REVIEW BY THE U.S. NUCLEAR REGULATORY COMMISSION OFFICE OF NUCLEAR MATERIAL SAFETY AND SAFEGUARDS OF THE U.S. DEPARTMENT OF ENERGY AGREEMENT RESPONSES RELATED TO THE POTENTIAL GEOLOGIC REPOSITORY AT YUCCA MOUNTAIN, NEVADA: IGNEOUS ACTIVITY KEY TECHNICAL ISSUE AGREEMENT IA.2.18

1.0 INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) issue resolution goal during the prelicensing period is to assure the U.S. Department of Energy (DOE) has assembled enough information about a given issue for NRC to accept a license application for review. Resolution by the NRC staff during prelicensing does not prevent anyone from raising any issue for NRC consideration during the licensing proceedings. Further, resolution of an issue by NRC during prelicensing does not prejudge the NRC staff evaluation of the issue during the licensing review. Issues are resolved by the NRC staff during prelicensing when the staff has no further questions or comments about how DOE is addressing an issue. Pertinent new information could raise new questions or comments about a previously resolved issue.

This review addresses Igneous Activity (IA) Key Technical Issue Agreement (KTI) IA.2.18, which was made between DOE and NRC during the IA Technical Exchange and Management Meeting (Reamer, 2001). This agreement is considered important to repository performance because the igneous processes covered by this agreement directly affect the number of waste packages affected by a potential igneous event. NRC preliminary analyses suggest that Agreement IA.2.18 has a high significance to risk calculations (Travers, 2003). In Travers (2003), staff described the basis for risk-ranking the KTI agreements. Agreements that affected risk calculations through significant increases in radionuclide transport characteristics were considered to have high significance in performance calculations.

2.0 WORDING OF THE AGREEMENT

IA.2.18 is defined in an NRC staff letter (Reamer, 2001), which summarized the IA Technical Exchange and Management Meeting held September 5, 2001. The wording of the agreement is as follows:

“DOE will evaluate how the presence of repository structures may affect magma ascent, conduit localization, and evolution of the conduit and flow system. The evaluation will include the potential effects of topography and stress, strain response on existing or new geologic structures resulting from thermal loading of HLW, in addition to a range of physical conditions appropriate for the duration of igneous events. DOE will also evaluate how the presence of engineered repository structures in the LA design (e.g., drifts, waste packages, backfill, etc.) could affect magma flow processes for the duration of an igneous event. The evaluation will include the mechanical strength and durability of natural or engineered barriers that could restrict magma flow within intersected drifts. The results of this investigation will be documented in an update to the AMR, Dike Propagation and Interaction with Drifts, ANL-WIS-MD-000015, expected to be available in FY 2003, or another appropriate technical document.”

3.0 SIGNIFICANCE OF ISSUE TO PERFORMANCE

NRC sensitivity analyses (Travers, 2003; Mohanty, et al., 2004) indicate that the number of waste packages disrupted during potential igneous events has a high significance to total system performance assessment results. This level of significance arises because the consequences from extrusive igneous activity (i.e., volcanism) are directly proportional to the number of waste packages intersected by a subvolcanic eruption conduit. Typical subvolcanic conduits are on the order of 5–50 m [16–164 ft] in diameter (e.g., NRC, 1999), although conduit diameters as large as 150 m [492 ft] may occasionally occur (Bechtel SAIC Company, LLC, 2003a). Processes that influence the formation of subvolcanic conduits also affect the number of waste packages impacted by a potential volcanic event. In addition, some physical conditions could potentially result in horizontal flow of magma along a drift, with a pathway to the surface forming some lateral distance away from the point of initial intrusion (Woods, et al., 2002). Although physical conditions for this horizontal flow pathway to develop during the initial minutes of a potential igneous event now appear less likely to occur (Bechtel SAIC Company, LLC, 2003b), development of this pathway at any time during the event could affect a significantly larger number of waste packages than a simple vertical conduit. Damage to waste packages intersected by magma likely occurs from the high thermal and mechanical stresses that occur during an eruption (e.g., NRC, 1999; Bechtel SAIC Company, LLC, 2003c). Potential flow paths to the surface that follow existing drifts could disrupt and entrain more waste than assumed for vertical subvolcanic conduits, affecting repository performance.

