Potential Igneous Processes Relevant to the Yucca Mountain Repository: Intrusive-Release Scenario

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ABSTRACT

As part of the Department of Energy’s (DOE’s) license application for the proposed high level radioactive waste and spent nuclear fuel repository proposed for Yucca Mountain, Nevada, the DOE must provide probabilistic dose estimates after repository closure. These estimates must consider all events and processes that are considered reasonably likely to occur, including potential igneous events [1-4]. Current estimates of the probability of a future igneous event intruding through the proposed repository [5] are just high enough that dose consequences must be estimated. Estimates of igneous-event probability and the extent of any radionuclide release resulting from such an event have drawn considerable attention. In general, these estimates have included multiple, compounded conservatisms resulting in significant predicted dose consequences compared to dose consequences from the nominal release scenarios.

This new independent study conducted for the Electric Power Research Institute (EPRI) provides a more realistic estimate of the likelihood and magnitude of doses to the public should such a low-probability event occur [6]. Analyses summarized here indicate that, under any reasonable expected conditions for a magmatic intrusion, the contribution to peak dose from such an igneous intrusion event would not affect peak dose estimates over the long term.

INTRODUCTION

The temporal and spatial proximity of geologically recent volcanic centers indicate that potential future igneous activity (i.e., an “igneous event scenario”) may be a factor in the assessment of post-closure risk for a proposed repository at Yucca Mountain. Two principle variants for an igneous event of a vertical magmatic dike intersecting the repository have been specified for analysis [6-7]:

- *extrusive-release variant,* in which waste packages are contacted and caused to fail by magma rising vertically in the conduit might release radionuclides that would subsequently be erupted with the magma at the surface with subsequent radionuclide transport controlled by atmospheric and surficial processes, and
- *intrusive-release variant, in which waste packages, either directly contacted by lateral intrusive flow of magma (magma that is not subsequently erupted to the surface) or indirectly affected by the elevated temperature and potential release of volatiles species from the intruding magma, would fail and release radionuclides via groundwater pathways at an earlier time than for waste packages unperturbed by these localized effects from an igneous event.*

With respect to the igneous event scenario, EPRI has previously independently evaluated the extrusive-release variant case [7], with emphasis on critical examination of the various assumptions and sub-processes inherent in such a scenario for a repository at Yucca Mountain. A key conclusion from that set of analyses was that the reasonably expected probability-weighted dose for this extrusive- variant case is zero because of multiple factors including waste package durability, finite extent, duration and magnitude of likely future igneous events, and limitations imposed by realistic consideration of magma-waste package and magma-waste form interactions.

EPRI has recently published a detailed study [6] that evaluates the intrusive-release variant case, again from the perspective of building on representative data and limiting characteristics for a future igneous event at Yucca Mountain. Additional constraints arising from magma-drift, magma- waste package, and magma-hydrological system interactions are also analyzed. Integrating these results, a series of safety assessment calculations are conducted to determine credible consequences for a postulated intrusive-release variant case. This present paper summaries these results.

GEOLOGICAL CONSTRAINTS

With respect to geological constraints, the igneous event probability of 1.6×10^{-8} /year previously derived by the Probabilistic Volcanic Hazards Analysis (PVHA) panel [5] is adopted. There is an on-going update to this previous PVHA activity, and any revised estimate on igneous-event probability can be readily applied to this EPRI analysis by re-normalizing the calculated probability-weighed dose rates.

In addition, recent data [8] on basaltic eruptive centers in the Yucca Mountain region support the conclusion that relatively low-temperature (~1010˚C), high-viscosity basaltic magmas are the most representative characteristics of future igneous events. Lower temperature implies lower and less prolonged thermal-perturbation of the host rock and contacted waste packages [9-10]. The high viscosity supports the contention that such magma will only partially penetrate into emplacement drifts intersected by the magmatic dike [11-12]. Both of these representative thermal and viscosity constraints are utilized in subsequent analyses.

