EPRI | ELECTRIC POWER RESEARCH INSTITUTE

28 February 2007

Dr. Michael Ryan, Chairman
Advisory Committee on Nuclear Waste
Two White Flint North
11545 Rockville Pike
Rockville MD 20852-2738

Subject: Electric Power Research Institute comments on the draft ACNW report: "Igneous Activity at Yucca Mountain: Technical Basis for Decision Making"

Dear Dr. Ryan:

I wish to thank the ACNW for providing EPRI an opportunity to make oral comments on the draft ACNW report at ACNW's recent public meeting on the subject. Attached please find a summary of the oral comments EPRI made at the February ACNW meeting, along with additional, more detailed comments on the draft ACNW report.

EPRI has also attached to this letter its preliminary response to a recent CNWRA publication that reviewed EPRI's Yucca Mountain igneous-related work conducted in 2004 and 2005. EPRI would like to provide the ACNW an oral presentation of its response to the CNWRA report at ACNW's earliest convenience.

If you have any questions on the attachments to this letter, please direct them to Dr. Meghan Morrissey, 303.385-2495 or mmorriss@Mines.edu

Sincerely,

jhk

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Attachments

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R. Yang (EPRI)

Attachment A:
Comments from the Electric Power Research Institute on the ACNW draft report on " Igneous Activity at Yucca Mountain: Technical Basis for Decision Making"

Citations are needed in the following lines:

Lines 134-136: Cite ICPR?

Lines 240-244 Please provide references to these State of Nevada documents where this 'suggestion' is made.

Lines 1339-1348 Can references be provided for these 8 letters?

Lines 1471-1472 Reference needed on these several tectonic models; McKague et al. 2006 perhaps?

Lines 1642-1644: Dike width is an important parameter and the source for values should be included

Lines 1697-1698 Reference regarding polygenetic cones

Section 3.3.2: Key features of dikes. This section needed references for the information one dike geometry, shape and propagation behavior.

Lines 1738-1740: This sentence mentions solubility of water in magma at depth and should include a citation for this.

Lines 1862-1865: A citation is needed for the values defining the difference for conduits and dike geometry. Is this a general statement or specific for Yucca Mtn – needs clarification?

Lines 2130-2132: References needed for the "geologic investigations" mentioned in sentence.

Lines 2322-2323: Reference for values of conduit diameter at surface and depth is needed.

Delete lines: 4142-4149 – This paragraph is repeated as first paragraph in Section 6.2.2.3.

Chapter-by-Chapter Comments

Executive Summary

Line 151 DOE, NRC and EPRI corrosion models all show most waste packages are relatively–to-completely intact for time scales on the order of 10,000 years to 100,000's years. And any early 'failed' packages are failed by localized corrosion, which would mean the strength of such waste packages would be largely unimpaired.

Line 156, Suggest replace 'detailed' with 'better'

Line 169 Should read "…based on a study of geological…"

Line 313 Suggest "…assumed in previous DOE and NRC analyses…"

Ch. 1

Fig. 1.2d: Suggest moving balloons titled waste fragmentation; contaminated ash; ash size; conduit diameter and # waste packages entrained come between igneous activity effects balloon and eruption effects and secondary eruption effects balloons.

Lines 1099-1101 (also Lines4238-4240) The ACNW rightly discussed 'reasonable assurance' and 'realistic scenarios' but fails to define these terms within the context of the igneous event scenario. For example, the DOE notes it has pursued a deliberate conservative approach (see lines 4096-4098). Furthermore. In Chapter 5, lines 3336-3337, it is noted that the NRC/CNWRA seem to be advocating a 'reasonably conservative' approach to the igneous scenario. Lines 3384-3386 and Lines 5027-5029 also touch upon this CNWRA (and DOE) tendency to focus on the upper, adverse parts of tails of distributions. Perhaps the greatest single source of disputes by all stakeholders with previous CNWRA studies is CNWRA's seeming adherence to the most conservative tails of ranges in properties and parameters. There is perhaps no more vital issue for the ACNW to address in this report than its own views and recommendations on how the regulatory requirements of 'reasonable expectation' and 'reasonable assurance' ought to be applied to the igneous event scenario. Right now this seems to be a missing piece in the ACNW report.

Lines 1240 (also later line 2142 and lines 2774-2776) Care should be made here. The assumption that the design (the 'footprint') of the repository might affect the event of intersection probability is based on one specific model, that magma ascent and potential intersection of dike length with a repository is not influenced by either structural control or topography. While the topography effect may be minimal (although we concur with lines 1730-1731), the ACNW report in numerous sections notes the strong evidence for structural control (see referenced papers by Fridrich et al. 1999, McKague et al. 2006 (a CNWRA report cited on lines 1383-12388), and Parsons, Thompson and Cogbill 2006, for example. If structural control of ascent and intrusion/ eruption location, then the probability of a future igneous event intersecting a repository well away from such structural features (including Solatario Canyon Fault) would NOT increase if the areal footprint of the repository were expanded.

Ch. 2

Okay as is.

Ch. 3

Section 3.2.1 line 1590 – Magma genesis could be discussed more as it was well discussed in the last PVHA-U workshop. There are several papers published years ago on trace element geochemistry that support magma mixing at greater depths than Pliocene volcanoes in YMR and smaller batches of magma.

Section 3.2.3 line 1668-1669: We suggest that this sentence be deleted as it could be argued that eruptions are Nature's way of releasing heat from its interior. Cone build up is well described in the next sentence and should be used as the topic sentence to discuss how deposition sequence has been used to identify processes in the magma column prior to eruption. Furthermore, this would be an appropriate section to discuss the expected eruption sequence at Lathrop Wells and how that may be used to infer the sequence of potential magma-drift interactions.

Section 3.2.3 EPRI encourages ACNW to include the 'Reasonably Expected' Volcanic Scenario for a future eruption in Yucca Mountain based on the sequence of eruptive deposits at Lathrop Wells basalt center (the best analog) as a series of bullets such as:

- Fissure eruption, fire fountains and *aa lava*
- Strombolian eruptions - cone building phase and tephra ejection
- *Aa lava* flows

Section 3.2.3 line 1696: This paragraph is a bit confusing. Stromboli is polygenetic, Quaternary YMR volcanoes are monogenetic. We suggest that the sentence in lines 1695-1696 be moved after the sentence that it follows (that ends with … are also uncommon.).

Line 1719 Dike velocities of kilometers per second?

Section 3.3.4 line 1813 EPRI encourages ACNW to recognize the work by EPRI (2004; 2005) on magma viscosity in which EPRI suggest viscosities several orders of magnitude greater than values used by DOE and NRC in modeling of lava flowing into drifts. Also, line 1818 – Reference to EPRI intrusive scenario should be EPRI (2005) rather than (2004).

Lines 1835-1846 Here and in a few other places (lines 3451-3456) the ACNW report touches upon the so-called 'dog-leg' scenario. Both the ICPR and EPRI analyses suggest that such a dog-leg geometry developing at the repository level is highly unlikely. However, the views/ analysis of the ACNW on this important sub-case (the occurrence of a dog leg might directly affect the number of packages contacted and erupted to the surface in the Woods et al. 2002 models, having a proportional effect possibly on dose consequences) are not clearly presented or summarized in the ACNW report. Based on all of it independent analysis of magma physics and eruption dynamics, what is ACNW's judgment on the dog-leg variant case?

