CONSIDERATION OF DISRUPTIVE EVENTS FOR THE YUCCA MOUNTAIN SITE RECOMMENDATION REPORT

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ABSTRACT

The United States Department of Energy (DOE) addresses features, events, and processes (FEPs) that could disrupt the performance of the potential repository at Yucca Mountain through a systematic identification and screening process. Four potentially disruptive events have been identified in the proposed DOE regulation 10 CFR Part 963 as requiring particular consideration in the Site Recommendation (SR): volcanism, seismicity, nuclear criticality, and human intrusion. Each of these events has been evaluated for the SR. Seismicity and nuclear criticality are unlikely to have adverse impacts on the long-term performance of the site. Consequences of volcanism and human intrusion are presented in terms of calculated annual dose rates to future humans living 20 km from the potential repository. Calculated mean dose rates are small, reaching approximately 0.2 mrem/yr at 50,000 years for igneous disruption and 0.008 mrem/yr at 1000 years for an human intrusion 100 years after repository closure.

INTRODUCTION

The proposed DOE regulation 10 CFR Part 963 requires that analyses supporting an evaluation of the suitability of the Yucca Mountain site for radioactive waste disposal consider a complete set of FEPs that might affect future performance (1). Although all potentially disruptive events are included under this broad requirement, the proposed regulation specifically identifies four potentially disruptive events as requiring consideration: volcanism, seismicity, nuclear criticality, and human intrusion. Each of these potentially disruptive events has been evaluated for the Site Recommendation Report, as have other potentially disruptive events, such as water-table rise, that have been the subject of interest or concern in the past. Discussion here addresses the four potentially disruptive events specifically identified in proposed 10 CFR Part 963, and focuses on the two potentially disruptive events, volcanism and human intrusion, that are analyzed quantitatively in the total system performance assessment for the site recommendation (TSPA-SR) (2).

The evaluation of disruptive events has been done as part of the process specified by the Nuclear Regulatory Commission (NRC) for the identification of FEPs that have a significant impact on long-term performance (3). The process includes identification and categorization of a comprehensive list of FEPs that are potentially relevant and screening of the FEPs to identify those that have an impact on performance and are also sufficiently likely to occur that they must be included in the TSPA. FEPs that are shown either to have an extremely low probability of occurrence (below one chance in 10,000 during 10,000 years) or to have no significant impact on the overall performance (in terms of expected annual dose) need not be included in the TSPA. Documentation of their low probability or low consequence forms the basis for the evaluation of these FEPs. FEPs that are shown to have both a probability of occurrence greater than one chance in 10,000 during 10,000 years and a significant effect on system-level performance are included explicitly in the TSPA-SR (2).

VOLCANISM

Volcanism, or more specifically, the disruption of the potential repository by either intrusive or extrusive igneous activity, has been evaluated through the FEPs process and included explicitly in the TSPA-SR as a disruptive event. The probability of igneous activity at Yucca Mountain in the future is very small, but slightly greater than the value given in the criteria in proposed 10 CFR Part 963. Probability analysis used the results of an expert elicitation, updated to apply to the current design. Consequence analysis included conceptual models of the magmatic environment in repository drifts with resulting waste package failure modes and releases based on a design without drift backfill. Modeling addressed both intrusive disruptions, in which waste packages are damaged by magma that enters drifts, and extrusive disruptions, in which waste is brought directly to the land surface by a volcanic eruption.

Probability of Igneous Disruption at Yucca Mountain

The probability of future igneous activity used in the TSPA-SR is based on the Probabilistic Volcanic Hazard Analysis conducted by the DOE in 1995 and 1996 (4). The result was a distribution for the annual probability of intersection of the repository by dike intrusion which, adjusted for the current repository footprint, yields a mean of 1.6×10^{-8} (5). The TSPA-SR Rev. 00 ICN 01 analysis uses sampled values drawn from the full distribution of frequencies, which spans roughly 2 orders of magnitude (2). The probability of extrusive disruption was calculated assuming that an eruptive conduit that develops along a dike that intersects the repository may or may not form within the repository footprint and intersect waste. Assuming the current repository design and uniform distribution of conduits along dikes resulted in a multiplier of 0.36 times the intrusive probability to determine the extrusive probability.