4.0 EVALUATION AND COMMENT

IA.2.18 is relevant to understanding important aspects of IA Subissue 2, “Consequences of Igneous Activity,” and has been reviewed by staff in that context. Staff reviewed the information provided by DOE using review methods for the Volcanic Disruption of Waste Packages in the Yucca Mountain Review Plan (NRC, 2003).

Basaltic magma rises buoyantly from depth by fracturing and dilating surrounding rock. Processes that affect the strength characteristics of rock can affect the ascent characteristics of basaltic magma. In CRWMS M&O (2000), DOE proposed that changes in rock stress surrounding the potential repository might divert rising magma away from subsurface drifts during the first 2,000 years following repository closure. In this analysis, the emplacement of high-level waste heated surrounding rock and reoriented the distribution of rock stress to directions that could divert rising magma from drifts (CRWMS M&O, 2000). These analyses, however, only evaluated a simplified stress distribution and did not fully consider the effects of variations in strain processes on potential magma ascent.

Additional analyses in Bechtel SAIC Company, LLC (2003b,d) more fully evaluate the strain response in heated rock surrounding drifts containing high-level waste. These DOE analyses consider a greater range of realistic physical conditions and coupled thermal-mechanical processes than were considered in earlier models (e.g., CRWMS M&O, 2000). The current DOE analyses indicate that potential stress redistribution effects from rock heating will be restricted to within approximately 10 m [33 ft] of the drifts. Significant variations in wall-rock properties (e.g., fracture density and orientation) also will likely result in complex stress redistribution patterns (Bechtel SAIC Company, LLC, 2003d). Thus, DOE concludes that the orientation of vertical stress would not change significantly due to thermal heating and that basaltic magma rising toward the central part of the repository would maintain a vertical ascent pathway and not be diverted away from repository drifts (Bechtel SAIC Company, LLC, 2003a,b).

Independent analyses (Smart, 2004) support the conclusion that thermal-mechanical effects on rock stress from potential high-level waste emplacement would have negligible effects on magma ascent processes. Using first-order calculations, Smart (2004) concludes that a large fraction of thermal-expansion strain from waste-generated heat can be accommodated through fracture closure. Thermally induced stress, therefore, would be much smaller than suggested in CRWMS M&O (2000), reducing the likelihood for large-scale reorientation of the principal stresses. Although the theoretical deflection of ascending intrusions (i.e., dikes) away from heated drifts is sometimes alluded to by DOE (e.g., Bechtel SAIC Company, LLC, 2003a), current DOE models for potential magma-repository interactions assume that any rising magma will not be deflected away from potential repository drifts due to thermal-mechanical effects from possible waste emplacement (Bechtel SAIC Company, LLC, 2003b; Detournay, et al., 2003). This assumption appears adequately supported by available information.

Previous DOE analyses (CRWMS M&O, 2000) indicated that magma flow down potentially intersected drifts may be restricted by the presence of debris plugs that formed during the igneous event. In DOE models, only waste packages that are directly contacted by flowing magma are assumed to fail in performance calculations (Bechtel SAIC Company, LLC, 2003c). Thus, restricting the extent of potential magma flow in drifts reduces the source term for hydrologic release following an intrusive igneous event. Because the potential flow of magma into drifts is a complex process, DOE uses insights from several types of numerical models for the flow of volatile-absent (i.e., degassed) magma. By assuming that magma is degassed, models in Bechtel SAIC Company, LLC (2003b) conclude that flow rates into potentially intersected drifts will be on the order of 10 m/s [33 ft/s]. Debris plugs do not occur in current DOE models for magma flow in potentially intersected drifts, and magma is allowed to fill the intersected drift with no significant retardation in flow due to interaction with engineered systems (Bechtel SAIC Company, LLC, 2003b).