Section 3.4.1: We encourage ACNW to read the section on ash dispersal analysis that EPRI conducted in 2004. In the EPRI report (2004) the Suzuki model (discussed on pages 52-53 of the white paper) is compared to other well used tephra dispersal models and demonstrates that essentially no reparable size ash. We encourage ACNW to mention results from these other models.

Section 3.4.2 (also Section, 6.3.4 Lines 4800-4814 and Lines 4859-4867) A very interesting and risk-significant figure was presented by Dr. Coleman at the ACNW meeting that is not part of this section of the ACNW report. It appears that between TPA 3.0 and TPA 4.0 versions, the CNWRA staff shifted the expected particle distributions for UO2 to LOWER values, whereas the test data on breaking UO2 would suggest the distribution of UO2 particle size should have been shifted to HIGHER values. This is an absolutely critical topic, and the information presented by Dr. Coleman at the ACNW meeting should be include in this section, with appropriate added text.

Ch. 4

Section 4.2: ACNW mentions throughout the paper that the selection of appropriate volcanic analogs is important because use of analog characteristics has implications not only for understanding and bounding magmatic processes, but also in correctly estimating potential consequences of magma disruption of a repository. However, there is no mention of criteria for selecting an appropriate analog. EPRI proposed the following criteria in paper presented at the IHLRWM 2006 conference (see attached paper) based on similar criteria proposed by DOE at the 2005 PVHA-U workshop:

1. Magma composition is alkali basalt with 1.9-4.6 wt% H_2O and < 3 vol. % phenocrysts of olivine, amphibole and/or clinopyroxene.
2. Monogenetic scoria cone.
3. Total eruption volume < 0.01-0.6 km^3
4. Extensional tectonic setting

Section 4.3.2 The use of vent throughout the white paper (e.g. line 2163) should be restricted to when referring to the surface expression of the conduit. In other words, a vent is where magmatic material enters the atmosphere from a conduit or exit plane of a conduit. Vent diameter should not be confused with conduit diameter. Conduit diameters should be described as a function of depth since DOE has demonstrated with its recent fieldwork in and around the Yucca Mountain region (e.g. Pauite Ridge) that conduits decrease in diameter with depth. Is a minimum dike width of 2-4 m reasonable for the small volume of a potential eruption at Yucca Mountain? ACNW only recognizes this near the end of it paper; it should be mentioned in the executive summary and in this section.

EPRI encourages ACNW to consider the dike model in Fig. 3.1 as defining a dike as a single event. A series of conduits (vents) located along a fissure should not be counted as separate events in PVHA type calculation.

Lines 2459-2460, 2481-2484 It would be welcomed if the ACNW integrated these two issues of conduit size and number of conduits into a risk-importance context. The number and long-term dimensions of continuously flow conduits feeding surface vents directly affects the number of packages possibly degrading and/or being erupted to the surface. Assuming no dog-leg or filling of all emplacement drifts initially intersected by the initial rising dike, relatively few waste packages will ever see continuous magmatic conditions during an igneous event.

Ch. 5

Section 5.1: Waning of basaltic volcanism in YMR followed by a ~1 Myr period of no volcanism as discussed by Bruce Crowe in ACNW presentation and 2006 PHVA-U workshop.

Section 5.1: EPRI encourages ACNW to include the 'Reasonably Expected' Volcanic Scenario for any future eruption in Yucca Mountain based on the sequence of eruptive deposits at Lathrop Wells basalt center (the best analog):

- Fissure eruption, fire fountains and *aa lava*
- Strombolian eruptions - cone building phase and tephra ejection
- *Aa lava* flows

Line 2739 Should this sentence read "..DOE in its evaluation of probability does not consider…"?

Lines 2862-onward This is a good beginning to a section that might be expanded to address the topic of 'reasonable assurance' vs. 'reasonably conservative' approaches.

Line 2949 Suggest "Connor et al. (2000) hypothesize that…" They can hardly' report' on something that is this hidden/buried and speculative.

Section 5.5 Given the number of strong and adverse comments made by some scientists against the use of 'prediction' and 'validation' and Karl Popper philosophy, it might be better to change "Prediction Methods' to "calculation Methods". In line 3014, "The ability to predict future volcanic activity is uncertain." is a good example.

Lines 3078-3082 In other places the ACNW deconstructs and comments on models by DOE, CNWRA and EPRI, yet there is no analysis of comments on whether ACNW agrees with these speculative scenario by the State of Nevada. Either this ACNW report should comment on all important stakeholders' studies or not comment on any.

Lines 3643-3645 Based on what all US stakeholders (DOE, NRC/CNWRA, State of Nevada, EPRI, ACNW) have presented on a future igneous event at Yucca Mountain, this notion of studying bimodal basaltic-rhyolitic volcanism seems outlandish and unsupported. Perhaps the ANCW report should gently rebut such this specific NEA suggestion?

Ch. 6

Lines 4063-4072 Who is the 'we' that is referred to? ACNW? Prof. Marsh? Use of personal pronouns can be a matter of taste, but this one section sticks out awkwardly compared to all other sections in which the personal pronoun is omitted.

Section 6.2.1.3 There are now a huge 11-orders of magnitude range of proposed viscosity values cited, ranging from 100 poise (Woods et al, 2002) up to ACNW's value of 10^{13} poise (line 4008). The EPRI range of 10^5 to 10^8 seems to bridge the ranges proposed by the CNWRA at the low end and the range proposed in the ACNW report at the upper end. Hopefully, the final ACNW Conclusions will clearly address this viscosity topic and set forth what it believes is a credible range in viscosity and the implications of this range.

Lines 4237-4240 This observation and caution about potentially missing important processes should highlighted. Also, there does not seem to be any independent ACNW analysis directly addressing quenching of magma against drift walls and waste packages; are such independent analyses planned and will they be included in this report?

Lines 4444-4447 This states a very important opinion, and while references are cited, it is not entirely clear what is the basis for this statement. While EPRI agrees with this statement, it would be helpful if text were added to clearly explain why is there 'no chance' that the Woods et al. (2002) analysis is correct.

Lines 5004-5507 This text somewhat misses the point (or ignores the possibility) that there may be little or no radioactive material in the ash to be remobilized and "significantly affect airborne radioactive particle concentrations for the RMEI". The entire ash dispersal and remobilization analysis are the last steps in the analysis, and it might be prudent to at least note that earlier steps/ mitigating factors may have significantly diminished the potential amount (or concentration in particles) of radioactive material available for remobilization.

Attachment B:
EPRI's preliminary response to NRC's "Review of Two Electric Power Research Institute Technical Reports on the Potential Igneous Processes Relevant to the Yucca Mountain Repository"

EPRI's technical reports in 2004 and 2005 describe the sequence of expected igneous events for both an extrusive and intrusive event, respectively. The report also includes analyses of certain stages of the sequence of events that EPRI considers relevant to the performance of the potential repository at Yucca Mountain. The two reports were recently reviewed by the Nuclear Regulatory Commission (NRC). The two NRC reviewers (Drs. Stephen Sparks and Andrew Woods) focused on three aspects of these reports: (1) the nature and evolution of the magma as it enters the drifts; (2) the thermal conditions of the magma and waste packages in the drifts; and (3) the dynamics of magma flow into the drifts. EPRI has gone through the review and discusses and clarifies below several salient points that EPRI believes have been misinterpreted by the two reviewers.