Modeling the Consequences of Igneous Disruption at Yucca Mountain

Conceptual models of the magmatic environment in the repository drifts resulting from intrusive and extrusive (eruptive) igneous disruption led to consideration of three different levels of waste package damage (6) in the TSPA-SR; disruption sufficient that the packages provide no further protection to the waste, disruption sufficient to allow water to enter packages, and negligible damage to packages in drifts that are not intersected by the magmatic event. The nature of waste package damage combined with the release mechanism for intrusive and extrusive disruption determined the manner in which the release was modeled (7). Eruptive release modeling used the ash plume dispersion code ASHPLUME (8). Intrusive release was modeled using a groundwater pathway and the same flow and transport parameters used for undisturbed performance.

Eruptive event release modeling used distributions for dike and conduit properties combined with the repository layout to calculate the number of waste packages encountered by conduits. Waste packages in the path of the conduit were assumed to be sufficiently damaged that they provide no protection, resulting in all waste being available for transport to the surface (level 1 damage). Input and derived parameters used by ASHPLUME to characterize the eruption include eruptive power, duration, column height, and total volume of erupted material.

The distribution of contaminated ash from a volcanic eruption is a function of wind speed (0 to approximately 2,000 cm/s, median 650 cm/s) and direction (fixed blowing southward toward the critical group for all realizations) and the volume and particle size of ash and waste erupted. Values for future wind speed and direction are based on past observations in the region. Waste particle diameters (1 to 500 µm, mode 20 µm) were based on laboratory observations of particle sizes of unaltered spent nuclear fuel following mechanical grinding (9). Ash particle diameters (0.01 to 1 mm) were based on observations from violent eruptions at modern analogue volcanoes (10).

Regardless of whether or not an eruption occurs at the repository, igneous events that involve intrusion of magma into the emplacement drifts may damage waste packages and expose waste for groundwater transport. Intersection of high-pressure magma with atmospheric pressure in the emplacement drifts could result in rapid exsolution of volatile phases (primarily water) from the magma, causing propagation of a shock wave accompanied by pyroclastic flow within the drift. Three waste packages on either side of the dike and one at the point of intrusion are assumed sufficiently damaged that all contents are exposed (level 1 damage). Waste packages in intersected drifts not immediately adjacent to the dike are damaged by high temperature and pressure, resulting in openings of varying size in the package lids (level 2 damage). Because current design plans call for backfill in the main access drifts (11), waste packages in drifts that are not intersected by the intrusion will experience far smaller effects, and are assumed to have negligible (level 3) damage.

Modeling Igneous Disruption at Yucca Mountain: Results and Interpretation

For dose calculations, the consequences of igneous disruption are multiplied ("weighted") by the probability of occurrence to yield the annual probability-weighted risk following NRC guidance (3). Dose was calculated for 10,000 years following repository closure per proposed regulations (1). For additional confidence, the TSPA-SR analysis (2) was performed for igneous disruptions for 50,000 years after closure (Figure 1). Igneous disruptions were assumed to be equally likely to occur at any time during the simulation. For the purposes of the analysis, consequences of eruptions were calculated for events occurring at 31.5-year intervals, and consequences of intrusions were calculated for events occurring at random times. Probabilities of both eruptive and intrusive events were adjusted in weighting to yield the correct overall probability (the sampled value on the order of 10^{-8}/yr) that an igneous event will occur in any single year.

