REVIEW OF THE FINAL REPORT OF THE IGNEOUS CONSEQUENCES REVIEW PANEL

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April 2, 2003

The following are a series of questions asked of me by the Nuclear Waste Technical Review Board in my review of the final report of the igneous consequences review panel and public meeting on the Panel that took place on February 26, 2003.

1. Provide general comments on the Peer Review and the report including the qualifications of the Panel members, the range of disciplines, the impartiality and independence of the Panel, and the overall quality of the Report.

The Peer Review Panel produced a very thorough and comprehensive final report on Igneous Consequences at the Potential Yucca Mountain Repository. The choice of panelists was excellent and quite diverse. The expertise of the Panel covers many areas of volcanology from petrology and geochemistry to dike propagation mechanics and conduit flow dynamics. The majority of the Panel had extensive field experience in related volcanological environments. Several fields of engineering were represented in the Panel such as solid mechanics and fluid mechanics. These areas of engineering aided the Panel in evaluating the response of the repository to igneous consequences. The Panel appeared to take an unbiased, independent approach to reviewing the issues regarding igneous consequences by looking at the problem systematically from the origin of magma, ascent of magma and how it may interact with the repository and might make its way to the surface. Where needed, my recommendations are underlined in my reply to the remaining questions.

2. What, in your mind, are the most significant conclusions and recommendations of the Panel?

The most significant conclusion of the Panel is that there is a general consensus on the nature (magma composition including volatile content) and sequence of events related to any future volcanic event in or around the potential Yucca Mountain Repository. This narrows the focus of studies on the response of the repository to igneous activity related to a certain magma composition and sequence of eruptive events.

Another important conclusion by the Panel is that numerical models of dike propagation are limited to viscous, volatile depleted magmas. These models do not accurately portray the flow behavior of magma inside the dike at depths < 1 km where the repository is located. As discussed by the Panel, future eruptions may involve basaltic magma containing 2.5 to 4 wt. % volatiles. As magma ascends, volatiles exsolve forming bubbles in the magma. The presence of bubbles in the magma will change the behavior of the magma from viscous, incompressible to compressible and inviscid if the bubble fraction exceeds 0.7. The thermodynamic and transport properties of the magmatic fluid (magma and gases) play a key role in understanding magma-drift and magma-canister interaction. It is highly recommended by this reviewer that a more robust dike propagation model be developed that include fluid dynamic equations that represent the range of magma flow behaviors related to the bubble fraction near the magma front as it approaches repository depths. The recommendations of the Panel for future model development should be considered as they include this factor and other factors that affect the propagation of the dike. The approach that they describe in Chapter 3 and related appendices should be followed such as including compressibility, gas-bleed of into the permeable host rock and magma flow splitting from the dike into drifts. The latter factor effects the propagation speed of the crack tip and has implication on the probability a dog-leg scenario.

Other significant conclusions by the Panel are related to the dog-leg scenario and the orientation of the dike through the repository. The Panel concluded that the dog-leg scenario for erupting waste into the atmosphere is not a highly probable scenario. The significance of this is that it suggests that the only canisters that will reach the surface are those that are directly impacted by the intersection of the main dike. The difference here is that an eruption through the main dike is assumed to involve 10 canisters whereas an estimated 100 canisters would be involved with an eruption through a dog-leg type conduit. As stated by the Panel, they were not able to quantify this result mainly because the uncertainty associated with the pressure history inside the drift after the intersection of a dike. The probability of the dog-leg scenario needs to be re-evaluated and quantified once a dike propagation model as described above is developed.

The Panel also concluded that a probability could be estimated on the orientation of a dike if one would pass through the repository. The Panel agreed with the PVHA analysis that the orientation of a dike intersecting the repository will range between N10E and N60E. This range is based on the orientation of pre-existing fractures as well as the present principle stress. The significance of this result is that a maximum value can be constrained for the number of drifts that would be intersected by a dike and possibly the number of packages affected by it once more conclusive studies are made on magma-drift interaction. It was also recommended by the Panel that the preferred dike orientation be considered in the final repository design to minimize the number of potentially effected drifts. This recommendation should be considered in the final design of the repository.