NRC Views
In Section 2 (Nature of Magma in the Drift), the reviewers believe EPRI asserts that the magma at the tip of the ascending column just prior to and at the point of intersection with the repository will be degassed. Furthermore, the reviewers believe EPRI asserts that magma rising from depth (>> repository depth) will have a viscosity of 10^5 Pa-s. The reviewers demonstrate (Section 2.1) using solubility equilibrium relations of water in magma as a function of depth that magma at repository depths will have < 1 wt% H_2O thus is in direct contradiction with their assumed definition of EPRI's degassed magma. The reviewers go on to demonstrate (Section 2.2) how exsolved volatiles form bubbles and how those bubbles will be prohibited from rising through an ascending magma that has a viscosity of 10^5 Pa-s thus prohibiting the magma from degassing. The reviewers continue this argument in Section 2.3 with a statement that EPRI's "intruding magma will likely be a volatile-depleted, viscous magma with a low bubble fraction and a rheology characteristic of an *aa* lava flow is largely unsupported by the condition govern exsolution". The last paragraph of this section asserts that EPRI believes magma initially entering the repository that was just intersected by the dike tip will be quiescent. The reviewers go on to state that analogs of monogenetic cinder cones start off with an intense jetting-style of explosive discharge and that effusive discharge of lava flows erupt continuously throughout these eruptions.

EPRI's Rebuttal to Section 2:
In EPRI's 2004 technical report, a conceptual model for dike ascent (Ch. 3) and potential future eruption is described based on the geology and physical volcanology described in published DOE, NRC reports (i.e. OCRWM, 2003; Detournay et al., 2003). EPRI's dike ascent model follows the approach described in the final report from the Igneous Consequence Review Panel (Detournay et al., 2003) that describes a leading crack tip that is under vacuum (</= 0.1 MPa) connected to the ascending magma filled dike. In this model, the low pressure inside the crack tip lowers the pressure at the magma front or tip of the magma column thus following magma-H_20 solubility relations as well stated by the NRC reveiwers, H_20 will exsolve from the magma near the tip of the magma column

to a concentration in equilibrium with the pressure of the crack tip. This is EPRI's definition of a degassed magma (relative to 4.7 wt% H_20). This process would indeed produce a degassed magma at the tip of a magma column. However, EPRI also goes onto describe the sequence of expected eruptive events (bullet #6 pg 3.17 and Ch. 4 Introduction pg 4-1 and Section 4.1.1) for a potential future eruption at Yucca Mountain. Below the tip of the magma column, magma is vertically gradational with respect to volatile content and bubble fraction.

EPRI***'s*** conceptual model is based on the physical volcanology observed at Lathrop Wells and other Quaternary basalt centers in the Yucca Mountain region (Ch. 1 in EPRI, 2004 and in EPRI's paper presented at IHLW '06). The general sequence of expected eruptive events is as follows (from Valentine et al., 2005): Initial cone building stage that includes fissure eruption, lava fountains and aa lava flows and the final cone building stage that includes Strombolian eruptions with continuous tephra ejection and aa lava flows.

As stated on pg 4-1 (EPRI, 2004), EPRI believes that "the type of flow regime that develops as magma rises in a dike dictates the eruption style at the surface … Understanding the range of eruptive styles that occur at the surface during a basaltic eruption allows the type of activity expected inside the drift to be inferred." Figure 1 shows EPRI's conceptual model for the active or fluid portion of the dike. At this stage of the model, the initial eruptive phase is expected to be a fire fountain or spray of magma. Lava fountains are thought to be driven by an annular flow regime that is characterized by a continuous gas phase flowing out of the fissure at velocities greater than magma located along the margins of the fissure. This flow regime is expected near the top of the magma column below the degassed tip that intersects the drift (Fig. 1). Below the annular flow regime is a slug flow containing large pockets of released gases from ascending magma. Slugs form by bubble coalescence as they rise in basaltic magma. This is the flow regime that is thought to produce Strombolian eruptions (cone building phase). The slug flow regime grades into a foam-flow regime that is characterized by 70% volume fraction of gas bubbles (Fig. 1). These bubbles will fragment into a mixture of gas and ash. This flow regime is thought to produce violent Strombolian eruptive events. At the base of the magma column is the bubbly flow regime (Fig. 1). This regime produces the effusive lava flow phase of the expected eruption. As well stated by the NRC reviewer, magma with a viscosity of 10^5 Pa-s ascending from depths greater then the repository would not be capable of producing rising and coalescing bubbles as required for the previously described flow regimes. EPRI has stated in 2004 and 2005 that the portion of magma that produced the aa flows at the surface at Lathrop Wells has a viscosity of 10^5-10^7 Pa-s (Sec. 2.1 last sentence in first paragraph). EPRI has never stated or assumed this viscosity range for all magma in the entire dike system – we do not assume a uniform rheology for magma filling the dike.

EPRI's 2006 model (see attachment) suggests that a dike in the Yucca Mountain region is expected to be non-uniform both laterally and vertically with respect to rheology. Magma with the lowest viscosity is expected in the active or the widest part the dike (Fig. 1) and more crystalline viscous magma is expected along the outer regions or the thinner parts of the dike. The lateral variation in magma properties will produce in general two different styles of expected activity upon entering a drift. Magma may either be a mixture of gas and fragmented clots of magma characteristic of a lava fountain phase (non-crystallizing liquid in which volatiles are being released) or a mixture of crystals and liquid characteristic of *aa* lava (crystallizing magma relatively depleted in volatiles). We refer the reader to the attached paper (Attachment C) entitled "Conceptual Model For Defining Natural Analogs for Future Yucca Mountain Volcanism And Expected Consequences" for more detailed description of EPRI's current model utilizing recently published data from DOE (i.e. Valentine et al., 2005). EPRI will be reviewing additional papers recently published by DOE in 2006 and 2007 as we continue to develop our conceptual model based on field observations made in the Yucca Mountain region.

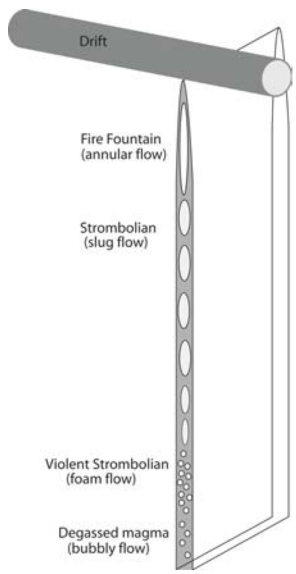

Fig. 1: Conceptual model of flow regime in magma filled dike prior to intersection with a drift (not to scale). White areas denote gas phase and grey denotes liquid magma.