Figure 1 shows a range of probability-weighted dose histories representing possible doses to an exposed individual following disruption of the potential Yucca Mountain repository by igneous activity. Results do not include doses that might result from the nominal performance of the repository, in the absence of igneous activity. The figure shows 500 individual curves (in gray) that represent every tenth realization from the total of 5,000 that were completed for the TSPA-SR. These curves display probability-weighted annual dose rates calculated using different sets of sampled values for uncertain input parameters in the model. The range of results shown by these individual curves displays the uncertainty in the calculated dose history resulting from uncertainty in model parameter values. Four additional curves, shown in color, provide summary information about the distribution of results from the full set of 5,000 realizations. The mean curve, shown in red, is the average probability-weighted annual dose rate. The percentile curves, shown for the 95th, 50th (i.e., median), and 5th percentile, show an annual dose rate that is greater than 95 percent (or 50 or 5 percent) of the calculated values at that time. The mean curve lies above the 95th percentile curve throughout the interval between approximately 3000 and 8000 years because the mean is dominated by the relatively small fraction of the total number of realizations that contribute to a high groundwater dose rate at early times. The number of realizations contributing to this pathway increases through time as the cumulative probability of an intrusion having occurred increases, causing the 95th percentile curve to climb above the mean at later times.

For approximately the first 2,000 years, the dose history is a smooth curve dominated by the effects of a volcanic eruption. The probability-weighed mean dose during this period reaches a peak of approximately 0.004 mrem/yr roughly 300 years after repository closure, and then drops off due to radioactive decay of the relatively shorter-lived radionuclides that contribute to doses from the ashfall exposure pathway. The major contributors to the eruptive dose are ^{241}Am, ^{240}Pu, ^{239}Pu, and ^{238}Pu. ^{90}Sr is a significant contributor at extremely early times, but drops off rapidly because of radioactive decay. Inhalation of resuspended particulates in the ash layer is the primary exposure pathway during this period, and the smooth decline of the mean dose curve from approximately 300 to 2,000 years results from decay of ^{241}Am, which has a half-life of 432 years.

From approximately 2,000 years after closure onward, the mean igneous dose is dominated by groundwater releases from packages damaged by igneous intrusion. The irregular shape of the curve from this point forward is in part a result of the complex groundwater transport processes, and in part also reflects the occurrence of intrusive events at random times, rather than the prescribed intervals used for the extrusive simulations. Close examination of Figure 1 shows that individual realizations display distinct peaks occurring at times that are controlled by the sampled time of intrusion and the time required for radionuclide transport through the geologic system. The intrusive event may occur at any time, and the first appearance of groundwater doses in the mean curve at approximately 2,000 years reflects retardation during transport, rather than the absence of intrusions at earlier times. The observation that some of the 500 individual curves continue to be dominated by the smooth eruptive doses for essentially all of the 50,000-year period indicates either that for those realizations the sampled time of intrusion was relatively late or that, in some cases, retardation of radionuclides during transport in the geologic system was effective for a relatively long period of time.

The overall probability-weighted mean igneous dose rate reaches a peak during the first 10,000 years of approximately 0.08 mrem/yr, occurring at 10,000 years. At later times, the calculated mean igneous dose rate is higher, increasing slowly to approach 0.2 mrem/yr at the end of the 50,000-year period. This peak mean igneous dose is dominated entirely by the groundwater releases following igneous intrusion, for which ^{239}Pu and ^{237}Np are the primary contributors.

SEISMICITY

Direct effects of seismic events have been evaluated for the Site Recommendation Report in the context of two separate phenomena: disruption due to fault displacement within the waste emplacement area, and damage caused by vibratory ground motion from earthquakes in the larger region surrounding the site (DE FEPs AMR) (12). Displacement may occur in the future on the larger faults that bound the repository block (e.g., the Solitario Canyon fault), and design specifications therefore require a 60 m setback, sufficient to ensure negligible damage. The occurrence of significant new fault displacements within the potential repository block is shown to be of sufficiently low probability that it need not be considered in the TSPA-SR. Potential damage to the waste packages and drip shields due to vibratory ground motion, both from seismically induced rockfall and from direct shaking of the engineered barriers, is shown to be insignificant during the first 10,000 years following closure, and is also omitted from the TSPA-SR. Cladding on commercial spent nuclear fuel is more susceptible to damage from shaking than the waste package or drip shield, and cladding failure due to vibratory ground motion is included explicitly in the TSPA-SR (2). Cladding failure due to seismicity is estimated to occur with an annual frequency of 1.1×10^{-6}, and is assumed to affect all cladding in the repository. For modeling efficiency, seismic cladding failure is included as a random process in the nominal scenario, and has little effect on performance as long as other engineered barriers (the waste package and drip shield) remain functional.

