Review of Final Report of the Igneous Consequences Peer Review Panel", presented in Las Vegas, February 26, 2003

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Introduction

My comments and recommendations are assembled as responses to the questions posed by Leon Reiter. I have listed most of my recommendations under Dr. Reiter's final question 6, but some are bold-faced Italics in the text. An appendix summarizes the properties of Strombolian eruptions and scoria cones to help clarify the sometimes-obscure volcanological nomenclature applied to igneous consequence analysis at Yucca Mountain.

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

Background and General Comments. The principal function of the Panel was to review work so far done by DOE and its contractors to assess the consequences of igneous activity on the proposed Yucca Mountain Repository as part of the TSPA (Total System Performance Analysis). More precisely, what would be the consequences of a dike(s) intersecting a drift(s)? This issue was brought to the fore by a paper[1] and unpublished reports by Woods and others funded by the NRC-supported Center for Nuclear Waste Regulatory Analysis.

The most likely disruptive scenario will involve drift(s) intersections with a dike that will reach the surface, and centralize into a single conduit that will produce a scoria cone, probably lava flows, and Strombolian eruptions (see Appendix). This potentially will disrupt canisters, bringing some of their contents to the surface and some disrupted in drifts and thus accessible by percolating groundwater that eventually will reach the water table.

Of special concern is the potential movement of magma and/or disrupted magma (pyroclastic 'blast') down one or more drifts followed by a breakout – eruption – to the surface (the so-called dog-leg model). This scenario more than others would result in disruption of the largest number of canisters in the modeling. An important aspect

[1] Woods, A. W., S. Sparks, O. Bokhove, A.-M. LeJeune, C. B. Connor, and B. E. Hill, Modeling magma-drift interaction at the proposed high-level radioactive waste repository at Yucca Mountain, Nevada, USA, *Geophys. Res. Lett.*, *29*(13), 10.1029, 2002.

proposed by Woods et al.[1] involves generation of intense and probably disruptive shock waves in an intersected drift.

The Peer Review moved beyond its review function by performing a number of analyses and computations to examine specific issues about magma properties and the influence of the concentration of volatiles, especially of water and carbon dioxide, on these properties, and the mechanics of faulting. They also did innovative modeling of the effect of adding compressibility (usually rising magma is considered incompressible) due to exsolving bubbles in the magma of a rising dike as pressure decreases.

Qualifications of the Panel: Two panel members (Larry Mastin and Frank Spera) have published widely in my particular discipline (petrology, geochemistry, and volcanology) and their knowledge in these areas is extraordinary. Both these scientists made major contributions to the Panel's report and to the meeting presentations and discussions. The Panel included two members (Rubin and Detournay) who have researched the mechanics of the emplacement of dikes, a subject I am less familiar with and in places in the Report and in appendix 2 provide detailed mathematical treatments that are obscure to me. The final member and chair (Anthony Pearson) is an expert on fluid mechanics.

The disciplines covered by the Panel were sufficient to cover most of the questions posed to them to my knowledge with two exceptions noted under question 6.

Impartiality and Independence of the Panel. Those on the Panel to my knowledge would not benefit by the construction or abandonment of the proposed repository. I saw no evidence to neither minimize nor maximize potential hazards, but, to the extent possible, to produce an objective assessment of igneous consequences.

Overall Quality of the Report. The report, I believe, is of considerable value. It assesses the previous work, including the TSPA and the Woods et al. work, as well as providing starts in elaboration of igneous event consequences. The Panel is well aware of the difficulties in assessing quantitatively the results of igneous disruption: **"The Panel recognized that the consequences of most likely igneous events and their interactions with the repository are not obvious nor satisfactorily quantifiable"** (p. 7).

***Questions 2 and* 4**. I have combined these two questions, as they seem to flow together. *What, in your mind, are the most significant conclusions and recommendations of the Panel? Please review the analysis, conclusions, and recommendations in specific areas. The specific areas are: A. Volcanological setting, eruption chronology, and magma and rock properties. B. Dike propagation, significance of tip cavity, and dike/drift interactions. C. Dog-leg scenario and its likelihood. D. Eruptive characteristics and waste entrainment. F. Ash dispersal.*

Most Significant Conclusions and Recommendations

Total System Performance Assessment. ***The Panel's most significant conclusion, I believe, and in accord with its review function, is that the TSPA's conceptual model "is both adequate and reasonable."*** This model is that, in the unlikely event that a dike does reach the repository, the dike will intersect several drifts and produce eventually a single conduit that reaches the surface. Furthermore, the Panel views the numerical values of eruptive parameters as realistic to conservative. The Panel regards the TSPA model that all the canisters within three canister lengths of the conduit will be converted into small particles that become widely dispersed as "overly conservative"(bullet 5, p. 77). Given the uncertainties involved, I agree with the Panel's assessment that the TSPA ranges from realistic to overly conservative. In particular, total release of all HLW from all canisters in anyway involved in igneous activity is unlikely. Not all canisters will be heated to high temperatures (>600º C) and even the idea that the dike will effect an area as large as that in the TSPA, and that a dike will feed a long distance along a drift are controversial.