NRC Views

In Sections 3.1-3.2, (Development of a Chilled Layer and Magma Solidification), the reviewers believe that EPRI asserts that metallic objects will not be thermally damages by lava flows and radiative cooling dominates cooling in subsurface drifts. The reviewers describe work be other scientists that have demonstrated how radiative cooling is the dominate heat transfer mechanism for cooling the surface of lava flows and airbourne lava fountains. The reviewers go to discuss solidification of magma in a dike though which magma is flowing upwards in the center and the margins are cooling by conductive heating with the wall rock. The reviewers believe that flow through a dike is analogous to flow through a drift and that this contradicts EPRI's idea of flows terminating in a drift before it is filled.

EPRI's Rebuttal to Sections 3.1-3.2:
As stated by the reviewers and illustrated by Bruce Marsh in his presentation to the ACNW in February 2007, magma that touches a colder metallic object will form a chilled crust at the contact surface. EPRI too believes that when magma comes into contact with a cool body (p. 4-5 in EPRI, 2004). As described in the first paragraph of Section 3.3.2 in EPRI (2005), using the base curve from a calculation in which heat transfer at the base is by conductive cooling. As stated on page 17, " The time-temperature profile at the base shows that a rapid 200-300^{0}C temperature drop occurs within the lower 1 m of a 7 m a basalt within 10 days upon contact with a cool substrate." EPRI has never stated that radiative cooling is the main mechanism for cooling a lava flow. The termination of a lava flow in a drift in EPRI's model is associated with crystallization of the lava as it enters a drift and decompresses from 10 MPa to 0.1 MPa. This decompression of a volatile depleted (<1 wt.%), crystallizing lava will likely enhance crystallization thereby increase that lavas viscosity thus slowing and terminating further movement.

NRC Views
In Sections 3.3 (In Drift Thermal Calculation), the reviewers acknowledge the use of TOUGH2 code for EPRI's thermal calculations. The reviewers list the assumptions in EPRI's calculation that includes heat conduction as the main heat transfer mechanism and that the temperature profile used in consistent with DOE's in a similar calculation. The main argument by the reviewers is that the assumptions of the model were difficult to follow. The reviewers list deficiencies on the model that mostly relate to including convection as another mode of heat transfer and phase changes. The reviewers state that EPRI's approach "is not representative of observations made a volcanoes and that the conclusions are inconsistent with fundamental physics and chemical processes."

EPRI's Rebuttal to Sections 3.3:
EPRI's approach followed that by DOE in OCRWM (2003). As stated on page 19 of EPRI (2005), "less newer, more representative data for the basaltic magma of a potential igneous event should be substituted for the more conservative data assumed by OCRWM (2003)." In particulate a lower eruption or emplacement temperature was used compared to that used in OCRWM (2003). EPRI acknowledges the lists of deficiencies that the reviewers gave and may consider them in other thermal calculations designed to simulate those conditions.

NRC Views
In Section 4 (Magma Dynamics), the reviewers state that the thermal and heat transfer analysis in EPRI's flow analysis does not appear to be consistent with fundamental physical and chemical processes at volcanic eruptions. The main criticism is that EPRI does not provide sufficient information to assess the numerics of the simulation such as numerical scheme, spatial and temporal discretization and details of the computational grid. The reviewers comment that the geometric condition of the dike and the drift cannot be adequately modeled as a nozzle flow problem and there is no rationale provided to explain the significance of the divergent feature in the dike geometry.

EPRI's Rebuttal to Section 4:

EPRI clearly states that the simulations were set up using the geometry of for calculations published in Woods and others (2002) and Bokhove and Woods (2002). As shown in Fig. 2, the one-dimensional model is the configuration used by the reviewer. EPRI used the same dimensions and geometric shapes for both the dike and drift from the Woods and others (2002) model. As shown in Fig. 3, the only difference is that EPRI moved the dike to a vertical orientation that EPRI deemed more reasonable (EPRI, 2004). EPRI did use a steam rich fluid however the physics are essentially the same. The main difference (assuming the Woods and others (2002) model included it) is the heat transfer between fragmented magma that would create more vapor phase then the initial conditions, the fluid is more compressible than an ash-gas mixture which would reduce the propagation speed of pressure waves moving through the subsonic flow regions and magma mixture-air interface (Morrissey and Chouet, 1997). The main effect of a single phase is the magnitude of parameters; the physics remains essentially the same. EPRI believes that the result from using the 2-dimensional – vertical dike- configuration is more important to understanding the physics of magma-drift interaction. As stated in EPRI (2004, p.4-20), "Results from the 2-dimensional re-analysis of the Woods et al. (2002) model demonstrate that at high-pressure gradients between the dike and drift, the original dike would be expected to propagate to the surface. This is because the significance of the vertical flow is that it creates a high-pressure (stress) region at the top of drift immediately above where the dike intersects the drift. These localized stresses far exceed what is necessary to open or create a fracture in the roof of the drift that will enable the dike to continue propagating upward. This favors the original dike as the main pathway for magma to reach the surface."

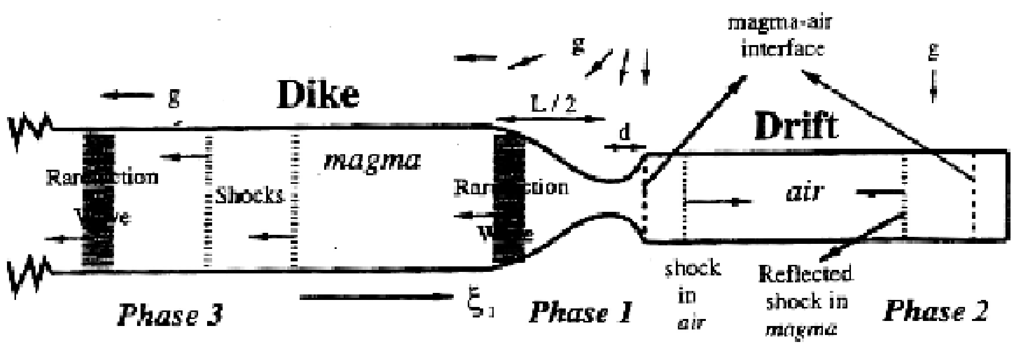

Figure 2 (Fig. 4-1, EPRI, 2002): Computational configuration of the Woods et al. (2002) model (taken from Figure 3 in Bokhove and Woods, 2002).