MAGMA-DRIFT INTERACTIONS

Partial intrusion of magma into emplacement drifts with controlled cooling and solidification of the magma implicitly leads to development of three "zones" within the emplacement drift, derived in this report from thermal analyses of peak temperatures as (Fig. 1):

- 'Red Zone:' waste packages fully or partially engulfed by magma,
- 'Blue Zone:' waste package not physically contacted by magma but experiencing significantly elevated, high temperatures (for example, above the >350˚C thermal limit for cladding of spent nuclear fuel), and
- 'Green Zone:' waste packages experiencing modest (<350˚C) and transitory high temperatures, with possible deposition of reactive magmatic volatiles onto the waste package surface.

The range of the spatial extent and the number of waste packages in each zone are also derived (Table I).

MAGMA-WASTE PACKAGE INTERACTIONS

Based on the characteristics of these 3 zones, analyses of a wide range of potential failure mechanisms for waste package materials (notably the Alloy-22 Waste Package Outer Barrier (WPOB), Ti drip shield, and the Zircaloy cladding of the spent nuclear fuel) are made. In summary (Table I), it is expected that:

- the 'Red Zone' is characterized by displaced/disrupted drip shields, thermally sensitized Alloy-22, and spent fuel cladding at that fails at the time of the igneous event,

- the 'Blue Zone' is characterized by intact drip shields, but failure of the Alloy-22 WPOB and spent fuel cladding at the time of the igneous event, and
- the 'Green Zone' is characterized by intact drip shields, Alloy-22 WPOB and spent fuel cladding that are unperturbed from their nominal corrosion behavior.

MAGMA-TUFF INTERACTIONS

Analog analyses of tuff rocks penetrated by past magmatic dikes indicate minor and highly localized (a few 10's of centimeters) changes in hydrological properties of the host rock adjacent to such dikes. While there is potential for enhanced vertical mixing and dilution of radionuclide concentrations in the saturated zone along such a dike interface, this potential process has been conservatively ignored in the presented analyses. Accordingly, the unsaturated-zone and saturated-zone hydrological properties for the intrusive-release case are directly adopted from the nominal case for a repository at Yucca Mountain.