Flow rates for degassed magma calculated by models in Bechtel SAIC Company, LLC (2003b) are consistent with the results of experimental and numerical models developed by Lejeune, et al. (2002). In these models, flow rate is controlled by the pressure difference between the ascending magma and the potentially intersected drift, with rheological effects contributing to the shape and rate of flow down the drift. For gas-bearing magmas, however, fully coupled gas-magma flow models in Bokhove and Woods (2000) and Woods, et al. (2002) indicate that a gas-bearing magma could flow into potentially intersected drifts with velocities on the order of 100 m/s [328 ft/s]. These higher flow rates result from the rapid expansion and acceleration of gas during decompression, as the magma potentially travels from a highly confined intrusion into a less confined drift. Although uncertainty in the amount of magma degassing may affect calculations of flow velocities, uncertainty in flow velocity does not affect risk-significant assumptions in current DOE models for waste-package damage during potential intrusive igneous events. Thus, current DOE models for the extent of magma flow into potentially intersected drifts appear adequately supported by available information.

Magma in a typical shallow dike that is ascending slowly can solidify in several hours (e.g., Huppert and Sparks, 1985). Thus, any subsurface feature that favors vertical ascent of magma could favor the localization of a subvolcanic conduit, because the conduit will not form in stagnated, solidifying basalt. Repository drifts represent one possible low-resistance flow path for vertically ascending magma, as calculations show that magma will accelerate into the intersected drifts because of decompression effects (e.g., Woods, et al., 2002; Bechtel SAIC Company, LLC, 2003b). Thus, magma flow directions in a dike that potentially intersect a drift could focus on the drift, with lower ascent velocities or possibly stagnation occurring in parts of the dike locationed in pillar areas between drifts. The effect of focusing the vertical ascent of magma toward drifts could then favor the subsequent localization of a conduit at the dike-drift intersection.

Potential magma flow into repository drifts is evaluated in Bechtel SAIC Company, LLC (2003b), using a three-dimensional model that couples vertical flow of degassed magma in a narrow dike to simplified rock-mechanical relationships. Using these relationships, Bechtel SAIC Company, LLC (2003b) concludes that magma-flow streamlines could focus on intersected drifts. However, these models also indicate that magma in the pillars between drifts would possibly rise tens of meters above the level of the drifts and possibly form conduits in pillars rather than at drifts (Bechtel SAIC Company, LLC, 2003b). Intersected drifts are filled by degassed magma within approximately five minutes, with subsequent magma rise along the initial plane of ascent. The short time necessary to completely fill a potentially intersected drift, however, does not appear sufficient to induce significant cooling effects in areas of low vertical velocity in the dike. Thus, conduit localization does not appear affected by the transient effects of rapid magma flow into intersected drifts. Based on these analyses, DOE concludes that subsurface repository structures do not influence the localization of subvolcanic conduits (Bechtel SAIC Company, LLC, 2003a,b).

Independent analyses support the conclusion of rapid inflow of ascending, degassed magma into a potentially intersected drift (Lejeune, et al., 2002). If the magma is not degassed, however, decompression associated with flow into the drift will accelerate the magma-gas mixture as gas bubbles expand (Bokhove and Woods, 2000; Woods, et al., 2002). Gas-driven acceleration would likely cause the drifts to fill more rapidly than modeled for gas-absent magmas, further decreasing the amount of time available to induce thermal effects in the ascending magma system. Although DOE has not evaluated the effects of decompression-induced flow of gas-bearing magmas into potentially intersected drifts, these effects do not appear to affect risk-significant assumptions in current DOE models for risk calculations from igneous events.

Previous DOE models did not provide an adequate technical basis to conclude that potential magma ascent would remain localized in a single vertical intrusion following possible drift intersection (CRWMS M&O, 2000). Based on potentially significant variations in bedrock thickness over drifts, and the distribution of possible rock fractures, Woods, et al. (2002) hypothesized that magma might emerge from a drift along a different vertical pathway than used to ascend from depth. If the drift filled with magma and began to repressurize, hydro fracturing and breakout through the drift roof might be more likely to occur on the eastern part of the drift, or perhaps subvertically toward Solitario Canyon where the overlying rock is thinnest and less fluid pressure would be needed to dilate a fracture (e.g., Bechtel SAIC Company, LLC, 2003d). In this situation, magma could flow horizontally through the drift between the initial intersection point and the final breakout point, potentially entraining more waste packages than intersected by a simple vertical conduit.