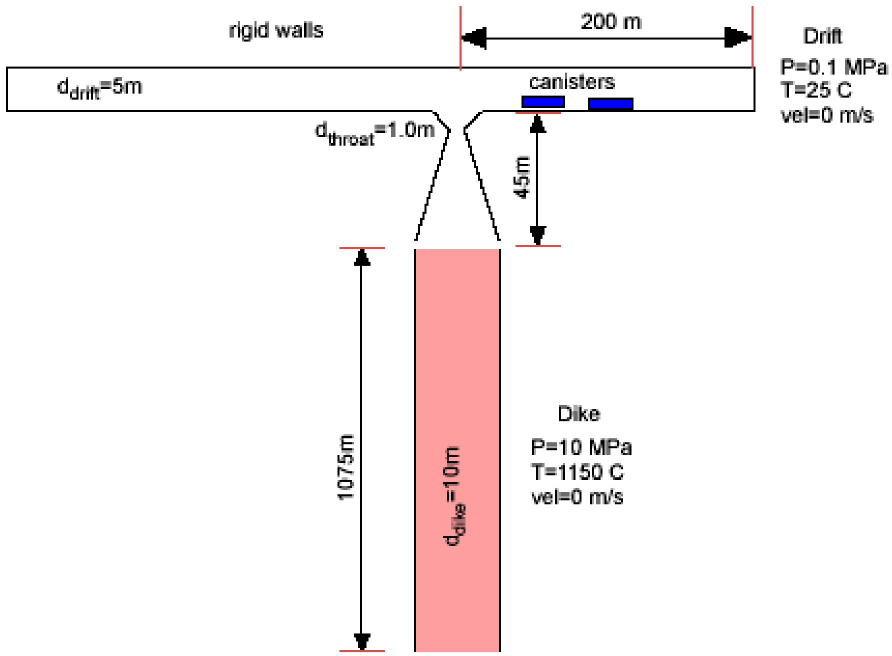

Figure 3. Schematic cross-section of dike intersection with emplacement drift (Fig. 3-3, EPRI, 2004).

References:
Bokhove, O. and A. Woods (2002) – Draft copy of "Explosive magma-air interactions by volatile-rich basaltic melts in a dike-drift geometry."

Detournay et al. (2003). Final Report of the Igneous Consequences Peer Review Panel. pp. 86.

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Valentine, G., D. Krier, F. Perry, and G. Heiken 2005. Scoria cone construction mechanism, Lathrop Wells volcano southern Nevada, USA. Geology 33: 629-632.

Woods, A.W, S. Sparks, O. Bokhove, A. LeJeune, C. Connor, and B. Hill 2002. Modeling magma-drift interaction at the proposed high-level radioactive waste repository at Yucca Mountain, Nevada, USA. Geophysical Research Letters 13.

Attachment C: Conceptual Model For Defining Natural Analogs for Future Yucca Mountain Volcanism And Expected Consequences

Meghan M. Morrissey

Addendum to EPRI 2006 Internal Report on Igneous Events

Introduction

This report presents an updated version of EPRI's conceptual model for a possible future (< 10^6 yr) igneous event at Yucca Mountain from which natural analogs are defined. The most credible and defensible basis for assigning characteristics to a postulate future volcanic eruption at Yucca Mountain is the geological evidence from recent volcanic events in the region. Field observations and petrologic data (Crowe et al., 1988; Perry et al., 1998; Nicholis and Rutherford, 2002; OCRMW, 2003; BSC, 2004; Valentine et al., 2005) made at basalt centers found in YMR that include Thirsty Mesa, Amargosa Valley, southeast Crater Flat, Buckboard Mesa, Quaternary basalts of Crater Flat, Sleeping Butte, and Lathrop Wells, suggest that a future eruption in YMR will likely be a typical basaltic fissure eruption where < 0.1 km^3 of magma could reach the surface. Lathrop Wells basalt center is considered the best example of a natural analog of a future eruption in the Yucca Mountain region, YMR. EPRI continues to support the hypothesis that any magma that erupts in the Yucca Mountain region within the next 10^6 year will be a low volume (< 0.1 km^3) water bearing, crystallizing basaltic magma with an eruption temperature between 975-1010^{o}C. The expected series of eruptive events for a future igneous event in Yucca Mountain within the next 10^6 yr would be comparable to that at Lathrop Wells basalt center. Recent data published by DOE and academic institutes (i.e. Nicholis and Rutherford, 2002; BSC, 2004; Valentine and others, 2005) on Lathrop Wells basalt center have provided new insight on the interpretation of the eruption history at the center. The report is divided into two sections: summary of Lathrop Wells volcanology and inferred eruption history, and expected scenarios for a future eruption in the Yucca Mountain region.

Figure 1: Geologic setting of the Lathrop Wells basalt center (Fig. 2.8 in Perry et al., 1998). Lathrop Wells main cone (denoted by Qbs within the dark grey area) is located along two sets of fissure (cross-hatched lines). Stars mark sites where distal fall deposits have been found (Perry et al., 1998). Mt and Pb identify locations where Miocene tuff and Pliocene basalt are exposed.

I. Summary of Lathrop Wells Physical Volcanology and Eruption History

Physical Volcanology

The Lathrop Wells basalt center (0.09 km^3; Fig. 1) consists of a large scoria cone and three or four sets of fissures marked by accumulations of spatter, bombs and scoria deposits that represent eroded smaller cones (possibly 3-10 small scoria cones (Crowe et al., 1988)). Multiple eruptive events occurred along two sets of fissures that extend 0.2-2 km. The main scoria cone (Lathrop Wells cone) is 140 m high and has a base of 875 m by 525 m and is roughly 0.018 km^3 in volume. Based on data from a recent petrologic and field study of deposits at Lathrop Wells (Valentine et al., 2005), it has been suggested that the cone may have been built from several distinguishable eruptive events occurring essentially in two phases. The first phase (Fig. 2a) produced the lower portion of the cone (0.006 km^3) comprised of lapilli and bomb sized scoria, ribbon and spindle shaped bombs meter in length (Valentine et al., 2005). This phase began with a fire fountain event that produced a thin (1 m) scoria deposit at the base on the cone containing mostly sideromelane clasts (quenched reddish-brown glass). Overlying this sideromelane rich layer are 4-5 layers of coarsening upward tachylite (crystalline clasts) rich layers (lower portion of the cone) suggesting pulsating eruptive events. The south (0.015 km^3) *aa* lava flow (Fig. 2b) is thought to have occurred contemporaneously with the initial cone building stage. The second phase was the upper cone-building stage that was accompanied by a sustained eruption column from which 0.04 km^3 of mostly tachylite tephra was produced (Fig. 2c). As noted in Valentine et al. (2005), the contact between the upper and lower cone deposits is sharp suggesting a dramatic change in emplacement and eruption mechanisms. The lower cone deposits appear to dip both inward and outward and have characteristic features of grain avalanches (Valentine et al., 2005). The upper cone deposits appear to mantle the lower deposits characteristic of emplacement from fall out and are finer grain then the lower cone deposits (Valentine et al., 2005). The upper cone-building stage also emitted the northeastern (0.015 km^3) lava flow (Fig. 2d). The last eruptive event was a small hydrovolcanic event. The hydrovolcanic event is thought to involve a shallow groundwater source in particularly water stored in the alluvium or sand ramp deposits or pre-volcanic surficial deposits (BSC, 2004).

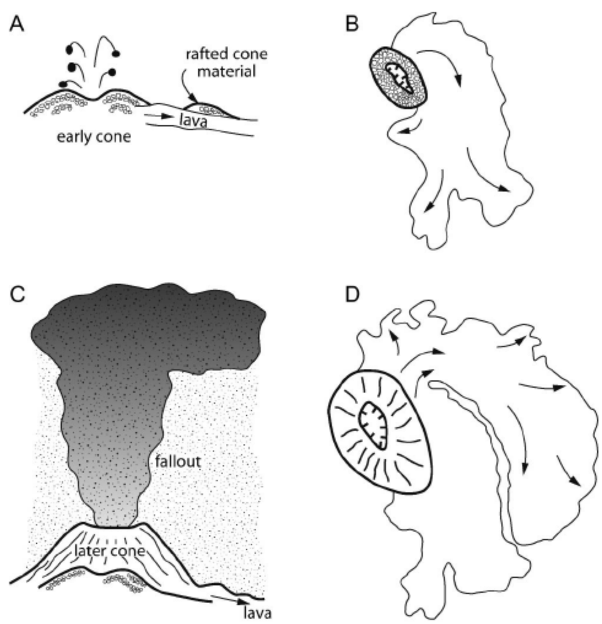

Figure 2: Schematic of (a-d) four possible eruptive events for the main cone at Lathrop Wells basalt center (Valentine et al., 2005).

