Department of Energy
Office of Civilian Radioactive Waste Management
Office of Repository Development
1551 Hillshire Drive
Las Vegas, NV 89134-6321

QA: N/A
Project No. WM-00011

JUN 10 2004

OVERNIGHT MAIL

ATTN: Document Control Desk
Director, Division of High-Level Waste
Repository Safety
U.S. Nuclear Regulatory Commission
11555 Rockville Pike
Rockville, MD 20852-2738

KEY TECHNICAL ISSUE AGREEMENT IGNEOUS ACTIVITY (IA) 2.18: EFFECTS OF ENGINEERED REPOSITORY STRUCTURES ON MAGMA FLOW PROCESSES

Reference: Ltr, Reamer to Brocoum, dtd 9/12/01 (NRC/DOE Technical Exchange and Management Meeting on Igneous Activity, September 5, 2001)

In the referenced letter, the U.S. Nuclear Regulatory Commission (NRC) documented an agreement (IA 2.18) between NRC and the U.S. Department of Energy (DOE). The wording of the agreement is as follows:

> IA 2.18
> "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-00015, expected to be available in fiscal year 2003, or another appropriate technical document."

NMSS07

For purposes of the response, the agreement has been divided into six topics related to potential interactions between a possible future basaltic dike and the repository:

1. Effects of repository structures on dike propagation
2. Effects of topography and stress on dike propagation
3. Effects on dike propagation of strain response on existing or new geological structures resulting from thermal loading
4. Effects of repository structures on conduit localization
5. Effects of repository structures on evolution of the conduit and flow system
6. Backfill and confining magma flow between drifts

The enclosure to this letter provides the DOE response which addresses each of the six elements of the agreement. The DOE requests that Agreement IA 2.18 be closed based on the information in the response.

There are no new regulatory commitments in this letter or its enclosure. Please direct any questions to Timothy C. Gunter at (702) 794-1343 or e-mail timothy_gunter@ymp.gov, or Eric T. Smistad at (702) 794-5073 or e-mail eric_smistad@ymp.gov.

Joseph D. Ziegler, Director
Office of License Application and Strategy

OLA&S:TCG-1215

Enclosure:
Effects of Engineered Repository Structures on Magma Flow Processes, Revision 2 (Response to IA 2.18)

cc w/encl:
D. D. Chamberlain, NRC, Arlington, TX
G. P. Hatchett, NRC, Rockville, MD
R. M. Latta, NRC, Las Vegas, NV
J. D. Parrott, NRC, Las Vegas, NV
D. B. Spitzberg, NRC, Arlington, TX
B. J. Garrick, ACNW, Rockville, MD
H. J. Larson, ACNW, Rockville, MD
W. C. Patrick, CNWRA, San Antonio, TX
Budhi Sagar, CNWRA, San Antonio, TX
J. R. Egan, Egan & Associates, McLean, VA
J. H. Kessler, EPRI, Palo Alto, CA
M. J. Apted, Monitor Scientific, LLC, Denver, CO
Rod McCullum, NEI, Washington, DC
W. D. Barnard, NWTRB, Arlington, VA
R. R. Loux, State of Nevada, Carson City, NV
Pat Guinan, State of Nevada, Carson City, NV
Alan Kalt, Churchill County, Fallon, NV
Irene Navis, Clark County, Las Vegas, NV
George McCorkell, Esmeralda County, Goldfield, NV
Leonard Fiorenzi, Eureka County, Eureka, NV
Michael King, Inyo County, Edmonds, WA
Andrew Remus, Inyo County, Independence, CA
Mickey Yarbro, Lander County, Battle Mountain, NV
Spencer Hafen, Lincoln County, Pioche, NV
Linda Mathias, Mineral County, Hawthorne, NV
L. W. Bradshaw, Nye County, Pahrump, NV
Mike Simon, White Pine County, Ely, NV
R. I. Holden, National Congress of American Indians, Washington, DC

cc w/o encl:
A. C. Campbell, NRC, Rockville, MD
L. L. Campbell, NRC, Rockville, MD
N. K. Stablein, NRC, Rockville, MD

ENCLOSURE

EFFECTS OF ENGINEERED REPOSITORY STRUCTURES ON MAGMA FLOW PROCESSES (RESPONSE TO IA 2.18)

Note Regarding the Status of Supporting Technical Information

This document was prepared using the most current information available at the time of its development. This Technical Basis Document and its appendices providing Key Technical Issue Agreement responses that were prepared using preliminary or draft information reflect the status of the Yucca Mountain Project's scientific and design bases at the time of submittal. In some cases this involved the use of draft Analysis and Model Reports (AMRs) and other draft references whose contents may change with time. Information that evolves through subsequent revisions of the AMRs and other references will be reflected in the License Application (LA) as the approved analyses of record at the time of LA submittal. Consequently, the Project will not routinely update either this Technical Basis Document or its Key Technical Issue Agreement appendices to reflect changes in the supporting references prior to submittal of the LA.

ENCLOSURE

EFFECTS OF ENGINEERED REPOSITORY STRUCTURES ON MAGMA FLOW PROCESSES (RESPONSE TO IA 2.18)

This enclosure provides a response for Key Technical Issue (KTI) agreement Igneous Activity (IA) 2.18. This KTI agreement relates to providing an evaluation of the effects of engineered repository structures on magma flow processes.

KEY TECHNICAL ISSUE AGREEMENT

Agreement IA 2.18 was reached during the U.S. Nuclear Regulatory Commission (NRC)/U.S. Department of Energy (DOE) Technical Exchange and Management Meeting on IA, held September 5, 2001, in Las Vegas, Nevada (Reamer 2001).

The wording of the agreement is as follows:

IA 2.18

> 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-00015, expected to be available in FY2003, or other appropriate technical document.

BACKGROUND

Modeling of potential dike/drift interactions associated with the unlikely event of intersection of the repository by a basaltic dike indicated that a level of damage could result that would be sufficient to involve the entire inventory of waste in the repository. The basis for the damage models was consideration of extreme conditions (Elsworth 2001; Melson 2001; Morrissey n.d.) associated with generation of severe shock waves in intersected drifts (Bokhove and Woods 2000) and development of paths to the surface distant from the point of intersection (Woods et al. 2002). To address concerns associated with the likelihood of these processes and the damage to engineered barrier system components that could result, DOE agreed to evaluate the effects of repository structures on the potential for dike propagation and magma flow in drifts (Reamer 2001).