In this regard, Peter Swift, in charge of the TSPA modeling, asked the Panel and, I believe, the audience, if anyone could think of a scenario that was in fact worse than that in the TSPA model, in addition to the dog-leg model. No one added any serious new scenarios that could worsen the TSPA's worst-case scenario used in their modeling.

The Panel reviewed the volcanological processes and volcanic chronology of the Yucca Mountain region, and repeated the probability of disruption from previous PVHA work. They mentioned during the discussion "violent Strombolian eruptions" with a column height to 35 km. As pointed out by some of the audience, this seems unrealistically high, and is high based on the literature of eruptions likely to produce small scoria cones like those in Crater Flat (see Appendix***). I recommend more precision in the use of such terms as "violent Strombolian" and a careful scrutiny of the literature be continued as to the likelihood of what amounts to Plinian eruption column heights from eruptions of scoria cones the size of those in Crater Flat.***

The Panel stressed a number of analogies, including Paricutin and some others included in their appendices. This aspect of the review augments what was already well covered by earlier work.

I understand that the TSPA assumes that the integrity of any canister brought into contact with magma is totally compromised. Yet, a detailed assessment, as quantitative as possible, of the ranges of interactions is called for as well.

Dog-leg Intrusive Model. The so-called dog-leg intrusive model (Woods et al., 2002)[1] is the only possibility that could result in more release of waste than in the TSPA estimates. For example, a single diversion down a drift followed by eruption to the surface could release an order of magnitude more waste than the "typical" standard vertical intrusion. However, the Peer Review Panel believes that a dog-leg scenario, even a single one, is at least a magnitude less likely than a standard vertical intrusion. Thus, its effect is "small and more than offset by the level of conservatism built into existing estimates."(p. 77). However, the Panel had difficulty in resolving this issue and recommends that it be further evaluated.

Much of this analysis focuses on the properties of a low-pressure gas-filled tip that precedes the rising magma (the magma front) and its consequences on drift-dike interactions. The Panel defines the tip cavity as the "magma lag zone at the tip of a dike propagating in largely elastic rock … arises as a consequence of the large pressure drop required to force a viscous fluid through a slot of ever-decreasing thickness."

The properties of the tip have important implications on the conditions that a dike creates when it intersects a drift. Yet, these interactions remain difficult to predict. The Panel notes, though, that "Perhaps most importantly, as is shown below, there exist plausible conditions at Yucca Mountain for which the dike daylights at the ground surface before the magma front reaches the repository depth, thus greatly reducing the possibility of a dog-leg scenario." (p. 49). The Panel also notes that there will not be a sudden release of high pressure into the drift as suggested by Woods et al. Instead there will be a gradual increase in pressure because of the trip intersection, possibly ameliorating shock-wave development. Initial chilling (solidification) of the magma in a newly opened and thus "cold" fracture also will impede dike development at the far end of an intersected drift, a factor noted in the text and during the discussions.

The Panel notes that they have done this and a number of other analyses in a preliminary manner given the time constraints and limited scope of their charge. For this reason, they suggest that the DOE carry out additional numerical modeling. ***As the dog-leg and shock-wave scenarios are important, I support these recommendations.***

Interactions of the Panel with those deeply involved in the repository construction, especially those civil and mechanical engineers knowledgeable in the technical side of the construction would be fruitful and are called for. The Panel repeatedly suggests drift modifications, some of them seemingly simple, others not, that could ameliorate the consequences of igneous intrusion. I believe these suggestions ought to be carefully examined by those who can assess their feasibility and effects on other aspects of the repository (e.g. hot or cold).

Shock-Wave Generation. The Panel envisions that the tip cavity will be at low pressure, a pressure below the fragmentation pressure (the fragmentation pressure marks the transition from liquid-dominated flow below to gas-dominated flow above) of the magma. This may result in high gas and particle velocities as the magma front approaches the drift. The Panel recognizes two limiting cases of pressure increase at the intersection at the repository depth (p. 51):

Case 1. The tip cavity is expected to be on the "order of meters" in the presence of large (10 MPa) thermal stresses in the hot repository model, the dike aperture at the magma front on order of centimeters, and "the magma pressure behind the magma front to increase to the horizontal in-situ stress level over a distance of an order of meters. Under these conditions, the drift may be approached within seconds by magma that quite recently was at pressures exceeding 10 MPa; eruption into the drift may quickly become violent, but will be hampered by the small aperture of the dike." The calculated small aperture of the dike, in itself, will decrease the likelihood of shock waves.

