. Nuclear Regulatory Commission).

> "An Abstracted Model for Assessing the Effect of Seismically Induced Rockfall on the Waste Package Performance for High-Level Radioactive Waste Disposal" by Sui-Min Hsiung and Sitakanta Mohanty (Center for Nuclear Waste Regulatory Analyses).

Please advise me of the results of your programmatic review. Your cooperation in this matter is appreciated.

Sincerely,

Budhi Sagar
Technical Director

GWW/jw
enlcosures

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