In early 2002, the Igneous Consequences Peer Review Panel was formed by DOE to review the technical basis used to analyze the consequences of igneous events that might interact with the repository structures and to recommend any additional tasks that would be appropriate for adequately assessing the consequences of igneous disruption of the repository. The panel provided recommendations regarding investigations of dike propagation under unperturbed and perturbed conditions, magma flow within intersected drifts, gas flow between drifts, and cooling and solidification of magma. Additional modeling and analyses were conducted (BSC 2003a; BSC 2003b; BSC 2004a) to address the potential consequences of igneous intrusion into the repository.

RESPONSE

For purposes of response development, six topics related to potential interactions between a possible future basaltic dike and the repository were identified from the agreement:

1. Effects of repository structures on dike propagation
2. Effects of topography and stress on dike propagation
3. Effects on dike propagation of strain response on existing or new geologic structures resulting from thermal loading
4. Effects of repository structures on conduit localization
5. Effects of repository structures on evolution of the conduit and flow system
6. Backfill and confining magma flow between drifts.

The information in *Dike/Drift Interactions* (BSC 2003a) and two supplemental calculations (Detournay et al. 2004; Gaffney and Damjanac 2004) provide the basis for a response to agreement IA 2.18. The report (BSC 2003a) describes the conceptual model for magma ascent via dike propagation, magma flow in excavated drifts, heat loss and volatile migration, and cooling and solidification of the magma. Once the magma front in the propagating dike reaches the repository, some magma would be diverted into the intersected drifts as an effusive flow of partially degassed magma (BSC 2003a, Assumption 16). The possibility of breakout to the surface of a pyroclastic dike, at a location removed from the original dike/drift intersection has been addressed (Gaffney and Damjanac 2004). The potential to prevent magma flow between drifts using a combination of backfill plus a filled keyway(s) excavated in the crown areas of access drifts and between emplacement drift turnouts has also been addressed (Detournay et al. 2004).

Effects of Repository Structures on Dike Propagation–Results of dike propagation simulations indicate that the propagating fracture tip that precedes ascent of the magma front could reach the surface before the magma front itself reaches the repository level (BSC 2003a, Section 8.1.1; Detournay et al. 2003, Section 3.2.2.2) for the case of effusive flow of magma. This result indicates that a primary magma pathway to the surface could be established before the magma reaches the repository level (BSC 2003a, Section 6.3.9.2.3.4). Hence, for the effusive case, movement of the magma front toward the surface would be expected to follow the primary pathway generated by the fracture that precedes the magma front. Repository structures would be expected to have little or no effect on propagation of the magma front, except for delaying ascent while drifts fill with magma.

Effects of Topography and Stress on Dike Propagation–The topographical relief of Yucca Mountain causes vertical stresses beneath the mountain to be about 6 MPa higher than beneath adjacent valleys (BSC 2003a, Section 6.3.9.1). Based on earlier field measurements (DTN: SNF37100195002.001), the increase in horizontal stresses at the repository level is expected to be approximately 2 to 3 MPa (inferred from BSC 2003c, Figures 6-35 and 6-36). The effect of the vertical relief is expected to broaden laterally downward, and, at depths greater than a few kilometers, no topographical effect on horizontal stress is expected (BSC 2003a, Section 6.3.9.1). The effect of topography is that both vertical and horizontal principal stresses increase in magnitude as an effect of overburden associated with the mass of the mountain. The major principal stress (i.e., most compressive) remains vertical or near vertical. It is unlikely that stress effects are sufficient to cause deflection of a dike (BSC 2003a, Section 6.3.9.1).

Effects on Dike Propagation of Strain Response on Existing or New Geologic Structures Resulting from Thermal Loading of High-Level Radioactive Waste–Thermal effects associated with heating of the repository from emplacement of waste would be transient and not present during most of the postclosure performance period. No new geologic structures will be formed because the stresses and strains are less than the strength of the rock and insufficient to create new structures through deformation.

Strains generated by heating from radioactive decay of waste would induce compressive stresses in the rock surrounding the drifts. The maximum increase in horizontal stresses, about 8 MPa for a hot repository design (1.45 kW/m) (Williams 2003, Table 2), would occur about 1,000 years after closure. These excess compressional stresses would not extend more than about 200 m from the drifts, and the minimum compressive stress would become vertical rather than horizontal for only about 50 to 60 m above and below the repository. On average, the vertical stresses would not change significantly because of the effects of heating associated with emplacement of waste (BSC 2003a, Section 6.3.9.2.2). Diversion of a dike ascending toward the central part of the repository would be unlikely to occur as a result of localized thermal effects.

Effects of Repository Structures on Conduit Localization–A dike moving toward the surface after intersecting one or more drifts could follow the pathway generated by the crack or fracture tip that precedes the magma front (BSC 2003a, Section 6.4.4.2). Model results (BSC 2003a, Section 6.3.9.2.3.3.2) indicate that magma continues up along the pathway but some magma would be diverted into drifts. Because of the diversion, the vertical velocity of the magma front would be less above a drift than in a pillar, until the intersected drift is filled with magma. Based on spatial considerations (i.e., ratio of drift cross-sectional area to pillar cross-sectional area) and decreased magma volume from diversion of magma into drifts, conduits might be more likely to form within pillars between drifts than directly above a drift (BSC 2003a, Section 6.4.4.2). The number of waste packages intersected by an eruptive conduit is treated as the product of conduit area times the average waste package density within the repository. The average waste package density is calculated by dividing the total planned number of waste packages by the total planned active repository area, including pillars. This relationship was used in association with a distribution incorporating variabilities in eruptive conduit diameters and in the number of eruptive conduits that could intersect the repository (BSC 2004a, Section 7.1). In practice, the method is similar to assuming conduits form randomly within the repository footprint. Although conduit formation might be expected to favor pillars separating drifts, no credit is taken for that tendency.