Case 2. If the horizontal stress is a comparable to the present in-situ values of only a few MPa, pressurization of the drift will be slow, as the length of the tip cavity may be of order of 100 m." ***Thus, in both cases, formation of shock waves is unlikely***.

The Panel points out too that the large permeability of the proposed repository host rocks means that above the water table at about 600 m depth outgassing of the tip cavity into the host rock is very efficient. Assuming quasi-steady propagation in which the magma front moves at more-or-less the magma flow velocity behind the magma front, the permeability is too high by orders of magnitude to maintain pressures approaching 10 MPa proposed by Woods et al.

The work by underway by Edward Gaffney (LANL) in modeling of shock waves and other aspects of dike intersection is an important part of the shock-wave assessment.

In summary, the Panel deems the boundary conditions (magma eruption into the drift at a pressure of 10 MPa that is fed by a dike 1 m wide) of Woods et al. (2002), as unrealistically large.. ***I see no reason to challenge this view. I find the above arguments made above and elsewhere in the report convincing.*** Important to note again, though, that the Panel has concerns about the quantitative adequacy of its analyses.

Probabilistic Volcanic Hazard Analysis. "Old business" concerns an update of the PVHA based on additional magnetic anomalies that are most likely buried volcanic features. The Peer Review, as had NRC, recognized the importance that magnetic anomalies and their ages have on changing the probability calculations of dike intersection**.**

Ash Dispersal Models. Both NRC contractors and the TSPA use ash dispersal distributions and thickness based on the ASHPLUME model. The Panel recommends, and I strongly support, comparison with the results from other models, such as ASHFALL and AMS/HYPACT***. I don't expect great differences but I support the need for such comparisons.***

Thermal Stress Dike Diversions. As the drifts heat up ("hot" design) from the high-level waste packages after closing the repository, the drift walls will expand causing an increase in the stresses around them, creating in effect a "stress barrier" that may (1) deflect a dike, avoiding entry into a drift and (2) promote formation of a sill beneath the repository. The Panel suggests that this effect will begin a few years in individual drifts and will affect the entire repository after about 100 years, and lasting for 2000 years. In their assessment, they note that this is a relatively short period and in all their calculations ignore this effect. After 2000 years the repository will begin to cool down and thermal stresses will disappear in about 100,000 yrs.

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

I have included the response to this important matter in question 6.

Question 4. *See 2 above.*

Question 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)?* See 2 above.

The Panel's review, I believe, considerably lessens estimates of the likelihood of shock waves and the dog-leg model of Woods et al. (2002), for the reasons noted in questions 2 and 4 above. The Panel notes, however, that their analyses need additional examination by the TSPA modeling team.

Question 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?*

I have included must of my recommendations under this question:

(1) My principal concern is integration of disciplines in additional reviews of the TSPA and its addenda. Particularly, the comments of specialists in repository construction and canister properties concerning the Panel's suggestions and questions that involve their expertise may prove fruitful in ameliorating some of the consequences of igneous intrusion. The Panel's ability to deal with these two areas of their interest expressed at the meetings and in their report need additional investigation by a number of possible means, some as simple as additional workshops:

> (a) Arrangements to include discussions with a mechanical engineer(s) familiar with the strength aspect of waste packages and a metallurgist familiar with strength, thermal behavior, and corrosivity in acid solution of the alloys used in the packages would have allowed the Panel to deal more effectively with the interactions of the volcanic materials (magma, pyroclast, and gases) with the canisters.
>
> (b) Similar arrangements with a civil engineer(s) or equivalent intimately familiar with the construction options of the repository would add realistic input to suggestions about construction changes that would ameliorate the consequences of igneous intrusion.

It is important that these two aspects be integrated with the igneous consequence analysis. It may be that the TSPA modeling team plans to deal with these aspects in the areas suggested by the Panel, but it was not clear to me at the meetings that this would be the case.

(2) ***The work by underway by Edward Gaffney (LANL) in modeling of shock waves and other aspects of dike intersection to my knowledge is not complete and remains an important aspect of igneous consequence analysis. It is important that this work be completed and reported.***

(3) ***It is essential to an accurate PVHA that detailed magnetic surveys be conducted to reveal any new magnetic anomalies and at such a detailed level that edge effects in gradients may help reveal anomaly depths. Those deemed for whatever reasons top be < 5 ma old ought to be drilled to obtains samples for radiometric dating.***

(4) The Panel recommends that high-resolution radiometric dating be carried out to further constrain the fine-scale of the eruptive chronology and even eruption duration in Crater Flat. ***This could not hurt and may prove useful***. Because of sample contamination and analytical errors and precision I am not sure that the kind of resolution desired (e.g. 1 ka or less in 1 ma?) is realistically obtainable.