Indirect effects of seismicity, including changes in the elevation of the water table induced by earthquakes or changes in groundwater flow paths caused by fault displacements, have been examined through the FEPs process and are shown to be of low consequence (13).

NUCLEAR CRITICALITY

The possibility of a nuclear criticality event at the potential repository has been the subject of extensive research by the DOE (e.g., see *Disposal Criticality Analysis Methodology Topical Report* (14). Criticality in the waste and the engineered barrier system has been excluded from the TSPA-SR on the basis of low probability of occurrence during the first 10,000 years of performance. As described in *Probability of Criticality Before 10,000 Years* (15), the probability of a nuclear criticality event at Yucca Mountain has been examined under conditions of nominal performance, potential damage due to seismicity, and igneous disruption. The probability of criticality in the waste package, near-field, and far-field has been shown to be below one chance in 10,000 in the first 10,000 years following repository closure for nominal performance for all waste types. This conclusion is based on the low probability of waste package failure during the first 10,000 years (waste package failure is a necessary condition for all configurations that could lead to criticality), and includes consideration of potential seismic effects. For the igneous disruption scenario, the probability of criticality in commercial spent nuclear fuel (CSNF) both within partially damaged packages and in fuel/magma mixtures that might occur following complete damage of packages are also shown to be below one chance in 10,000 in 10,000 years. The screening decision is preliminary because calculations are incomplete for criticality of defense spent nuclear fuel in magma following igneous disruption, and for criticality events of all waste types outside the package following igneous disruption, in both the near-field and far-field.

HUMAN INTRUSION

Human intrusion is analyzed explicitly in the TSPA-SR (2) consistent with requirements in proposed 10 CFR 963. Regardless of the likelihood or physical reasonableness of the event, a borehole is assumed to penetrate the potential repository 100 years after closure, providing a pathway for radionuclide transport from a damaged waste package to the saturated zone (SZ). Transport within the SZ occurs laterally away from the site, using the same models used for nominal performance.

Design of the Human Intrusion Analysis

The human intrusion borehole is assumed to be drilled from the ground surface (at a random location within the footprint of the potential repository), through the drip shield and a single waste package (top and bottom), to the water table. The borehole is assumed to have a diameter of 20.3 cm, consistent with a standard rock bit used for water well drilling.

Infiltrating water was assumed to flow preferentially down the degraded borehole, bypassing the unsaturated zone (UZ). The infiltration rate was sampled from a distribution based on the modeled infiltration calculated for the glacial transition climate (16). Infiltration rates at the upper end of the distribution account for the possibility of enhanced infiltration if the borehole is located in an area where it might capture significant runoff (e.g., a wash or other surface water collection basin). Infiltration was not modeled explicitly for the human intrusion scenario: rather, the calculated volumetric flux down the borehole from surface infiltration was assumed to flow directly into the penetrated waste package, with no gain or loss from the surrounding UZ.

Water from infiltration was assumed to flow directly into the penetrated waste package, with no resistance from the drip shield or waste package. The penetrated waste package was represented by a mixing cell in which the entire volume of waste from the waste package was available for degradation, with all cladding assumed to be perforated by the intrusion. The waste package type was sampled based on the relative number of CSNF and co-disposed waste packages present in the inventory. Under the current thermal loading, the penetrated waste package would be thermally hot at 100 years to the extent that liquid water entering the waste package would be converted to vapor. Therefore, a conservative bias is incorporated into the human intrusion scenario by assuming that liquid water flows through the penetrated waste package and dissolves radionuclides at 100 years.