Effects of Repository Structures on Evolution of the Conduit and Flow System–Preliminary modeling results indicate that magma rising from depth at 1 m/s would flood intersected drifts in about 5 minutes (BSC 2003a, Section 6.3.9.2.3). The results also indicate that viscosity variations between 10 and 100 Pa·s would have slight effects on the lengths of time needed to inundate the drifts (BSC 2003a, Section 6.3.9.2.3).

Model results indicate that the repository would have negligible effects on evolution of the conduit system (BSC 2003a, Section 6.4.4.2) and on the evolution of the magma flow system. Open drifts are expected to divert magma until the intersected drifts are filled (BSC 2003a, Section 6.3.9.2.3.3), and the filling of a drift(s) would delay ascent of the magma front above the drift for a period of several minutes as a drift fills with magma. However, since the crack leading the magma front would have most likely reached the surface before the magma fills the drift (BSC 2003a, Section 6.3.9.2.3.3), the preferred pathway for the dike already would have been established.

One alternative model for dike propagation involves the potential for a dike to reach the repository level, divert some distance away from the point of intersection, and establish a new path to the surface removed from the point-of-drift intersection. This alternative has been referred to as the dog-leg scenario (Woods et al. 2002). The dog-leg scenario was evaluated by the Igneous Consequences Peer Review Panel (Detournay et al. 2003), by the Nuclear Waste Technical Review Board (Elsworth 2001; Melson 2001; Morrissey n.d.), and by the DOE (BSC 2003a, Section 6.4.11.3). These reviews found the dog-leg scenario to be highly speculative because of its dependence on very conservative assumptions about material properties. Based on simulations of crack-opening rates (BSC 2003a, Section 6.4.10.2), by the time the drifts are filled with magma, the crack tip developed ahead of the magma would already have reached ground surface (assuming an effusive magma-front velocity of 1 m/s). Filling of drifts with magma would not significantly slow magma ascent.

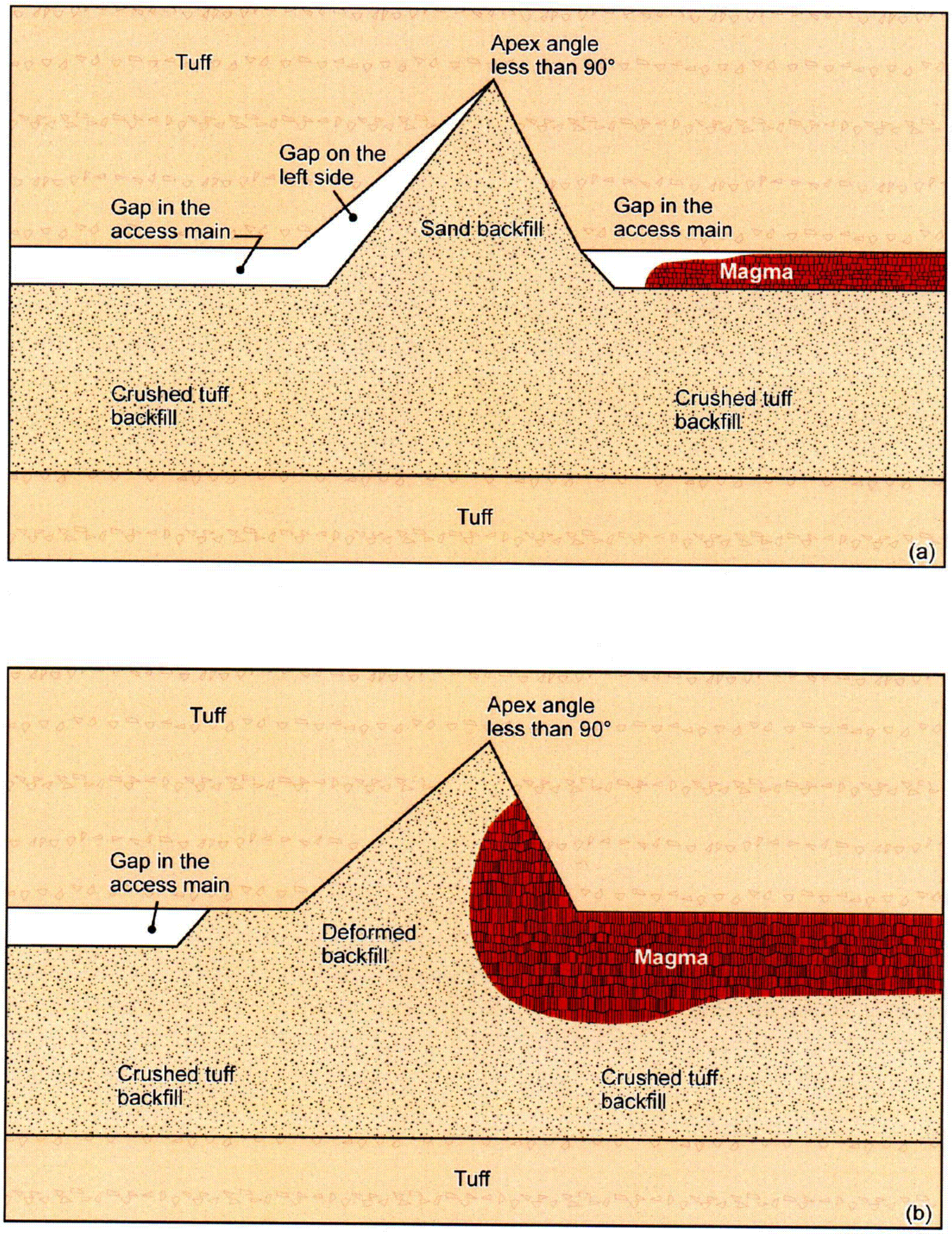
Analysis of the loss of heat from newly forming magma-filled cracks in cold rock shows that such cracks would not be able to grow to any appreciable width before partial solidification of magma would halt the crack development process. The situation of a new crack opening from a drift in cold rock differs from that of the extension of a propagating dike into cold rock. Crack opening near the tip of the propagating dike is driven by the large moments that result from the application of pressure by the magma many meters (i.e., ten to hundreds of meters) away from the crack, where the crack width is at least a large fraction of a meter. The new crack, on the other hand, is driven by pressure applied by magma that is near the crack tip, where the crack is narrow. Because the magma in the already propagating crack is nearly 1 m thick, its temperature is little affected by the cold rock in the time it takes for the crack to move an appreciable distance. Magma in the newly opening fracture, however, is only a few millimeters thick and would congeal in only seconds, before the crack could open over a length of more than about 8 m from the drift (BSC 2003a, Section 6.4.11.4.2, pp. 197 to 198). These results apply to magma with a density and viscosity near that of basalt.