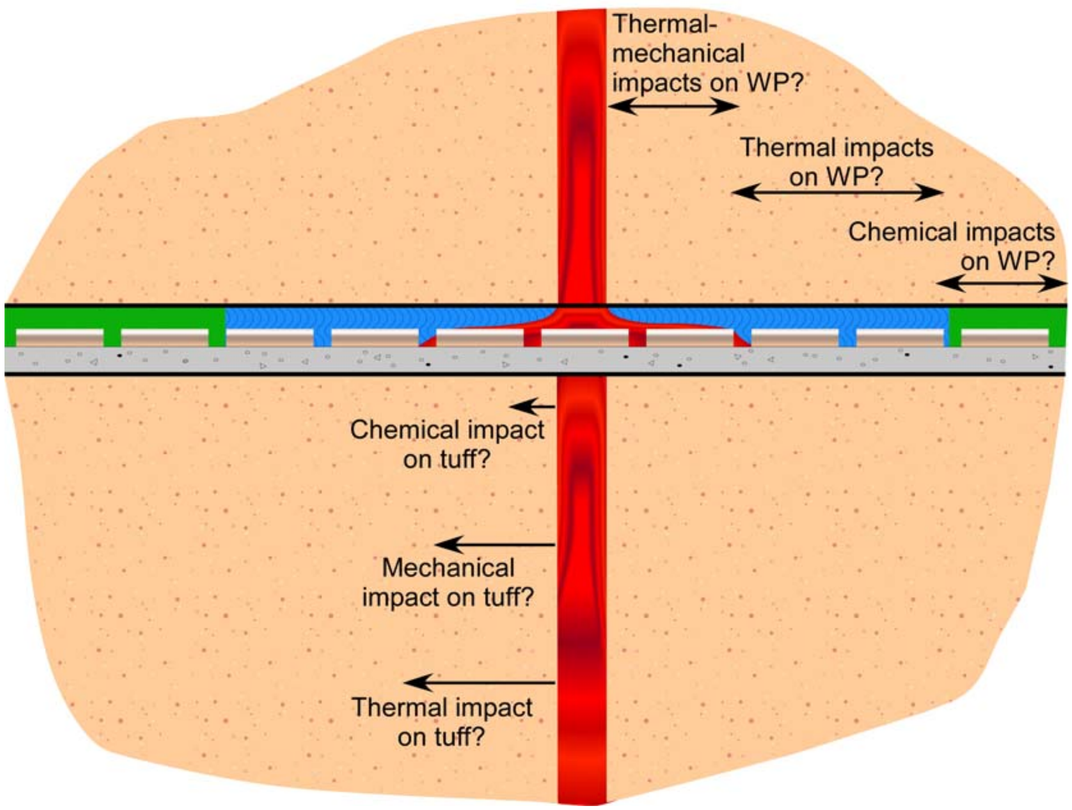

Fig. 1. Schematic of intrusive-release variant case. The spatial extent of thermal, mechanical and chemical impacts arising from magma intrusion, shown as arrows with question marks, are initially open issues that are analyzed.

SOURCE-TERM MODIFICATIONS

Modifications of the existing source-term COMPASS sub-model of IMARC Version 8.0 [13] are made to specifically model radionuclides releases for each of the 3 zones:

- 'Red Zone': The potential for favorable water diversion by solidification of massive basalt around waste packages in the 'Red Zone' is shown through sensitivity analyses, but this potential contribution is also conservatively ignored in the presented analyses.

Table I. Summary of Impacts for the Intrusive-Release, Reasonable-Expectation Case (Fig. 1)

Zone	**Description of zone**	**Extent of Zone**	**# WPs in Zone**	**Cladding Condition**	**Condition of Alloy-22 WPOB and Drip shield**	**Impact on transport properties**
Red	waste packages (WPs) engulfed by magma intrusion	0-20 m from magmatic dike¶	0-6 ¶	Failed	Additional considerations: • WPs are unlikely to fail by over-pressurization because of restraint by the external magmatic load. • Creep failure is considered unlikely as the magma will prevent sufficient strain of the WP. • Potential for DS displacement by magma intrusion.	Fractured basalt • flow diversion • sorption • fractured matrix
Blue	waste packages experiencing significant thermal impacts	37-66 m from end of Red Zone (front of magma intrusion)	14-24	Failed	All of the WPs in the ‘Blue Zone’ are conservatively assumed to fail by creep. Additional considerations: • 1-2 WPs in the region immediately in front of an intruding magma plug, in addition a single WP that might be only partially engulfed by magma plug, are likely to fail by over-pressurization. • The hottest WPs may become sensitized and subject to enhanced general corrosion and greater localized corrosion susceptibility. • Corrosion due to volatile gases will range from 0.1-1 mm for the 10 hottest WPs. • Drip shield displacement unlikely.	Open air
Green	waste packages contacted by magmatic volatiles.	The remainder of the intersected emplacement drift beyond the limit of the ‘Blue Zone’.	All of the remaining the WPs in the emplacement drift outside the ‘Red’ and ‘Blue Zones’	Intact	No WP failures are expected in the ‘Green Zone’. Additional considerations: • No WP failures due to over-pressurization because of the relatively low temperatures. • No creep failures are predicted in the ‘Green Zone’. • WP temperatures are too low to cause thermal aging of the Alloy 22. • Extent of corrosion due to exposure of approximately 12 WPs to volatile magmatic gases is expected to be <0.1 mm. • DS displacement unlikely.	Open air

As an extremely conservative bounding case, complete filling of all emplacement drifts intersected by the dike of an igneous event has been previously considered [7].

- 'Blue Zone': The release behavior for waste packages in the 'Blue Zone' conform with the nominal release case, except that both the WPOB and cladding are assumed to be physically failed immediately after the igneous event, rather than any sequential failure of such barriers for the nominal case.
- 'Green Zone': The release behavior for waste packages in the 'Green Zone' exactly conform to the nominal case following failure of the Alloy-22 WPOB.