Clast Analysis

Clast component analyses of scoria deposits from the two phases provide a method for assessing the magma ascent history. For instance, magma that was transported to the earth's surface rapidly then fragmented and quenched while airborne produces reddish-brown basaltic glassy clasts known as sideromelane. Sideromelane droplets are thought to be products of energetic lava fountains or Hawaiian eruptions (Heiken and Wohletz, 1985; BSC, 2004). Magma that was transported to the earth's surface slower and/or stopping along its way will crystallize producing crystalline clasts known as tachylite. Tachylites pyroclasts are microcrystalline textured fragments of basalt that have been described as "quenched crystal" textures (Heiken, 1978). A significant number of samples from scoria deposits at Lathrop Wells were collected and analyzed for clast components by DOE (BSC, 2004). Six different clast types were identified in each sample (BSC, 2004): tachylite, glassy tachylite, sideromelane and crystals (broken olivine, amphibole and/or feldspar phenocrysts) or lithics (tuff or carbonate). Results from this study (BSC, 2004) show that the earliest material erupted produced mostly sideromelane clasts whereas material erupted during the lower and upper cone building phases produced mostly tachylite clasts.

Crystal size measurements of both phenocrysts (> 1 mm) and microlites (< 0.01 mm) can be used to determine ascent rates from results from decompression petrologic experiments (Cashman, 1992; Geschwind and Rutherford, 1995). Isothermal decompression experiments can determine the pressure and temperature conditions of crystal phase equilibrium observed in tephra and lava samples. A study of this type was conducted on tephra and lava samples collected at Lathrop Wells (Nicholis and Rutherford, 2004). According to Nicholis and Rutherford (2004), most of the Lathrop Wells samples contain < 2-4 vol% phenocrysts of olivine and amphibole. The phenocrysts assemblage along with the known water content of < 4.6 wt.% from previous experiments (Luhr and Housh, 2002) suggested a phenocryst-melt equilibrium pressure and temperature of < 175 MPa and 1010^{o}-$975^{o}C$, respectively (Nicholis and Rutherford, 2004). Plagioclase (An_{69}) is found rarely as microphenocrysts (>0.1 mm) in a crystalline groundmass (microlites) of plagioclase (Nicholis and Rutherford, 2004). The experiments determined that to achieve the crystal size range of the plagioclase microlites observed in the samples, an ascent rate of > 0.04 m/s is required for magma with < 4.6 wt % H_2O (Nicholis and Rutherford, 2004). Equilibrium conditions can also be determined from reactions rims of amphibole (water-bearing mineral) crystals that are very reactive with the liquid phase of magma (melt). The rims of amphiboles in Lathrop Wells' samples suggest a short-lived residence time at a depth roughly 800 m below the surface. At this depth, amphiboles react with the liquid phase of magma to produce the reactions rims visible on amphibole phenocrysts (Nicholis and Rutherford, 2004).

Lathrop Wells Eruption History

The above mentioned petrologic and field data are used by EPRI to derive an eruption history and a magma plumbing system for the Lathrop Wells basalt center. EPRI's eruption history is divided into two phases as recognized by DOE from field deposits (Valentine et al., 2005). Within each phase, a series of eruption styles are described that correspond to eruption products at Lathrop Wells basalt center described by DOE (BSC, 2004; Valentine et al., 2005). The first eruptive phase begins with a series of fissure eruptions that lasted only a few days that transitioned to focused eruptions where the main cone is located. This phase includes the lower cone building deposits and *aa* lava found to the south of the cone. The lower cone building eruption is thought to have formed from Strombolian eruptive events whereas the *aa* lava was eruptive effusively (non-explosive, less energetic than the Strombolian events).

As note by Valentine et al. (2005), the lower cone deposits have characteristic features related to an emplacement and eruption mechanism modeled by McGetchin et al. (1974) as ballistic trajectories of hot fluid fragments of magma. The travel distance is not sufficient to solidify large fragments (bomb size) such that partially welding of ejected material occurs. The model (McGetchen et al., 1974) also considers the accumulation of scoria as rim deposits that may develop into grain avalanches. This model appears to be applicable to the lower cone deposits and is commonly used to describe scoria cone formation. The second phase includes the northern lava flow and the final cone-building event that produced a sustained ash column (Valentine et al., 2005). As note by Valentine et al. (2005), the upper cone deposits have characteristic features unrelated to the ballistic emplacement model (McGetchin et al., 1974). They propose that the magma in the later stages was likely more viscous and fragment similarly to more silicic magmas thus producing the sustained column of finer grain tephra (Valentine et al., 2005).

II. EPRI's Interpretation of the Magma Plumbing System at Lathrop Wells

The magma plumbing system (Figs. 3A-3B) during the first phase is inferred from the relative amount of sideromelane and tachylite clasts found in the respective pyroclastic deposits and crystal content of lavas following a similar approach taken by Corsaro and Pompilio (2004) at Mt. Etna. Lathrop Wells basalts are thought to have originated from 7-8 km depth and transported through the crust in a system of dikes (ICRP, 2002; Nicholis and Rutherford, 2004). Magma that reached the surface first and erupted along the fissures was essentially crystal poor associated with lava fountains. Magma erupted at this time (Fig. 4) is characterized as fragments of molten magma carried by exsolved gases as an annular flow or dispersed flow (Verniolle and Manga, 2000) and was likely partially depleted in volatiles (< 1 wt% H_2O; Holloway and Blank, 1994). This interpretation is based on the presence of sideromelane clasts (quenched glass basalt) found in deposits at the base of the lower portion of the cone (BSC, 2004). To form quenched glass, magma ascended rapidly through the dike to inhibit the formation of microlites then cooled rapidly as it erupted at the surface during the lava fountain phase. The later part of the lower cone building event erupted more crystalline magma based on the predominate appearance of tachylite in the samples from deposits from the lower portion of the cone (BSC, 2004). Magma that reached the surface during the later part of the lower cone building event may have ascended slower allowing crystals to begin nucleating and growing in magma. Tachylite pyroclasts are also thought to form from quench crystallization of fragmented basalt that becomes clogged in the vent during a

Strombolian eruptive event (Heiken, 1978). Unlike magma that erupted along the length of the fissure, magma associated with lower cone building Strombolian events erupted from a point source along the fissure. Strombolian style of eruption (characterized by ballistic spatter bombs) are thought to be produced by the expansion and bursting of gas slugs (Fig. 4) at the surface or vent produces the (Verniolle and Manga, 2000). Gas slugs form in rising magma from exsolved volatiles that form bubbles and rise through magma and coalesce to form larger bubbles (slugs) when the bubble fraction reaches at least 70% (Verniolle and Manga, 2000). Slugs are thought to be separated by regions of magma containing bubbles (Verniolle and Manga, 2000).