DOE provides additional detailed analyses in Bechtel SAIC Company, LLC (2003b) to evaluate thermal-mechanical processes associated with potential breakouts from magma-filled drifts at locations away from the point of initial intrusion intersection. These analyses compare rates of dike-tip propagation along a vertical fracture of original intersection, and for vertical fractures located away from the point of initial intersection. These analyses examine fracture propagation rates using simplified rock mechanical models for hydrofracture processes, which appear to reasonably abstract magma propagation processes. Based on these analyses, Bechtel SAIC Company, LLC (2003b) concludes that if an intersected drift was wholly filled with magma, ascent rates along the original vertical plane of intersection would be approximately twice as rapid as likely to occur along secondary vertical planes located along the drift. This reduction in ascent rate occurs because lower effective fluid pressures result if magma has to travel horizontally along the drift, relative to continued vertical ascent. Because of this reduction in ascent rate, secondary dikes would only propagate a short distance before magma in the main dike reached the surface and depressurized the system. Magma in the secondary dikes also would rapidly cool against the surrounding rock, further retarding initial propagation rates. Thus, Bechtel SAIC Company, LLC (2003b) concludes that the horizontal dog-leg scenario of Woods, et al. (2002) appears unlikely, relative to the scenario of continued vertical magma ascent along the original plane of intersection at the beginning of a potential eruption. Although a quantitative reduction in scenario likelihood is not specified in Bechtel SAIC Company, LLC (2003b), the analyses in Bechtel SAIC Company, LLC (2003b) support the conclusion for a relatively lower likelihood of occurrence for the horizontal dog-leg scenario of Woods, et al. (2002) during the initial minutes of a potential eruption.

Although magma initially propagating along secondary fractures may rapidly cool during the initial minutes of a potential eruption, most of the magma in an intersected drift would remain molten for the duration of the volcanic eruption (NRC, 1999; Bechtel SAIC Company, LLC, 2003b). DOE analyses conclude that a subvolcanic conduit localizes on a drift in approximately 77 percent of the model realizations (Bechtel SAIC Company, LLC, 2003a). In these realizations, magma in the erupting volcanic conduit would be a contiguous fluid with magma remaining in the intersected drift. Thus, magma in the potentially intersected drift would respond to pressure variations occurring in the erupting conduit. Currently available information shows that water contents in Yucca Mountain region basalt were significantly higher than estimated in Bechtel SAIC Company, LLC (2003e) and most likely were on the order of four weight percent (Luhr and Housh, 2002; Nicholis and Rutherford, 2004). High water contents significantly increase the amount of gas in the erupting conduit, and commonly lead to relatively high-velocity eruptions that are choked at the vent exit (e.g., Wilson and Head, 1981). Choked flow conditions can lead to pressures in the shallow subvolcanic conduit that exceed lithostatic pressure (e.g., Woods, et al., 2002). During periods of steady flow, overpressures in the conduit may be readily transmitted to the magma remaining within the drift. Unlike the condition of initial magma ascent, when pressure in the shallow dike system drops significantly when the dike reaches the surface, overpressure in the flowing conduit may lead to a condition of sustained overpressure in a potentially intersected drift. These overpressures can exceed the pressures needed to dilate secondary fractures in the drift walls (e.g., Woods, et al., 2002; Bechtel SAIC Company, LLC, 2003b,d). Although DOE has provided an analysis that indicates a low likelihood for secondary magma breakouts (i.e., dog-legs) to occur during the initial minutes of a potential igneous event, available information (e.g., Sparks, et al., 1997; Woods, et al., 2002, 2004; Bokhove, et al., 2004) indicates overpressure conditions sufficient for secondary breakouts may occur throughout the duration of the volcanic eruption. Information provided by DOE (Bechtel SAIC Company, LLC, 2003b; Ziegler, 2004) does not indicate that

DOE has evaluated the effect of magma flow processes on the formation of secondary breakouts for the potential duration of an igneous event.