COMPASS calculations show [6] that there is a delay in the release of radionuclides from the 'Red Zone' attributable to sorption properties of the encompassing basalt, but that the long-term release rates for key dose-contributing radionuclides (Tc-99, I-129, Np-237, Th-229) from the 'Red Zone' and 'Blue Zone' eventually converge. The long-term release rates, on a per waste package basis, from the 'Red' and 'Blue' zones are found to be higher (by a factor of ~40) than the release rates for the nominal case (and 'Green Zone') because there would be no contribution by the time-dependent distribution of cladding failure.

TOTAL SYSTEM PERFORMANCE ASSESSMENT (TSPA)

Fig. 2 presents the calculated release rate curves for the 'nominal case' scenario for a repository at Yucca Mountain for current IMARC assumptions and parameters [13]. The peak dose for the nominal performance is about 4 mrem/y, given current assumptions and parameter values.[1]

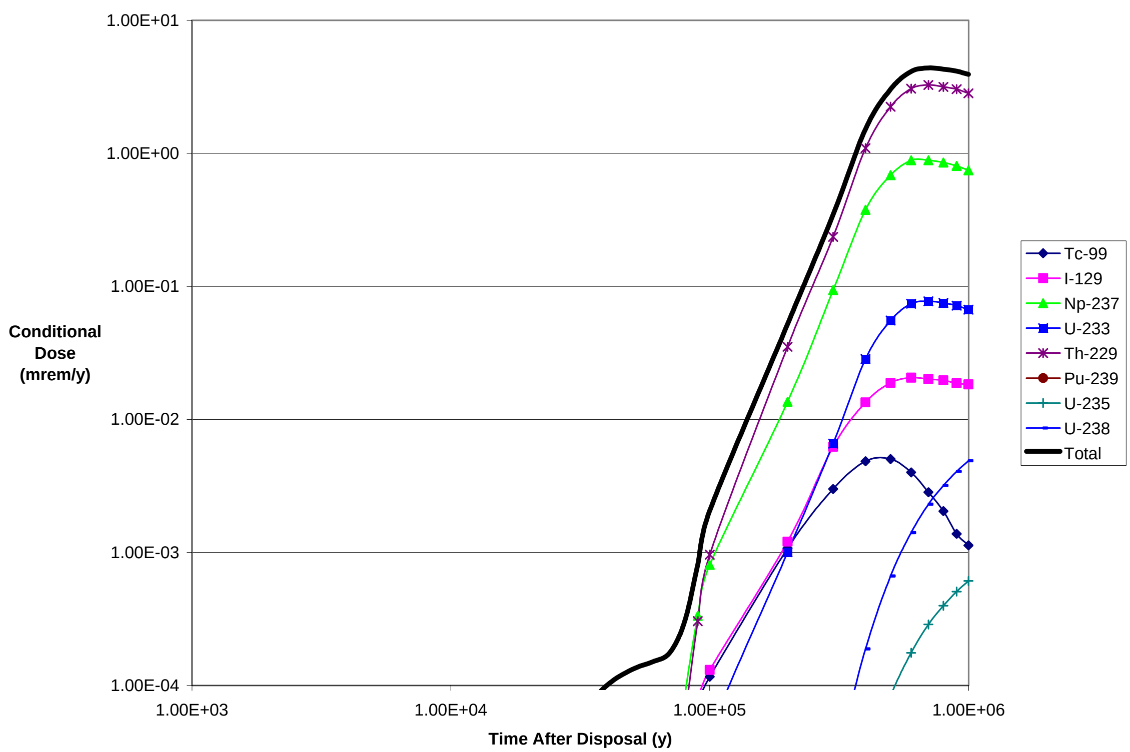

Fig. 2. 'Nominal case' doses for a repository at Yucca Mountain based on IMARC 8.0 [13]

[1] Current ongoing investigations by EPRI suggest that some of the IMARC assumptions and parameters may be too conservative for the nominal case. Nominal case results will continue to be updated using IMARC.