Another analysis was conducted to investigate the possibility of a dog-leg developing as a result of hydrovolcanic activity from rapid mixing of magma and water producing pyroclastic material in intersected drifts. Such a material would have a lower density and a much lower viscosity than pure basaltic magma. The material could move into a crack in only seconds, thereby avoiding the effects associated with cooling of the magma that would tend to increase the viscosity of the magma and thereby inhibit dike propagation (see previous paragraph). Results of an initial analysis indicated that, in response to a steady source of low-viscosity fluid at high pressure, a joint opens fairly quickly to a centimeter in hundreds of milliseconds, reaching the maximum joint aperture of almost 0.10 m, with the pyroclastic dike reaching the surface in 6 to 10 seconds. However, it is unlikely that the pressures accompanying hydrovolcanic flow could be sustained above the confining stress and thereby continue to open a crack for sufficient time to allow the continuous flow of two-phase magma (Gaffney and Damjanac 2004, Section 3.1). Other analyses considered the extreme hypothetical case of water contact with advancing magma. This hypothetical scenario used a fixed mass of magma–water mix to evaluate rapid expansion of magmatic gas into an existing crack. The results of these analyses indicate that crack propagation depends on the mass of water involved in the hydrovolcanic reaction (Gaffney and Damjanac 2004, Section 2.0). These results show that for masses of water (from postulated seepage) less than about 50 to 100 kg, even if hydrovolcanic activity were to produce a pyroclastic phase in an emplacement drift and initiate crack propagation, the crack would not reach the surface, and no secondary pathway would be established. However, accumulation of these quantities of water through seepage is considered highly unlikely even assuming the upper-bound mean annual seepage rates for the glacial transition climate state (BSC 2004b, pp. 207 and 208, Tables 6.8-1 and 6.8-2). Additionally, drift orientation, invert water retention characteristics, and highly permeable nature of the host rock will further preclude accumulation of these relatively large quantities of water. Furthermore, even if the crack and the following dike reached the surface, the amount of waste affected would be less than that for the eruptive case (p. 10 of this response) (BSC 2003b; Gaffney and Damjanac 2004, p. 5).

Backfill and Confining Magma Flow between Drifts–Consistent with the current plans, access drifts within the repository would be backfilled. Backfill will reduce the chance that magma could follow the access drifts to the surface in the unlikely event that future igneous activity disrupted the repository. However, the backfill is a loose granular material and might be subject to compaction or erosion or both, which could, in turn, result in larger cross-sectional areas (Woods et al. 2002). In addition, a small (about 0.3 m) open space would likely exist at the top of the backfill, and it is possible that magma could flow through that open space.

A set of numerical simulations (BSC 2003a, Section 6.4.10.1) were done to help identify a backfill design approach and to test the efficacy of the backfill approach for preventing magma spreading from an emplacement drift into access and ventilation drifts. The analysis was restricted to mechanical considerations, and magma flow was not modeled. The effect of the magma on the backfill material was taken into account by means of an applied mechanical pressure, but compaction from thermal welding of backfill material has not been included in the analysis. The modeling results indicate that the behavior of the fill, under influence of the pressure applied by the magma, would be inadequate to confine magma.

A subsequent calculation was conducted to examine the effectiveness of an alternative backfill design to confine magma and to prevent flow between drifts via access drifts (Detournay et al. 2004). The alternatives featured backfilled access drifts supplemented by backfilled keyways in the drift crown (Figure 1a) and between emplacement drift turnouts. The calculation considered confining effusive magma flow by mechanical obstruction and by magma freezing associated with limited magma infiltration into the backfill. The calculation showed that alternatives featuring either loose (less compacted) or dense (more compacted) backfill would provide an effective mechanical obstruction to confine magma flow (Figure 1b). Because either design would halt flow of magma between drifts, the design selected for the license application will be based on a variant of this analysis approach.



NOTE: (a) Keyway just prior to contact by flowing magma and (b) after contact with magma showing deformation of fill and closure of the open space in the keyway.

Figure 1. Example of Inverted V-Shaped Filled Keyway in the Crown of the Access Main

C01

The information in this enclosure is responsive to agreement IA 2.18 made between the DOE and NRC. The enclosure contains the information that DOE considers necessary for NRC review for closure of this agreement.

BASIS FOR THE RESPONSE

Information concerning dike propagation, fluid dynamics and thermal evolution of magma, and the migration of magmatic gases through rock was assessed to formulate a model for the interactions of a rising basaltic dike with a cylindrical drift excavated in silicic tuff. The model and results are documented in *Dike/Drift Interactions* (BSC 2003a) and are summarized here.

Effects of Repository Structures on Dike Propagation

The objective of dike-propagation modeling is to provide realistic conditions that support assessment of the interaction of magmatic products with drifts and drift contents. Of particular importance is the manner in which the dike intersects the repository, the pressure (and pressure history) of the magma and volatiles, the width of the dike (and, thus, the amount of magma available to flow into the drifts) as a function of time, and the effect of magma loss into the repository on the aforementioned items. The dike propagation mathematical model (BSC 2003a, Section 6.3) calculates: (1) the pressure conditions and dike parameters that exist at the point of intersection with the repository for use as initial conditions for the magma flow analysis; (2) the effect that magma loss into the repository would have on subsequent dike growth; (3) the changes in stresses adjacent to the repository due to the presence of the dike; and (4) the properties of a possible dog-leg dike that could initiate along a drift at some distance from the original dike/drift intersection. The model investigates the effects of in situ and thermally induced stresses on the dike path (e.g., the potential for deflection of the dike away from the repository). Stress analysis shows that potential diversion of a dike (i.e., increased horizontal stresses at the repository level could cause dike deflection) would be limited in both time and space following waste emplacement (BSC 2003a, Section 6.3.9.2).