The radionuclide mass (both dissolved and colloidal) released from the waste package was assumed to be transported to the water table through a one-dimensional "pipe" with properties similar to a fault pathway in the UZ, approximating the conditions in a degraded, uncased borehole. Volumetric flux was assumed to be the same as in the borehole above the waste package. The pipe transport included sorption (based on devitrified unit properties), but did not include matrix diffusion. The borehole length from the potential repository to the SZ of 190 m conservatively assumed a water level consistent with the glacial transition climate. The distance from the potential repository to the water table is greater for the present day and monsoon climates.

The transport of radionuclides through the SZ was identical to the nominal model, with two exceptions. First, two additional radionuclides (^{90}Sr and ^{137}Cs) were added. Second, the radionuclide source regions for the SZ were restricted to the regions directly beneath the repository footprint, consistent with vertical transport in a borehole. Biosphere modeling was unchanged from the approach used in for the nominal scenario.

Results and Interpretation of Human Intrusion Analyses

Figure 2 shows calculated dose histories for a human intrusion occurring 100 years after closure. Although the time period of regulatory interest is 10,000 years after the closure of the potential repository, performance is calculated to 100,000 years to provide a level of confidence that there are no unexpected changes in dose at later times.

Figure 2 shows 300 simulated dose histories along with some statistical measures of the dose distribution. The mean curve is generated by averaging the 300 dose values at each time step, and the percentile curves are generated by determining the location of the given percentile at each time step (for example, the median curve is generated by determining the dose which has half of the calculated doses above it and half below it at each time step). There is a considerable amount of variability in the projections of human intrusion dose, and there are non-zero doses within the first 10,000 years. However, no dose for any of the 300 realizations exceeds 0.5 mrem/yr over the first 10,000 years. The peak mean human intrusion dose during the first 10,000 years after potential repository closure is approximately 0.008 mrem/yr., occurring at approximately 1,000 years. Over the entire 100,000 years, the peak mean dose is also approximately 0.008 mrem/yr. and the peak median dose rate (50 percent probability) is about 0.00007 mrem/yr. The mean dose rate is significantly larger than the median dose rate because the mean is dominated by a few realizations with high dose rate histories, while the median represents the mid-point results from all 300 realizations.

CONCLUSIONS

Each of the four potentially disruptive events called out in the proposed DOE regulation 10 CFR Part 963 as requiring particular consideration in the SR has been evaluated. Seismicity and nuclear criticality have been examined through the systematic process used to identify and screen potentially relevant FEPs, and have been shown to have negligible effects on the long-term performance of the site. Volcanic disruption and human intrusion are modeled in detail as part of the TSPA-SR (2), and consequences are presented in terms of calculated annual dose rates to future humans living 20 km from the potential repository. Calculated mean dose rates are small, reaching approximately 0.2 mrem/yr at 50,000 years for igneous disruption and 0.008 mrem/yr at 1000 years for an human intrusion 100 years after repository closure.

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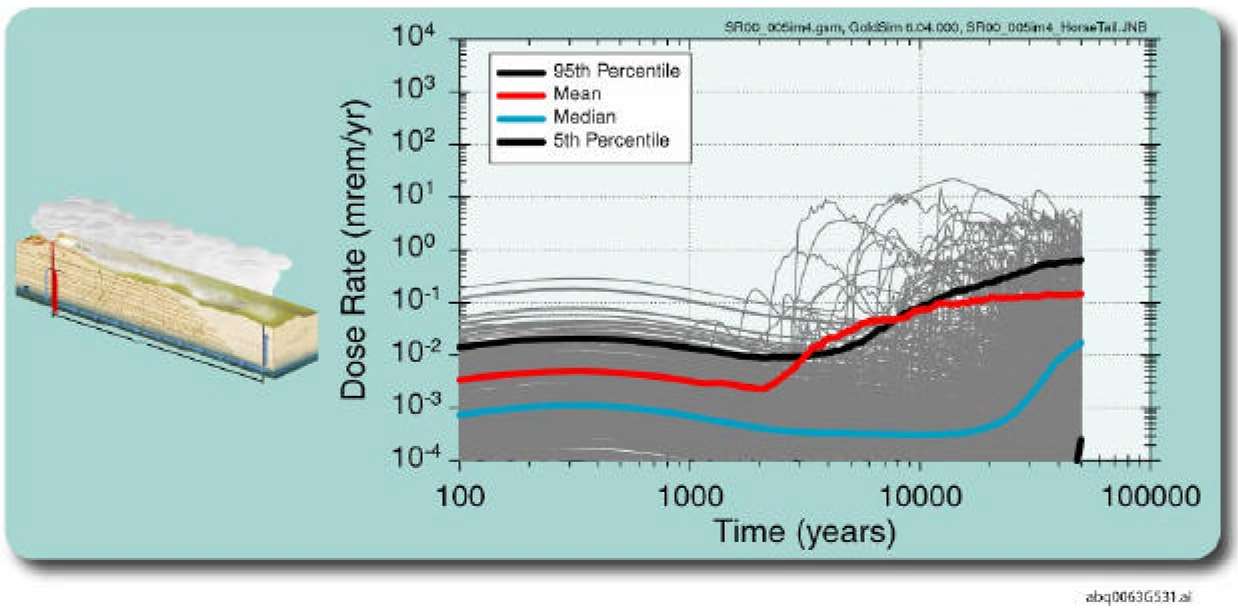