Based on the analyses presented conducted by EPRI [6-7], the intrusive-release variant case is characterized by the following features:

- a basaltic magmatic dike rises into the repository,
- magma laterally intrudes into the drift in both directions from the through-going dike and fills a portion of the open emplacement drifts,
- the magma contacts waste packages containing spent nuclear fuel,
- the magma enters the drift at a slow rate, which does not significantly affect the mechanical integrity of the drip shields away from the dike,
- the magma fully fills the drift as inflow laterally (plug flow), and cools and solidifies rapidly by multiple heat-transfer mechanisms,
- the quenched magma, and any radionuclides potentially released into it from failed waste packages, are not subsequently released via an extrusive pathway, so they remain available for release to groundwater,
- the far-field groundwater flow system returns to its undisturbed condition after a localized (tens of meters at most) and brief (tens of years at most) disruption,
- the near-field rock surrounding the ‘Red’ and ‘Blue’ zones requires on the order of 1000 years to re-saturate before groundwater can begin flowing into the drift,
- indirect thermal and chemical effects (i.e., release of magmatic volatiles) may be propagated along the drift further than the magma itself intrudes, and
- the repository otherwise functions according to the ‘nominal case’ scenario.

The physical form of the intruding basaltic magma may range from a high-viscosity, slow-moving “plug” flow (considered to be the most likely form [8]) to a more speculative low-viscosity “flood” flow [3]. These characteristics represent the possible range of behavior that may occur if a rising dike encounters a drift. For the representative slow plug flow, magma contacting the drift walls and engineered barrier components will rapidly cool and solidify partway along the drift. This scenario would lead to a situation (Fig. 1) in which a portion of the waste packages in the drift would be completely engulfed by magma (‘Red Zone’), a portion of the waste packages in the drift nearest the front of the magma plug would experience high thermal perturbation possibly leading to rapid containment failure (‘Blue Zone’), and the remainder of the waste packages in the drift would not be perturbed from their nominal behavior (‘Green Zone’). In addition to this most likely, ‘reasonable expectation case’ for magma characteristics, the ‘bounding case’ is also evaluated in which a low-viscosity, highly fluid magma is assumed to completely fill those few emplacement drifts intersected by a magma dike along their entire length. Thus, these two analyses are undertaken by EPRI to evaluate the effect of an intrusive-igneous event on the behavior of the repository compared to the ‘nominal case’ (Fig. 2).

For the ‘reasonable expectation case’, the number of waste packages assumed to be affected by the igneous event is 1610, or 14.4 percent of the repository [6]. The remaining waste packages in the repository (85.6 percent) are assumed to continue to behave as in the ‘nominal case’. Furthermore, analyses indicate that there would negligible impact on unsaturated or saturated zone flow and transport properties anywhere outside the EBS [6].

The conditional dose[2] from the analysis is then calculated as:

$$Dose = (f_{Red} Dose_{Red} + f_{Blue} Dose_{Blue} + f_{Green} Dose_{Green}) f_{drift} + (1 - f_{drift}) Dose_{Nominal}, \qquad \text{(Eq. 1)}$$

[2] The conditional dose is the dose calculated assuming the igneous event occurs. Therefore these calculated doses must be weighted by the probability of the event occurrence.

where f_i is the fraction of waste packages in each zone in an intersected drift, f_{drift} is the fraction of drifts intersected by a dike (with a median of 14.4 percent), and $Dose_i$ is the dose calculated assuming all waste packages in the repository are in the *i'th* zone, where the subscript *i* refers to 'Red,' 'Blue,' and 'Green,' zones or the 'nominal case'. Based on the assessment of the effects of the magma intrusion [6], the release behavior for the 'Green Zone' is the same as for the unaffected 'nominal case'.