3. Were there any important gaps in the Panel's report? If so, what are they?

One area that the Panel did not cover extensively is the behavior of magma between the repository and the atmosphere with respect to entrainment of waste. The Panel discusses several scenarios of magma-drift interaction involving a range of magma flow behavior from viscous magma, to a bubbly flow, to an ash-gas mixture. This approach was not taken when it came to analyzing conduit flow dynamics and how waste becomes entrained in the erupting magma. DOE studies jump from magma-drift interaction such as the Woods et al. (2002) model to ash dispersal with the computer code ASHPLUME. It is not clear how waste material becomes exposed from the fuel rods and the canister then fragmented to such a fine fraction and when all these events occur during transport from the drift through the conduit to the surface. This gap in the analysis is attributed to the lack of related project studies on the response of the canisters to magma of the type assumed for Yucca Mountain. The thermomechanical properties for alkali basalts are well documented and need to be used in analytical studies on the thermomechanical response of the Alloy 22 canister. As mentioned by the Panel, experiments need to be conducted that simulate canister-magma interaction with magma that is non-vesicular or depleted in volatiles, a bubbly fluid and an ash-gas mixture. This would be the most effective way to study the degree of the physical disruption by magma to completely remove all waste from canisters and fuel rods. Results from these experiments and related studies will provide more insight on how waste becomes exposed during a volcanic event that may lead to decreasing the risk of exposure.

4. Please review the analysis, conclusions, and recommendations in specific areas.

A. Volcanological setting, eruption chronology, and magma and rock properties:

There is good agreement between the Panel and Project studies on the volcanological setting and nature of any future volcanic activity in the Yucca Mountain region. The uncertainty is in when and where such activity would occur. Based on observed characteristics of Pliocene and Quaternary volcanism in the Crater Flat volcanic zone, the magma type of a future eruption will likely be alkali-basalt. The eruption volume will be 0.01-1.0 km^3 and the duration will be on a scale of days to months. The eruption behavior whether it is effusive forming a lava flow or explosive in the form of a Strombolian eruption, will depend primarily on the volatile content. The volatile content will range between 2.5 to 4.0 wt. % of the major volatile species H_2O, CO_2, SO_2. The Panel recognizes that magmas are not homogenous fluids so it is very difficult to predict the exact eruption scenario that may occur. The thermodynamic and transport properties of alkali-basalt are well known and are based on laboratory measurements from hundreds of samples of this type of magma/lava collected from volcanoes around the world. The Panel did an excellent job of compiling the range of values for these properties as a function on magma volatile content and bubble fraction (Figures 2-1A to 2-1G and 2-2, and Figure 2B in Appendix 2). These properties are vital for future numerical modeling of magma transport through a dike, a drift and the atmosphere. The Panel noted that the thermal conductivity of basaltic magma is not well known and recommends further experiments. This property is significant to studying the response of canisters to magma and magma flow behavior and should be considered in future DOE investigations.

B. Dike propagation, significance of tip cavity, and dike/drift interactions:

The dike propagation model presented by the Panel is based on linear elastic fracture mechanics and is defined by two regions, the main crack filled with magma and a leading tip cavity filled with vapor. The behavior of the tip cavity determines the propagation path of the dike and is controlled by the stress at the tip defined by the following condition: $-P=K/(2(l))$, where K is the stress intensity factor, l is the length of the crack and $-P$ is the pressure difference between the vapor pressure and the ambient compressive stress (Lister, 1990; Rubin, 1995). If $-P$ were less than the terms on the right then the crack will not propagate. If $-P$ were greater than the terms on the right then the related propagation velocity would be unrealistic. At the vapor-magma interface the vapor phase is assumed to be in thermodynamic equilibrium with the magma thus the vapor pressure is equal to the saturation pressure of the magma. The model assumes that the widening of a main crack is steady and depends on the difference between the fluid (internal magma pressure) and the least compressive stress, referred to as excess pressure, and the elastic properties or stiffness of the host rock. The model also assumes that magma inside the crack is viscous and incompressible, and the crack tip is filled with vapor at a constant pressure and temperature.

Based on these assumptions and boundary conditions, the model is able to predict the propagation path of a viscous magma as it ascends through the crust. The model accounts for regional and local stress perturbations such as topography, thermal loading and existing fractures. The model becomes invalid when the magma no longer behaves as a viscous, incompressible homogenous fluid. The transition from viscous, incompressible to viscous-compressible occurs when the bubble fraction of the magma is 0.4-0.7, defining a magma that behaves as a bubbly fluid. When the bubble fraction >0.70, the magma will be fragmented into ash and become a mixture of ash and gas. Thus, as the volume fraction of bubbles increases, magma behaves more compressible and becomes less homogeneous. The Panel made preliminary calculations that include compressibility. The results from these calculations demonstrated that a more robust dike propagation model is needed that includes compressible fluid dynamics. The importance of these calculations is to estimate or constrain the vapor and magma pressures associated with the full spectrum of magma flow behavior. The vapor pressure and magma flow pressure are one of the parameters that govern the behavior of the crack tip and the initial conditions of the magma-drift interaction scenario. The Panels conclusion on the low probability of a dog-leg scenario is based on results from the viscous, incompressible, quasi-steady dike propagation model. Once a more robust model is available, this conclusion should be re-evaluated along with those related to dike-drift interaction such as the dog-leg scenario, as the dynamics involved depend largely on the gas and magma pressures inside the dike.