Fig. 1. Probability-weighted annual dose rate calculated for Igneous Disruption (Figure 4.2-1 of Ref. 2).

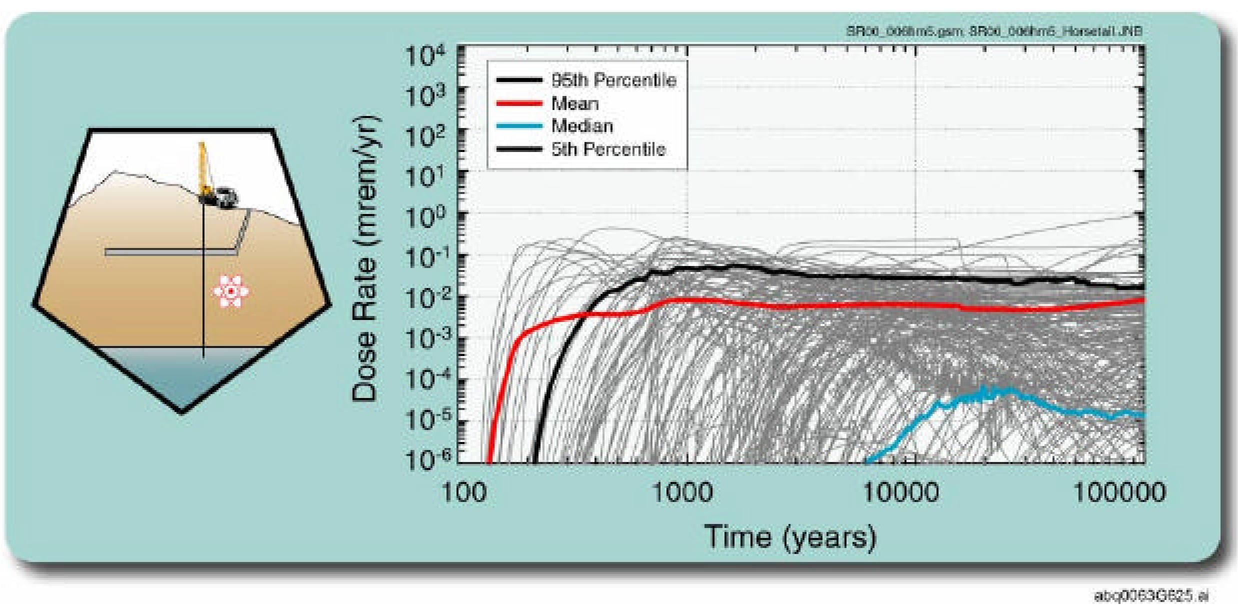

Fig. 2. Annual dose rate calculated for a human intrusion occurring 100 years after repository closure (Figure 4.4-11 of Ref. 2).