Some basaltic volcanoes comparable to those in the Yucca Mountain region form secondary vents during the eruption. These secondary vents often form on trend with the initial dike, with well-documented examples at, for example, Parícutin volcano in Mexico (Luhr and Simkin, 1993). If a basaltic dike formed through the potential repository at Yucca Mountain, this dike would likely trend obliquely across intersected drifts (e.g., Bechtel SAIC Company, LLC, 2003e). Thus, secondary vents forming on or near this trend would create secondary magma-flow paths that had very low potential to entrain additional waste packages. However, some basaltic volcanoes form secondary vents orthogonal to the trend of initial dikes, at distances on the order of 1 km [0.6 mi] away from the main conduit. For example, the 1975 Tolbachik, Russia, scoria cone eruption formed a secondary vent complex approximately 1.5 km [0.9 mi] off the axis of the main eruption (Fedotov, et al., 1984). This secondary vent was active for four days and produced both scoria and lavas. Field evidence at Lathrop Wells volcano, Nevada, also has been interpreted to indicate the formation of a large, secondary vent located approximately 1 km [0.6 mi] east of the main eruption axis (Perry, et al., 1998). The processes that lead to the formation of off-axis secondary vents have not been explained, but appear to involve the shallow migration of partially degassed magma along secondary fractures away from the main conduit. If these types of off-axis secondary vents formed during a possible volcanic eruption at the potential Yucca Mountain repository, horizontal flow down an intersected drift could develop between the main conduit and secondary vent system. Although this pathway might be active for only several days, magma could flow through the drift system with sufficient velocity to disrupt and entrain high-level waste (e.g., Woods, et al., 2002). Entrained waste would likely accumulate near the secondary vent, where it could be available for subsequent redistribution by surface processes after the eruption. Initial sensitivity studies (Travers, 2003; NRC, 2004) show that this type of an alternative conceptual model for magma flow could be of potential significance to performance calculations for volcanic risks.

5.0 SUMMARY

Current DOE models indicate that, although there may be potential thermal-mechanical effects on rock stress arising from waste emplacement in drifts, the magnitude of these potential effects is not sufficient to divert rising basaltic magma away from drifts. NRC will review any supplemental supporting information which DOE may provide in connection with a license application.

If rising magma intersects a subsurface drift, current DOE models conclude that depressurization effects are sufficient to cause magma flow into the potentially intersected drift. Current DOE analyses do not rely on the formation of debris plugs to artificially restrict the flow of magma into a potentially intersected drift, and all intersected drifts are allowed to fill with magma. Although these DOE models only evaluate gas-free magmas, independent staff analyses indicate that the presence of gas in magmas likely accelerates flow velocities by an order of magnitude. This increase in flow velocity, however, does not significantly affect the resulting performance calculations for the extent of magma flow into potentially intersected drifts.

DOE has provided a technical basis to evaluate possible effects of magma-drift interactions on the localization of subvolcanic conduits. These analyses show that the transient effects of magma inflow into potentially intersected drifts do not affect the thermal or mechanical structure of the magma system in ways that affect the subsequent formation of subvolcanic conduits. NRC will review additional relevant information which DOE may provide in a potential license application.

The formation of secondary vents that exploit repository drifts (i.e., dog-legs) is a conceptual model that could be of potential significance to performance calculations. DOE has provided mechanical and thermal analyses that conclude the formation of such secondary vents during the initial minutes of a potential igneous event appears unlikely. These analyses evaluate more realistic physical conditions in more rigorous detail than accomplished in initial calculations by Woods, et al. (2002). However, DOE has not extended these analyses to conditions likely to occur during the duration of an igneous event. Independent staff analyses and information from natural analog volcanoes indicate that secondary vents can sometimes develop during scoria cone eruptions, consistent with the likely occurrence of significant magma overpressures in an erupting conduit. Such overpressures are likely to occur in future volcanic eruptions in the Yucca Mountain region due to high volatile contents in the magma. Secondary vents may exploit existing subsurface structures, such as potential repository drifts, and lead to the horizontal flow of magma through parts of an intersected drift. If this type of horizontal flow pathway developed during the course of an eruption, it could significantly entrain more waste packages than assumed for a vertical conduit. DOE should provide sufficient information in its license application to enable staff to evaluate how the presence of engineered repository structures could affect magma flow processes for the duration of an igneous event.

6.0 STATUS OF THE AGREEMENT

Based on the aforementioned review, DOE has not provided information that satisfies the intent of IA.2.18. Therefore, staff considers the status of this agreement as need additional information. NRC will review any relevant information submitted, as part of its review of a license application with regard to the development of secondary magma-flow pathways for the duration of a potential igneous event.

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