C. Dog-leg scenario and its likelihood.

The Panel believes that the probability of a dog-leg scenario occurring is very small. This conclusion is based on hydrodynamics and dike propagation models in which two conditions have to be reached in order to achieve the dog-leg scenario. First, the main dike must terminate before it reaches the surface or be blocked so flow is disturbed and flow pressure at depth increases allowing the main flow to be in the drifts. Secondly, the secondary dike has to be wide enough and propagate fast enough to avoid thermal termination. These conditions are from a dike propagation models for viscous, incompressible flow and should be re-evaluated using dike propagation and dike-drift interaction models that considers the full spectrum of magma flow behavior related to its bubble fraction.

The Panel mentioned that a dog-leg scenario could occur if the tip cavity were on the scale of 10s meter or less. Under these conditions, the propagation of the main dike would terminate as it intersects a drift and the main flow of magma would be through the drift until the dike re-establishes its upward propagation. The conditions that favor this scenario such as stress field, vapor pressure, magma volatile content, magma flow type, need to be determined in order to evaluate the probability of this scenario. This can be done with the type of numerical model described by the Panel in Chapter 3 and related appendices and mentioned above. This model and implications on the Panels conclusions are discussed in detail in the next section.

D. Eruptive characteristics and waste entrainment.

The Panel cites that the TSPA calculations are based on the assumption that the amount of waste that enters the atmosphere is equivalent to that from 10 canisters if the dike intersects a drift plus as many as 6 from the drift or about 100 if a dog leg scenario develops. These calculations assume a mean conduit diameter of 50 m centered on a drift. The Panel goes on to show how numerical models of conduit flow estimate a conduit diameter of 1-6 m from the mass flux for violent Strombolian eruptions. This diameter is an order of magnitude smaller than the observed range. The Panel suggests that the discrepancy indicates that only a small fraction of the cross-sectional area of the conduit is active during an eruption. Conduit observed in the field after an eruption, are likely created from multiple episodes of erosion, collapse and expulsion of wall material. The Panel recommends that more observations be made on eroded conduits. This reviewer recommends that field observations be made at fairly young conduits not just on the width near the surface but down into the upper meter or so of the conduit. Based on this reviewer's field observations of conduits that were active during the 1975-1984 Krafla fissure eruption in Iceland, the conduits were several meters in diameter and contorted such that if you looked down inside, the walls turned away suggesting that a canister 5.5 m long and 1.8 m wide may have a difficult time moving up the conduit. Observations made at Old Faithful in Yellowstone National Park (Kedar, S., Kanamori, H. & Sturtevant, B. *J. Geophys. Res*. **103**, 24283-24299, 1998) from images take by a camera of the upper few meters of the conduit would also assist in understanding conduit geometry with depth not just in cross-section near the surface. The other approach to determining whether observed conduits diameters are realistic is to constrain the conditions that favor these dike widths using the dike propagation model. Also, the dike propagation model should be used to determine how a secondary dike with the range of observed widths develops from a drift to form the dog-leg scenario and evaluate whether these conditions are realistic. If the assumption that the canisters are not completely compromised during contact with magma, then any intact canisters may not reach the surface due to constrictions along the conduit.

The TSPA calculations also assume that the canisters some how become breached and all waste material fragmented and emitted into the atmosphere via an ash plume. The Panel mentions that very little is known about how magma will interact with a canister and exposed waste material and if and how the waste material becomes fragmented. Fragmentation of basaltic magma is related to its fluid nature and expansion of exsolving gases. There is no mention of the type of fragmentation process for the waste material except may be grinding. If the magma is still fluid and is not an ash-gas mixture that may abrade the waste, then it would likely coat the waste material providing a protective layer. As mentioned by the Panel, it is often observed that large size pieces of wall rock that are ejected during an eruption are coated or encased with basalt and rarely show signs of fragmentation to the grain-size of the component materials. More studies are needed to better understand how the canisters will respond to magma and as the Panel mentions, possibly redesign the exterior of the canister to improve its integrity based on these studies.

F. Ash dispersal.

The Panel presented a review of ASHPLUME, the numerical model used in the project to estimate ash dispersal characteristics. Although the model considers many factors that govern transport and deposition of ash, it excludes factors such as thermal buoyancy, the effect of tephra fallout on plume density and thermal disequilibrium. The Panel suggested that ASHPLUME be compared with more recently developed ash dispersal models that account for these and other factors and compared to ash dispersal maps from analog volcanoes. This type of study should be conducted to obtain a more accurate estimate of ash dispersal characteristics.