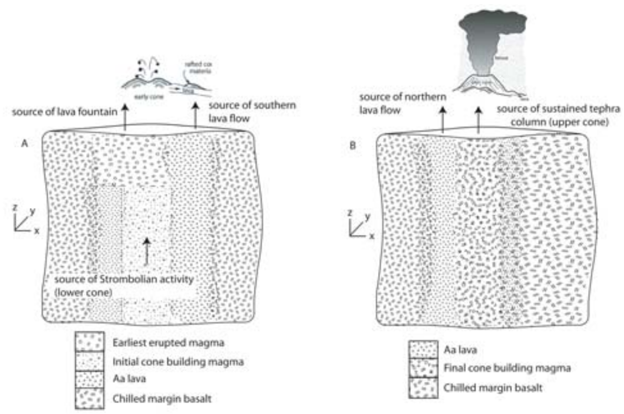

Fig. 3: Schematic drawing of EPRI's conceptual model of the magma plumbing related to the Lathrop Wells basalt center (not to scale).

The transition from a fissure eruption (lava fountains) to a point source or conduit eruption (Strombolian) is thought to occur when magma cools to near its solidus temperature along the dike where the thickness is < 2 m (ICRP, 2003; Delaney and Pollard, 1982). Magma erupted at the surface from the thicker or wider portion of the dike would produce Strombolian activity (Fig. 3A). The contemporaneous occurrence of Strombolian activity and *aa* lava extrusion suggest a lateral variation in crystallization and bubble content along the length of the dike at depth. These two processes are controlled in part by cooling rates. Lava likely extruded from a thinner portion of the dike adjacent to where the conduit developed (Fig. 3A). The thinner regions of the dike (< 2 m) conductive heat loss at the wall rock will induce crystallization of magma (Delaney and Pollard, 1982; Carrigan, 2002) and as magma crystallize it will become more viscous eventually reaching a critical crystal content at which it freezes (Delaney and Pollard, 1982). Exsolved volatiles (bubbles) in magma in the thinner regions of the dike may either move into less viscous magma located in the thicker, hotter, less viscous part of the dike or be released into permeable wall rock.

The second phase includes the northern lava flow and the final cone-building event that produced a sustained ash column (Valentine et al., 2005). From the observed reaction rims on amphiboles from Lathrop Wells samples (Nicholis and Rutherford, 2004), magma erupted during this time may have resided at depths of 800 m for a few days. At this depth, basaltic magma moving up from depth containing < 4.6 wt% H_2O would exsolve at least half of its H_2O (Holloway and Bank, 1984). The slow ascent or stalling of magma in the lower portion of the conduit (Fig. 4) would allow for the formation of microlites as suggested by the tachylite textures in eruptive products associated with this phase. The presence of crystals in magma would increase the viscosity. The ascent from 800 m would exsolve volatiles that would rise at the same rate as the magma (more viscous then earlier magma) thus forming a bubbly or homogenous fluid (Fig. 4; Sparks et al., 1997). As this magma approaches the surface volatiles will continue to exsolve and the magma will begin to fragment into an ash-gas mixture when the bubble fraction reaches roughly 75% (Wilson et al., 1980). The formation and behavior of bubbles in this later more crystalline magma would be similar to that in a silicic magma (Valentine et al., 2005). This process would explain the sustained eruption column (Valentine et al., 2005). During this phase of the eruption, more crystalline degassed magma (< 1 wt% H_2O; Holloway and Blank, 1994) is brought up to the surface at the northern end of the cone producing the later lavas.

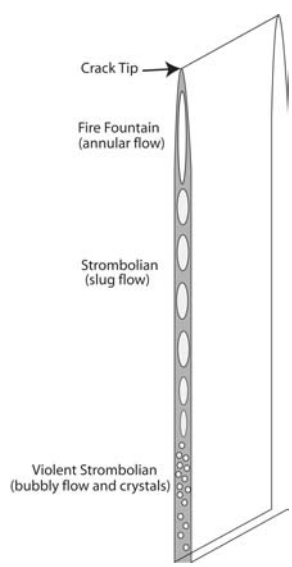

Figure 4: Conceptual model of the change in bubble content with depth in the magma column for Lathrop Wells. Not to scale.

EPRI's interpretation of the magma ascent history at Lathrop Wells becomes important when developing a conceptual model for possible eruptions in the Yucca Mountain region and analysis of dike-drift interaction. Previous models for dike-drift interaction assume magma entering a drift would have a viscosity of the order 1-10 Pa-s capable of filling all drifts and access drifts eventually creating secondary dikes from which magma will erupt at the surface (Woods et al., 2002). Such a model requires that all magma associated with a future eruption at Yucca Mountain remain essentially crystal-free throughout its ascent. As noted in the clast analysis of Lathorp Wells basalt samples, crystallinity of erupted material varies from quenched glass products (sideromelane) that is essentially crystal free to tachylite and crystalline lava that contain abundant microlites. Therefore, a crystal-free magma does not accurately represent Lathrop Wells magma.

Viscosity

In this section, we calculate the viscosity of magma in the conceptual model of the magma plumbing system suggested by the previously described field observations and petrologic data of Lathrop Wells basalts. An apparent viscosity (η) of magma containing crystals of any size may be estimated by the Einstein-Roscoe (McBirney and Murase, 1984):

$$\eta = \eta_o(1-R\phi)^{-2.5}$$

Where η_o is the initial crystal free viscosity, ϕ is the crystal fraction, and R is a constant with a value 1.67. The apparent viscosity for Lathrop Wells basalt is estimated using 2-4 vol. % for the initial crystal content constrained by the phenocryst content (< 2-4% olivine and amphibole). Values for the initial crystal free viscosity are available from experimental data for crystal-free, alkali basalt containing up to 5 wt. % H_2O (Cas and Wright, 1987) and at four temperatures 800°C, 1000°C, 1200°C, and 1400°C (denoted in Fig. 5 by vertical column of respective symbols). Also shown in Fig. 5 (solid black line) are the viscosities for H_2O depleted alkali basalt at temperatures between 1100°C to 1500°C (Murase and McBirney, 1973). Figure 5 demostrates how the exsolution H_2O in basalt increases the viscosity by 1-2 orders of magnitude depending on temperature (McBirney and Murase, 1984). For example, in Fig. 5 at 1000°C and 5 wt. % H_2O the viscosity is approximately 40 Pa-s and at 0 wt. % H_2O the viscosity is 800 Pa-s.

We calculate viscosity as a function of crystal content using the Einstein-Roscoe equation for a basalt magma at repository depths assuming basalt is crystal free and contains 2 wt% H_2O yielding an initial crystal free viscosity of 110 Pa-s. Results from this calculation are shown in the inset figure of Fig. 5. For basalt containing 2 wt. % H_2O, the presence of crystals in basalt increases the viscosity by < 5 orders of magnitude from 1.1 x10^2 Pa-s to ~6.0 x 10^6 Pa-s from a crystal content increasing to 0.6. Lava flows tend to terminate their advancement when the crystal content reaches a critical value 0.55-0.6 (Marsh, 1981; Griffiths, 2000).