Based on modeling results, an ascending dike is preceded by a crack, and the crack is likely to reach the surface before the magma front reaches the repository. Hence, a pathway to the surface is available before the magma reaches the repository. Once diversion of some amount of magma into repository drifts has occurred, the model indicates that dike ascent would resume and would most likely follow the pathway represented by the crack.

Results–When the magma front reaches the drifts of the repository, magma could be diverted into the drifts from the dike. Modeling considered the alternative of effusive flow (single-phase magma) into drifts (BSC 2003a, Section 6.3.9.2.3.1) at two magma-ascent velocities, 1 m/s and 10 m/s. Results showed that viscosity variations between 10 and 100 Pa·s would have little effect on the length of time needed to fill drifts (about 5 minutes and about 1 minute, respectively, for the two specified ascent velocities). At the higher ascent rate, magma would continue rising in the dike as the drifts are filled, although not as fast as in the absence of drifts.

Although leakoff of magma into drifts may slow the progress of the magma front to the surface, leakoff would have little effect on the dike tip cavity, which would already have begun accelerating in response to the presence of the free surface. The tip would reach the surface only seconds after passing the drift horizon (BSC 2003a, Section 6.3.9.2.3.2.2).

Three-dimensional simulation of loss of driving pressure in a dike due to intersection with a drift has demonstrated that the interaction would both depress the height of magma in the dike and decrease the pressure in the magma directly above the drift relative to the centerline between successive drifts (BSC 2003a, Section 6.3.9.2.3.3).

Effects of Topography and Stress on Dike Propagation

Some models (e.g., CRWMS M&O 2000, Section 7) indicate that heterogeneity of in situ stresses and rotation of the major principal stress from the vertical direction can have an effect on the dike path and potentially divert it from the repository. Heterogeneity of in situ stresses could be caused by the topography of Yucca Mountain. The dike propagation model calculates the growth history of a dike propagating toward the surface in the vicinity of the repository. The current model accounts for the potential influence of surface topography complexities by including variations in the horizontal in situ stress that occurs around the repository.

Results–A large-scale, three-dimensional, thermal-mechanical analysis of regional stresses accounting for topography at the Yucca Mountain site was conducted using the FLAC3D code (V2.1, STN: 10502-2.1-00). A detailed description of this analysis is found in *Drift Degradation Analysis* (BSC 2003c). The in situ stress state at Yucca Mountain (before heating) is such that the vertical stress is the maximum principal compressive stress, whereas two other principal stresses of smaller magnitude are in the horizontal plane. The vertical in situ stress is gravitational (a function of topography).

The topography above the repository will have a negligible effect on the dike path (BSC 2003a, Section 6.3.9.1). There is a variation of the magnitude of the vertical stress, which increases at the repository (compared to vertical stresses in the neighboring valleys) due to the larger mass of the mountain, but the vertical stress always remains the major principal stress (see BSC 2003a, Figures 11a and 11b). Effects of topography on formation of new pathways along intersected emplacement drifts are not expected to be significant because of effects associated with cooling of the magma that would tend to increase the viscosity of the magma and thereby inhibit dike propagation (BSC 2003a, Section 6.4.11.4).

Effects on Dike Propagation of Strain Response on Existing or New Geologic Structures Resulting from Thermal Loading

The temperature and stress changes due to heat generated by the emplaced waste were simulated through the regulatory period of 10,000 years. A description of that analysis is given in *Drift Degradation Analysis* (BSC 2003c), and results show that the maximum increase in horizontal stress from heating occurs between 500 and 1,000 years after waste emplacement (BSC 2003a, Section 6.3.9.2.2), but, on average, the vertical stresses (statically determined) would not change as a result of heating (BSC 2003a, Section 6.3.9.2.2).

Results–On average, the vertical stresses (statically determined) would not change as a result of heating. If heating increases the magnitude of the horizontal principal stresses so that both become larger than the vertical principal stress, the repository could be shielded from potential volcanic intrusion for a period of time (while the conditions of such stress inversion exist).

The temperature and stress changes due to heat generated by the emplaced waste were simulated through the regulatory period of 10,000 years. Detailed description of this analysis is found in *Drift Degradation Analysis* (BSC 2003c). The maximum increase in horizontal stress due to heating occurs between 500 and 1,000 years after waste emplacement.

Between 500 and 1,000 years of heating, the vertical stress becomes the least-compressive stress over a height of approximately 200 m and, at most, 3 MPa smaller than the smaller horizontal principal stress (BSC 2003a, Figures 13a and 13b). For duration of heating longer than 1,000 years, the stress difference and the spatial extent of the region with stress inversion decrease. After 2,000 years (BSC 2003a, Figure 13c) of heating, normal stress in the east–west direction is only 1 MPa larger than the vertical stress. No new geologic structures will be formed because the stresses and strains are less than the strength of the rock and insufficient to create new structures through deformation.

The stress change due to heating extends to a depth of about 100 m below the repository (BSC 2003a, Figures 13a, 13b, and 13c). Considering the repository width of more than 1 km, it would be almost impossible for a dike propagating toward the central portion of the repository to turn and pass by the repository without intersecting any part of it.

Realistic potential for dike deflection will exist only near the edges of the repository and for a limited time during the regulatory period (between 500 and 2,000 years after waste emplacement). For TSPA-LA, it was conservatively assumed that the repository would not have an effect on the dike path (BSC 2003a, Section 6.3.9.2.2). Hence, the stress changes from heating associated with emplacement of waste are expected to have little, if any, effect on dike propagation.

Effects of Repository Structures on Conduit Localization

The magma flow model and supporting analyses (BSC 2003a, Section 6.4) addressed the interaction of magma with drifts. The model calculates conditions that could occur if unpressurized magma were to encounter a representative emplacement drift. This approach provides a basis for reorganization and localization of flow in the dike, leading to formation of an incipient conduit.

Results–Three-dimensional simulation of the diversion of magma from a dike into a drift has demonstrated that the diversion would lower the height of magma in the dike and depress the pressure in the magma directly above the dike relative to the centerline between successive drifts (BSC 2003a, Section 6.3.9.2.3.3). Based on this result, as magma flows into the intersected drifts, dike ascent is expected to be concentrated in pillars separating drifts, and conduit formation could favor pillars rather than drifts. However, no credit is taken for this possible result.