The fractions, f_i, can be derived from assumptions and assessments about how far along the drift magma flows from the dike. For the 'reasonable expectation case' only a few waste packages per drift are expected to be in the 'Red' and 'Blue' Zones (Table I) estimates are provided for the number of waste packages per drift for each zone. The 'Red Zone' is estimated to include 6 packages/intersected drift, and the 'Blue Zone' is estimated to include 14 to 24 packages/ intersected drift. For a mean number of 115 waste packages/drift [3], this results in f_{Red}≈0.05 and f_{Blue}≈0.1 to 0.2. For the current analysis, the upper end (f_{Blue} = 0.2) of the reasonable expectation range for the 'Blue Zone' is used as a reasonably conservative estimate of the waste packages in the 'Blue Zone'. For the 'bounding case' case, the fraction of 'Red Zone' waste packages, f_{Red}, is 1.0. However, as discussed above, this speculative case is simply undertaken to evaluate behavior equivalent previous DOE's assumptions [3].

The conditional dose is the dose that is calculated *assuming that the igneous event occurs*. For the two conditional dose calculations considered above, it is assumed that an igneous event occurs early in the lifetime of the repository (say, sometime in the first 1000 years). The conditional dose calculations then represent the consequences from the event. Conditional doses *must be multiplied by the extremely low annual probability of an igneous event occurring*. The applicable regulations require an assessment of the probabilistic dose (i.e., the probability of receiving a specific dose from an event within a single year).

Conditional doses for the 'bounding case', in which the 14.4% of drifts contacted by the magmatic dike completely fill with magma along their length immediately after repository closure, are presented in Fig. 3. As expected, the early failure of waste packages from more rapid corrosion leads to an early peak associated with the mobile radionuclides, followed at a significantly later point in time by a higher peak associated with the Np-237 decay chain.

Conditional doses for the 'reasonable expectation case' where f_{Red}=0.05, f_{Blue}=0.2 are presented in Fig. 4. The first peak is associated with mobile radionuclides released from damaged waste packages; the second peak (at 100,000 years) is associated with the Np-237 decay chain released from damaged waste packages; the third peak is associated with the Np-237 chain from the unaffected part of the repository. The early doses are lower than the 'bounding case', owing to only a small percentage of the total waste packages being located in the 'Red' and 'Blue' Zones.

CONCLUSION

A set of analyses was conducted to investigate the intrusive-release variant of the igneous event scenario for a repository at Yucca Mountain. Potential release and mobilization mechanisms are considered, and credible "reasonable" models and data are presented based on literature analyses. Specifically considered is new evidence suggesting that intruding magma temperatures are lower than those assumed in existing studies. Lower temperature magma leads to a much higher magma viscosity such that EPRI's estimates of the distance that an intruding magma could move down a drift prior to solidification would be fairly short, perhaps engulfing only 10% of the waste packages in a drift. Furthermore, lower magma temperatures yield lower thermally driven waste package degradation effects, thereby reducing the negative impact on waste package performance engulfed by or near the intruded magma.