5. Based on the Peer Review Panel and your own evaluation, what is the current status of the Woods et al (2002) model and its different components (e.g., generation of shock waves, the dog-leg scenario)?

The Panel concluded that the initial and boundary conditions in the Woods et al. (2002) model are not realistic. The conditions that they refer to are the 10 MPa initial fluid pressure entering the drift, the 1 m width of the dike that intersects the drift and the impermeable drift walls. They dismiss the first two conditions bases on classical dike propagation models that assume a tip cavity will be the first to intersect the drift. The intersection on a narrow tip cavity 100 m long will gradually pressurize the drift as the magma from the dike moves up into the cavity and enters the drift from near atmospheric to the magma pressure. They also state that the permeability of the walls will allow most gases from the crack tip to escape prohibiting pressurization of the drift by the gases.

There is still some degree of discrepancy between The Panel and those involved or associated with the Woods et al. (2002) model such as those at the Southwest Research Institute, over the pressure inside the drift. The pressure inside the drift will increase to the pressure of the fluid entering the drift. The initial fluid from the dike will be gases or fluid filling the tip cavity and will have a pressure on the order of atmospheric. Following the tip cavity fluid will be the magma column that will have a pressure gradient increasing from the tip cavity pressure to the static pressure of magma at 300-400 m. As mentioned by the Panel, viscous, unvesiculated magma at 300-400 m will have a pressure of approximately 10 MPa. Depending on the length of the tip cavity, it will take on the order of seconds to minutes before the magma column moves up and enters the drift and begins to fill and pressurize the drift. As the magma column moves up, the diameter of the dike intersecting the drift will increase to a diameter of about that of the static magma column. The pressure inside the drift will eventually reach that of the magma that may be as high as 10 MPa. Under such conditions, the dog-leg scenario may be initiated but whether it continues to propagate to the surface depends on its propagation rate and pressure in the tip cavity. Therefore, for the Panel to conclude that the Woods et al. model is unrealistic and that a dog-leg scenario has a low probability of developing may be too harsh. If the dike is narrow and the magma front is steep, then it is plausible to reach pressures as high as 10 MPa inside the drift as the drift becomes filled with magma from below the magma front. The Woods et al. (2002) model predicts higher pressures than that of static magma initially entering the drift, due to the reflection of the leading shock wave.

For a shock wave to develop ahead of the magma front, as is the case in the Woods et al. (2002) model, a pressure or density step is required at the dike-drift interface. For an idealize dike with a narrow crack tip, the initial entry of fluid from the dike will not generate a shock wave in the drift as the gases entering the drift are near atmospheric that is the pressure inside the drift and the diameter of the tip cavity would be much smaller then the diameter of the drift. If a shock wave some how did occur, it would likely dissipate as it moves through the drift by the elasticity and permeability of the walls and any dust in the air. These are factors not included in the Woods et al. (2002) model and would prohibit the increase of pressure inside the drift by a reflecting or resonating shock wave.

This reviewer highly recommends that a series of calculations be conducted that consider the full range of magma flow type related to its bubble fraction and related transport properties to obtain a more accurate representation of the pressure gradient inside the tip cavity and dike the instant of its intersection with a drift. The Panel outlined an approach for developing such a numerical model in Chapter 3 and related appendices and it should be followed. This approach involves a series of numerical simulations using a 2-dimensional axisymmetric fluid-mechanics computer code that would use fluid pressure, mass flux and thickness profiles from a dike propagation model that treats the fluid similarly (both compressible or incompressible) and includes the elasticity and permeability of the walls. By including compressible flow in the tip cavity that is gas rich, processes that do not occur in incompressible flow such as compression and rarefaction pressure waves, will develop when there is a pressure difference between the air in the drift and gases in the crack tip. If the pressure is lower that atmospheric in the tip cavity, then a compression wave may move into the tip cavity increasing the pressure to that of the drift. This increase in pressure may reduce the propagation rate of the crack tip. This result has strong implications on whether the crack will continue to propagate to the surface and the rate of propagation. The model should also include canisters to evaluate the forces subjected on the canisters by the flow. Results from these calculations would define the conditions that favor the dog-leg scenario and would provide a more accurate representation of the response of a drift to an igneous event. This reviewer strongly recommends that the development of more robust models as described above be a high priority in future DOE studies.

6. Are there any areas where additional investigation could provide significant benefit to our understanding of, and the estimation of, the risk from igneous activity at Yucca Mountain?

The aeromagnetic data available for the Project appears somewhat controversial in terms of correctly identifying buried volcanic complexes. It would be beneficial to identify the most controversial anomalies then the less speculative ones by drilling or other geophysical techniques. The option for drilling would provide samples of the anomaly that if volcanic can be dated. These data are important for improving the risk assessment of igneous activity at Yucca Mountain.