Effects of Repository Structures on Evolution of the Conduit and Flow System

As a hypothetical dike ascends toward the repository, the crack that develops ahead of the magma front would intersect the drift before the magma (BSC 2003a, Section 6.3). Thus, the most likely scenario for magma to reach the surface after intruding the drift complex is for it to continue along the trajectory of the leading crack (BSC 2003a, Section 6.4.4.2). Alternative models in which magma reaches the surface after passing through some length of emplacement drifts were also investigated (Gaffney and Damjanac 2004). The results indicate that such an occurrence is unlikely. However, if such an unlikely hydrovolcanic event were to occur because of magma encountering an area of water in a drift, some magma (potentially contaminated) might reach the surface. However, because of the limited extent of the modeled hydrovolcanic event (one or two waste package lengths), the contents of no more than two waste packages could be carried to the surface.

Results–*Characterize Eruptive Processes at Yucca Mountain, Nevada* (BSC 2001) describes the basic processes by which the sheet flow of a dike is transformed into the more concentrated flow of a conduit. As magma continues up the original dike path while also being diverted into the drifts, the vertical velocity would be less directly above a drift than at the midpoint between two drifts (BSC 2003a, Section 6.3.9.2.3.3). In a dike, a balance exists between heat supplied from magma flowing upward and heat lost to the cold walls. Many dikes fail to reach the surface when they freeze in place as they propagate into colder rocks (Lister 1995). A change of an order of magnitude in the pressure driving the dike could cause flow to slow above drift intersections. As a result, a conduit might be more likely to form between drifts than directly over a drift, but no credit is taken for the possibility that the conduit might not intersect drifts (BSC 2003a, Section 6.4.4.2).

One alternative model for dike propagation involves the potential for a dike to reach the repository level and then divert some distance away from the point of intersection and establish a new path to the surface remote from the point of intersection with a drift. This alternative has been referred to as the dog-leg scenario (Woods et al. 2002). The dog-leg scenario was evaluated by the Igneous Consequences Peer Review Panel (Detournay et al. 2003), by the Nuclear Waste Technical Review Board (Elsworth 2001; Melson 2001; Morrissey n.d.), and by the DOE (BSC 2003a, Section 6.4.11.3). These reviews found the dog-leg scenario to be highly speculative because of its dependence on very conservative assumptions about material properties and initial and boundary conditions. Specific problems that lead the DOE to discount the Woods et al. (2002) pyroclastic dog-leg scenario include:

- The one-dimensional model takes no account of momentum as magma transforms from vertical motion in a dike to horizontal motion in a drift.

- The initial condition of a wall of high pressure magma across the entire dike/drift interface is extreme and leads to gross overestimates of dynamic effects, including formation of shock waves in the drift.

- The single-phase model for expanding (and recompressing) magma does not allow for separation of the vapor and liquid phases that occur in natural pyroclastic flows; this leads to unrealistic material properties and unrealistic magma pressures when a pyroclastic surge encounters a barrier, such as the end of a drift.

- The model ignores the presence of waste packages, drip shields, and various other in-drift structures that would act to dampen high-energy flow in a drift.

Although DOE believes that the high-energy dog-leg is not a realistic concern, other possible dog-leg scenarios have been investigated. Based on simulations of crack-opening rates (BSC 2003a, Section 6.4.10.2.1), by the time the drifts are filled with magma (about 5 minutes), the magma already would have reached ground surface (assuming a magma-front velocity of 1 m/s). Analysis of the loss of heat from newly forming magma-filled cracks in cold rock clearly shows that such cracks would not be able to grow to any appreciable width before solidification halts them. The dog-leg scenario is, therefore, unlikely for two reasons. First, a crack to the surface and a preferential pathway above the point of intersection are likely to have been already established, especially within pillars separating drifts. The tip of the crack leading the dike would accelerate as it nears the free surface, so that the crack would reach the surface only seconds after passing the drift horizon. This open pathway for flow would be the most likely path that magma would take to the surface after encountering the drift complex. Second, it is unlikely that a crack, remote from the point of intersection, could be opened and sustained. If a crack opened at a point remote from the dike/drift intersection point, and magma were to begin to move into the new crack, simulations show that the magma would freeze before ascending far up the crack (BSC 2003a, Section 6.4.11.4), and development of a dog-leg would be halted. The analysis indicates that insufficient pressures would accompany intrusion into drifts to sustain a pyroclastic dogleg unless magma comes into contact with a substantial source of water (more than 100 kg).

A second model for development of a dog-leg associated with possible pyroclastic flow, of hydrovolcanic origin, was also investigated (Gaffney and Damjanac 2004, Section 2.0). The analysis addressed injection of magma with a very low viscosity of 0.5 Pa·s, at a constant (static) magma pressure (9 MPa larger than the far-field horizontal stress) inside the drift. The products of this analysis, the rate of crack opening and magma-front velocity, were used to assess the potential for a dog-leg scenario, assuming pyroclastic flow under these very conservative source conditions. The results indicate that a joint opens fairly quickly to a centimeter in hundreds of milliseconds, eventually reaching the maximum joint aperture of almost 0.10 m. Under conditions of such a large aperture and small magma viscosity, the assumptions used in the model of laminar flow and the lubrication approximation for fluid flow inside the joint probably overestimate the magma flux. Turbulent flow would result in a smaller flux for the same pressure source. The results indicate that a pyroclastic dike could reach the surface in 6 to 10 seconds, provided an excess pressure of 9 MPa could be maintained for the 6 to 10 seconds needed for the pyroclastic dike to reach the surface. Further calculations with a decaying pressure source representative of a mixture of magma and water vapor that expanded down the drift while also opening a crack indicated that crack propagation would proceed to the surface only for water masses of about 100 kg or greater. (Note that this analysis conservatively ignores dissipation of pyroclastic and hydrovolcanic pressures at the drift wall through the rock mass and losses through access ramp tunnels.) Considering the spatially limited nature of hydrovolcanic activity in a drift (because of the small area needed to accumulate 50 to 100 kg of water (Gaffney and Damjanac 2004, Section 2.0)), if an unlikely hydrovolcanic event were to occur, it would not be expected to involve more than two waste packages. Thus, any resulting release would involve the contents of not more than two waste packages.