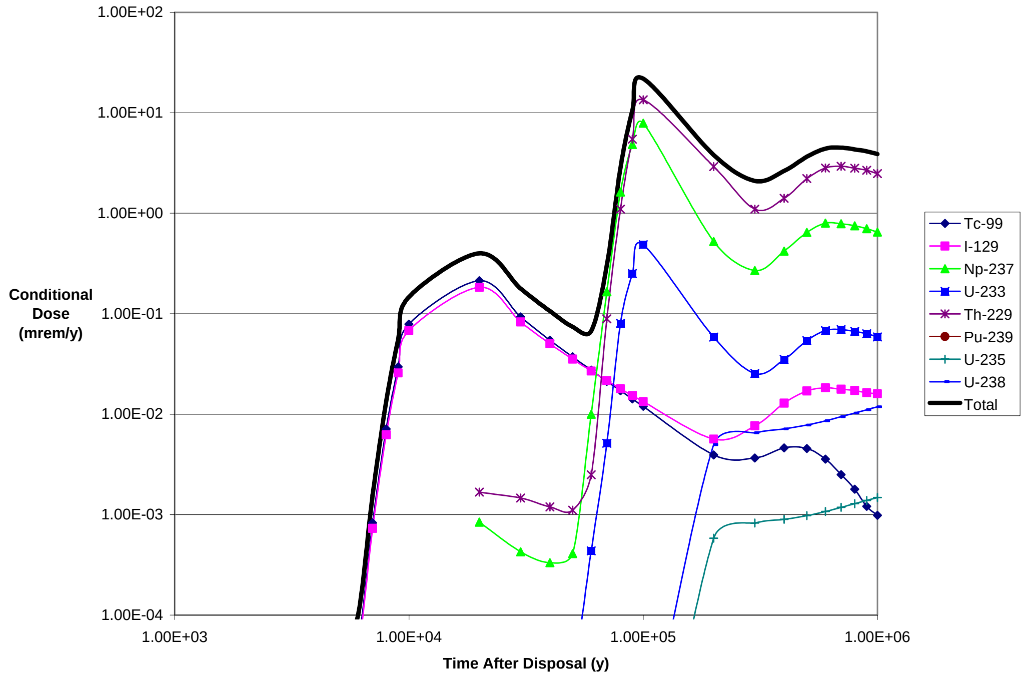

Fig. 3. Conditional doses for 'bonding case' assuming magma completely fills 14. 4% of drifts. These values must be multiplied by the annual probability of the igneous event (for example, 1.6 x 10^{-8} /year value from Ref. [5]) to derive a probability-weighted dose.

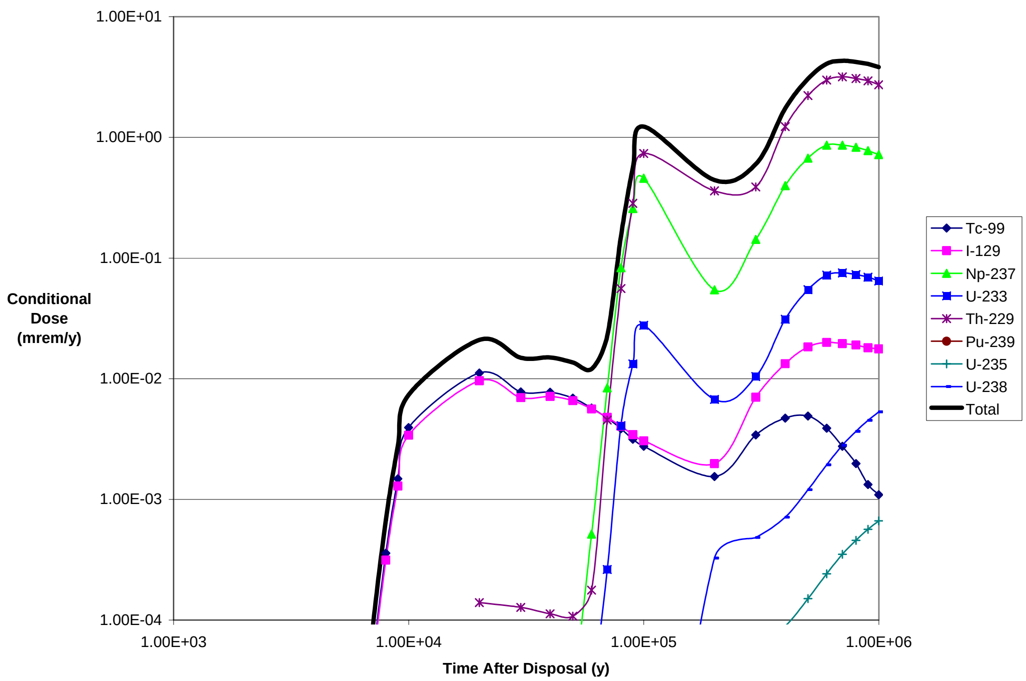

Fig. 4. Conditional dose for 'reasonably expected' case, with f_{Red}=0.05 and f_{Blue}=0.2 and the dike contacting 14.4% of the drifts. These values must be multiplied by the annual probability of the igneous event [5] to derive a probability-weighted dose.

Based on these representative characteristics of a potential future igneous event, EPRI conducted conditional dose ('consequence') analyses. First, for the 'reasonable expectation case' in which magma will only affect some of the waste packages in a drift intersected by a rising dike, the peak dose from the affected part of the repository is smaller than that produced from the unaffected part of the repository due to the small percentage of waste packages impacted. Therefore, there is reasonable expectation that radionuclide release for the intrusive-release pathway is inconsequential with respect to peak dose.

A further set of sensitivity analyses was conducted to evaluate increasingly extreme sets of assumptions about magma behavior and repository response. Even with highly conservative assumptions about the behavior of the repository and the dikes, and with a highly conservative estimate of the probability of occurrence of the event, the calculated resulting doses are extremely small. It is therefore concluded that, under any reasonable conditions, peak doses from the igneous intrusion scenario will be less than that of the nominal release case.

Given the above conclusions and the regulatory requirement that the DOE demonstrate that the probability-weighted doses for the repository will comply with applicable regulations, EPRI has concluded that no further activities need be pursued to address the intrusive igneous scenario.

REFERENCES

1. Crowe, B. S. Self, D. Vaniman, R. Amos, and F. Perry. 1983. Aspects of potential magmatic disruption of a high level radioactive waste repository in southern Nevada. Journal of Geology, 91: 259-276.
2. CRWMS M&O. 2000. Characterize framework for igneous activity at Yucca Mountain, Nevada. ANL-MGR-GS-000001 REV 00. Las Vegas, Nevada, CRWMS M&O.
3. Bechtel SAIC. 2003. "Technical Basis Document No. 13: Volcanic Events," Revision 2, November 2003.
4. Igneous Consequences Peer Review (ICPR). 2003. Final Report of the Igneous Consequences Peer Review Panel. pp. 86.
5. CRWMS M&O. 1996. Probabilistic volcanic hazard analysis for Yucca Mountain, Nevada. BA0000000-01717-2200-00082 REV 0. Las Vegas, Nevada, CRWMS M&O.
6. EPRI. 2005. Program on Technology Innovation: Potential Igneous Processes Relevant to the Yucca Mountain Repository: Intrusive-Release Scenario, EPRI Report 1011165, Electric Power Research Institute, Palo Alto, CA.
7. EPRI. 2004. Potential igneous processes relevant to the Yucca Mountain repository: Extrusive-release scenario: Analysis and implications. EPRI Report 1008169, Electric Power Research Institute, Palo Alto, CA.
8. Nicholis, M. and M. Rutherford. 2004. Experimental constraints on magma ascent rate for the Crater Flat volcanic zone hawaiite. Geology, Vol. 32, p. 489-492.
9. Douglass, D.L. and J.T. Healy. 1981. Corrosion of some pure metals in basaltic lava and simulated magmatic gases at 1150^{o}C. Oxid. Met. 15, 21-75.
10. Rebak, R.B., T.S.E. Summers, and R.M. Carranza. 2000. Mechanical properties, microstructure and corrosion performance of C-22 alloy aged at 260^{o}C to 800^{o}C. Mat. Res. Soc. Symp. Proc. (Materials Research Society, Warrendale, PA), 608, 109-114.
11. Cashman, K.V., C. Thornber, J.P. Kauahikaua. 1999. Cooling and crystallization of lava in open channels and the transition of pahoehoe lava to aa. Bulletin of Volcanology 61: 3.

12. Grossenbacher, K. and S. McDuffie. 1995. Conductive cooling of lava: columnar joint diameter and stria width as functions of cooling rate and thermal gradient. Journal of Volcanology and Geothermal Research, vol. 69, p. 95-103.
13. EPRI. 2005. Program on Technology Innovation: EPRI Yucca Mountain Total System Performance Assessment Code (IMARC) Version 8. EPRI Report 1011813, Electric Power Research Institute, Palo Alto, CA.

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