Although these preliminary calculations indicate that a pyroclastic dike in the form of a dog-leg could reach the surface if driven by a sufficient quantity of water, given the highly permeable nature of the invert fill and the permeability of the rock beneath the invert, it is unlikely that enough water could accumulate to present a hydrovolcanic venting hazard. An upper-bound, lithologically weighted, mean seepage rate for water percolating into emplacement drifts at Yucca Mountain during a glacial-transition climate (less than 2,000 years after closure) is estimated at 143.6 kg/yr per waste package (BSC 2004b, pp. 207 and 209, Tables 6.8-1 and 6.8-2). Combining this with values of 128 waste packages per drift, 800 m per drift, and a collection length of one drift diameter, it would take 289 days to accumulate 100 kg of water. Given the highly permeable nature of the invert fill and the permeability of the rock beneath the invert, it is unlikely that enough water could accumulate to present a hydrovolcanic venting hazard (Gaffney and Damjanac 2004, Section 2.0).

Backfill and Confining Magma Flow between Drifts

The analysis of the number of waste packages that could be contacted by a dike intersecting the repository (BSC 2003b) relies on an assumption that magma flow between emplacement drifts would not occur. Backfill could substantially restrict the flow of magma. However, the backfill is a loose granular material and, after emplacement, a gap of 1 m or less is expected to exist between the top of the backfill and the drift crown. Additionally, the backfill could be subject to further compaction or erosion or both, which could, in turn, result in larger gap cross sections.

The sealing efficacy of a segment of backfill was evaluated using numerical modeling (BSC 2003a, Section 6.4.10.1). The results showed progression of a gap forming at the roof as the magma advances, and the study concluded that the emplacement of backfill would probably not confine magma flow, even if a tight backfill were emplaced. Since a method to confine magma flow between drifts is needed to limit the number of waste packages damaged by igneous disruption of the repository, a new calculation (Detournay et al. 2004) examined the potential of a keyway backfilled with sand (Figure 1a) as a method to confine magma flow. The calculation examined two mechanisms to confine magma flow and evaluated the performance of two contrasting types of backfill. The first confinement mechanism is mechanical obstruction produced by deformation of sand backfill under mechanical pressure applied by the magma. The second mechanism is limitation of penetration or infiltration of magma into the backfill material based on heat loss and solidification of the magma as it penetrates the backfill. The backfill types considered are loose and dense sand. Results showed that both mechanisms were effective with either type of backfill.

Results for Deformation of Backfill–Numerical modeling, using the computer code FLAC3D (Detournay et al. 2004), shows that a new design option for backfill plugs could confine magma flow between emplacement drifts. The new design option features sand-filled keyways (Figure 1a) located in crowns of access drifts and between emplacement drift turnouts. For the analysis, a pressure of 0.25 to 8 MPa was applied at the top surface of the fill in the access main to simulate the effect of incursion of magma from an emplacement drift. The fill deformation was analyzed for loose and dense sand backfill material properties (Detournay et al. 2004, Section 2.2).

Magma that intrudes into the gap on the top of the backfill in the access main would apply a mechanical pressure on the fill, pressing the fill material down while pushing the sand backfill in the keyway to close the gap on the side of the keyway opposite the magma (Figure 1b) (Detournay et al. 2004, Section 3.3). The induced deformation of the backfill in the keyway ensures magma confinement, even though the amount of deformation will differ for loose and dense sand.

The simulation shows (Detournay et al. 2004, Section 3.3.1) that the gap between the backfill and the top of the keyway and a portion of the gap in the access main beyond the plug are closed completely under a magma pressure of 6 MPa. Results for magma pressures of 0.25, 0.5, 1, 2, and 4 MPa show consistent progressive closing of the gap on the far side of the plug (Detournay et al. 2004, Section 3.3.1 and Appendix A). For 0.25 MPa, the length of the shortest escape route for the magma from the chamber to the open part of the gap beyond the plug is in excess of 1 m (Detournay et al. 2004, Section 3.3.1).

The results of the simulation for a dense sand backfill (Detournay et al. 2004, Section 3.3.2) show that, although the magma pressure is higher (8 MPa) than the value considered in the loose-sand case (6 MPa), only part of the gap on the far side of the keyway is closed, and no contact with the rock is achieved in the backfill inside the access main beyond the keyway. Based on analysis of the closure results (Detournay et al. 2004, Figure 8-10), a dense sand backfill would be less efficient than loose sand in confining the magma. However, the analysis shows the magma flow between emplacement drifts would be confined by dense sand backfill in a keyway.

Results for Magma Infiltration–During intrusion, magma fills the gap between the top of the backfill and the crown of a drift and works its way up the side of the backfilled keyway. The pressure applied by the magma compresses the fill and partially closes the gap on the side of the keyway opposite the magma. As a result, a chamber (or gap) is created on the side of the plug nearest the magma, and the chamber is filled by the hot magma that is in contact with a large distant reservoir of temperature 1,379 K (Detournay et al. 2004, Section 2.3).

Magma infiltration is computed by assuming magma, at a pressure of 8 MPa inside the chamber, penetrates the porous fill. The flow of magma is controlled by its viscosity, which depends on temperature. As temperature decreases, the magma advance is slowed because of increased viscosity associated with an increase in the crystal fraction of the cooling magma (BSC 2003a, Section 6.4.11.4.1.1). Heat is transported from the chamber by conduction in the fill and the rock and by convection in the flowing magma. Also, as magma flows into the fill, it is replaced by an identical volume of magma flowing in from the distant reservoir, bringing with it additional energy.

The calculation evaluated the distance reached by the magma front between the time it begins infiltrating the fill and the time magma effectively solidifies (i.e., the freezing distance). The two types of backfill, loose and dense, differ by their permeability and porosity. To test the efficiency of the confinement, the freezing distance was compared to the length of the shortest escape route, from the chamber to the gap at the front of the plug (Detournay et al. 2004, Section 2.3).

For loose sand (Detournay et al. 2004, Section 3.4.1), magma in the chamber between the backfill and the back of the drift solidifies in less than 12 days, and the magma penetrates about 40 cm into the backfill. A model control point located approximately 0.13 m from the chamber never experiences a temperature above the solidification temperature for the magma.

For dense sand (Detournay et al. 2004, Section 3.4.2), freezing of the magma in the chamber would occur after about 3 days, and the magma penetrates less than 0.20 m. Again, a model control point located approximately 0.13 m from the chamber never experiences a temperature above the solidification temperature for the magma.

Summary of Backfill and Confinement of Magma Flow between Drifts

The analyzed configuration features a sand-filled keyway, shaped like an inverted V, located in crowns of access drifts and between emplacement drift turnouts. Magma confinement by loose sand and dense sand backfill material was evaluated. The results show that either material could be used in conjunction with the keyway to confine the flow of magma between drifts. Simulation results show the loose backfill, with its higher compressibility, has a higher sealing capability and provides a better mechanical obstruction than the dense sand backfill. On the other hand, dense sand, with its lower porosity and permeability, would be more efficient in limiting magma infiltration than loose sand backfill, but the differences between the loose sand and dense sand to limit magma infiltration appear to be modest (magma front reaches 0.4 m from the chamber for loose sand versus 0.2 m for dense sand). Because either alternative would halt flow of magma between drifts, the option selected for the license application will be based on a variant of this analysis approach.

REFERENCES

Documents Cited

Bokhove, O. and Woods, A.W. 2000. "Explosive Magma-Air Interactions by Volatile-Rich Basaltic Melts in a Dike-Drift Geometry." Interim Milestone 1402.461.040. Washington, D.C.: Nuclear Regulatory Commission. ACC: MOL.20030922.0077.

BSC (Bechtel SAIC Company) 2001. *Characterize Eruptive Processes at Yucca Mountain, Nevada.* ANL-MGR-GS-000002 REV 00 ICN 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20020327.0498.

BSC 2003a. *Dike/Drift Interactions.* MDL-MGR-GS-000005 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20031022.0001.

BSC 2003b. *Number of Waste Packages Hit by Igneous Intrusion.* ANL-MGR-GS-000003 REV 00. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20040323.0002.

BSC 2003c. *Drift Degradation Analysis.* ANL-EBS-MD-000027 REV 02. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20030709.0003.

BSC 2004a. *Igneous Intrusion Impacts on Waste Packages and Waste Forms*. MDL-EBS-GS-000002 REV 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20040421.0002.

BSC 2004b. *Abstraction of Drift Seepage*. MDL-NBS-HS-000019 REV 00 ICN 01, with errata. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20031112.0002; DOC.20040223.0001.

CRWMS M&O (Civilian Radioactive Waste Management System Management and Operating Contractor) 2000. *Dike Propagation Near Drifts*. ANL-WIS-MD-000015 REV 00 ICN 1. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20001213.0061.

Detournay, C.; Cundall, P.; and Damjanac, B. 2004. "Analysis of an Alternative Backfill Design Approach for Magma Containment." Technical memorandum from C. Detournay, P. Cundall, and B. Damjanac (ITASCA) to E. Gaffney, M. Cline, and M. Board (BSC), April 6, 2004, 04-2133-4-8TM. ACC: MOL.20040429.0140.

Detournay, E.; Mastin, L.G.; Pearson, J.R.A.; Rubin, A.M.; and Spera, F.J. 2003. *Final Report of the Igneous Consequences Peer Review Panel*. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20030325.0227.

Elsworth, D. 2001. "Summary Report to NWTRB The Consequences of Igneous Intrusion at Yucca Mountain Some Rock Mechanics Aspects of Dike-Repository Interaction." November 12, 2001, 23 pages. ACC: MOL.20030919.0074.

Gaffney, E. and Damjanac, B. 2004. "Dike/Drift Updates." Technical memorandum from E. Gaffney and B. Damjanac (ITASCA) to T. Crump, M. Cline, and D. Billaux (BSC), April 28, 2004, 04-2133-4-11TM. ACC: MOL.20040429.0139.

Lister, J.R. 1995. "Fluid-Mechanical Models of the Interaction Between Solidification and Flow in Dykes." *Physics and Chemistry of Dykes, Selected Papers Presented at the Third International Dyke Conference, Jerusalem, Israel, 4-8 September 1995*. Baer, G. and Heimann, A., eds. Pages 115-124. Brookfield, Vermont: A.A. Balkema. TIC: 254504.

Melson, W.G. 2001. "Responses to Questions Resulting from the November 8, 2001, Meeting at NWTRB Headquarters Regarding Igneous Intrusion Consequences." Memo from W.G. Melson (Smithsonian Institution) to L. Reiter (NWTRB), November 21, 2001. ACC: MOL.20030919.0073.

Morrissey, M.M. n.d. *Review of Shock Wave Models and Igneous Activity*. Unpublished consultant's report. ACC: MOL.20030919.0072.

Reamer, C.W. 2001. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Igneous Activity (September 5, 2001)." Letter from C.W. Reamer (NRC) to S. Brocoum (DOE/YMSCO), September 12, 2001, with enclosure. ACC: MOL.20011114.0008.

Williams, N.H. 2003. "Thermal Inputs for Evaluations Supporting TSPA-LA, Supplement." Interoffice memorandum from N.H. Williams (BSC) to Distribution, April 4, 2003, 0205035938, with enclosures. ACC: MOL.20030501.0081.

Woods, A.W.; Sparks, S.; Bokhove, O.; LeJeune, A-M; Conner, C.B.; and Hill, B.E. 2002. "Modeling Magma-Drift Interaction at the Proposed High-Level Radioactive Waste Repository at Yucca Mountain, Nevada, USA." *Geophysical Research Letters, 29,* (13), 19-1 through 19-4. Washington, D.C.: American Geophysical Union. TIC: 254467.

Data, Listed by Data Tracking Number

SNF37100195002.001. Hydraulic Fracturing Stress Measurements in Test Hole: ESF-AOD-HDFR1, Thermal Test Facility, Exploratory Studies Facility at Yucca Mountain. Submittal date: 12/18/1996.

Software

FLAC3D V2.1. STN: 10502-2.1-00.