For the types of magma rheology (Figs. 3a, 3b and 4) interpreted for the plumbing system at Lathrop Wells Figure 5 is used to estimate the viscosity for each magma rheology. EPRI considers 40 Pa-s to be a reasonable viscosity for magma ascending from source depth (7-8 km) at Lathrop Wells. As the magma ascend through the crust it will exsolve volatiles and as it does its viscosity will increase as shown in the black crosses in Fig. 5 assuming magma remains crystal free (Lathrop Wells basalts do contain a negligible amount of phenocrysts, 3-4 vol.%). Magma erupting in the first phase as lava fountains and Strombolian events will likely have a viscosity on the order of 10^2 Pa-s. Magma erupting as lavas will contain some volatiles (< 1 wt% H_2O; Holloway and Blank, 1994) and will be crystallizing therefore the viscosity will range from 10^3-10^5 Pa-s with the presence of bubbles from exsolving volatiles increasing the viscosity by up to an order of magnitude (ICRP, 2003). EPRI considers 10^3-10^6 Pa-s to be a reasonable range of viscosities for lava at its eruption temperature of 975-1010^{o}C. Viscosities will increase several orders of magnitude as the lava cools and crystallizes (Griffiths, 2000; Lore et al., 2002). A reasonable viscosity for magma before it erupted as a sustained eruption column may be at least 10^3-10^4 Pa-s accounting for microlites and bubbles in the magma.

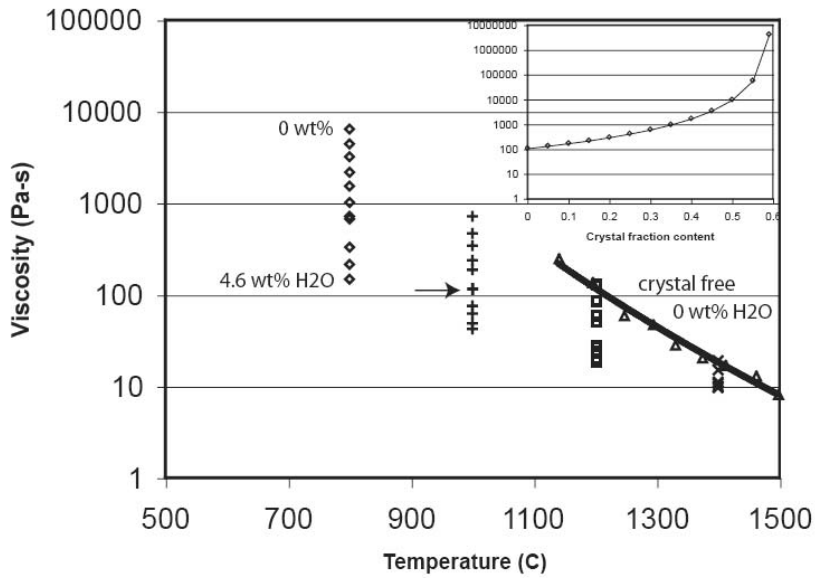

Fig. 5: Viscosity as a function of temperature and H_2O content for crystal free basaltic magma (Cas and Wright, 1987). Inset is viscosity as a function of crystal content calculated using Einstein-Roscoe equation with a crystal free starting viscosity denoted by the arrow (Griffiths, 2002).

III. Expected Igneous Consequences Scenarios

The expected extrusive igneous consequences are described in 5 stages. The expected consequences are based on the interpreted eruption history for the Lathrop Wells basalt center.

Extrusive Release Scenarios

Stage 1: Intersection of dike with drift

The first stage of the model considers the ascent of magma through the crust to depths of the proposed repository (300-400 m). The expected sequence of events during magma ascent is based on linear elastic fracture mechanic models for dike propagation (Lister, 1999; Rubin 1995). As discussed by the Igneous Consequence Review Panel (ICRP, 2003), the expected interaction of an ascending sheet dike with a repository drift would involve a < 0.2 m width and 100-200 m long crack tip propagating ahead of the magma filled dike (Fig. 6). Table 1 lists the range of values of characteristic parameters for dikes in the YMR. The ascent rate or propagation rate of a dike has been estimated from decompression experiment to be > 0.04 m/s (Nicholis and Rutherford, 2004). The maximum ascent rate observed at fissure systems in Hawaii and Iceland is 10 m/s (Lister, 1999; Rubin 1995) that provides the upper bound in Table 1.

The width of a future dike in YMR is expected to be < 4 m at depths below 100-125 m from the surface (BSC, 2004). Dike width with respect to depth is constrained from recent field observations of dikes and conduits at monogenetic volcanoes in Nevada and New Mexico (BSC, 2004). Dikes are believed to reach the surface with widths < 4.0 m. As flow activity along a dike (fissure) concentrates at points along the fissure, conduits develop. Magma rising through a conduit will begin to erode the walls by several mechanisms (e.g. thermal erosion, spallation (Valentine and Groves, 1995)) to diameters as large as 125 m, however these diameters develop only in the upper 100-150 m of the surface (BSC, 2004). In EPRI's model, conduit diameters on the order of >10s m are not expected below 100-150 m.

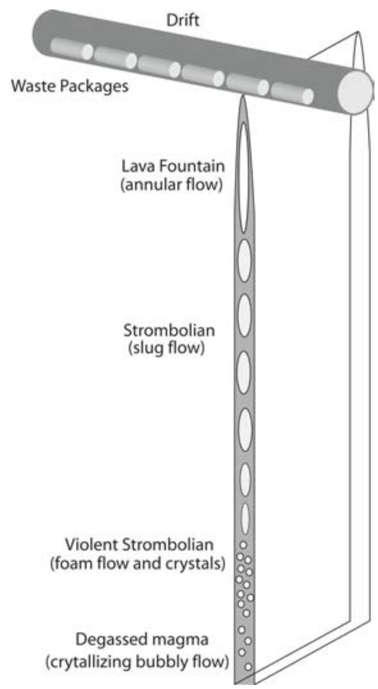

Figure 6: Conceptual model of the change in bubble content with depth in the magma column prior to intersecting a drift. Not to scale.

An important part of the conceptual model is the geometry of the crack tip and dike because it provides initial conditions for modeling dike-drift interaction. According to linear elastic models for dikes expected in YMR (ICRP, 2003), the width of a crack tip is expected to be < 0.2 m and when magma reaches the drift the dike will expand to 1.5 m, the mode width of dike found in YMR (OCRWM, 2003). The number of drifts that will be intersected by the dike will depend on the lateral extent of the dike that is expected to be 0.5-5.0 km (Crowe et al., 1983). Following the initial intersection of the dike with a drift, the ascending dike tip can be expected to reach the ground surface above a repository in a matter of minutes (ICRP, 2003; BSC, 2004).

Stage 2: Initial stage magma-drift interaction

Magma that first reaches the repository (Fig. 6) is expected to be similar to that interpreted for the first eruptive phase at Lathrop Wells. EPRI's model suggests that a dike in the Yucca Mountain region is expected to be nonuniform both laterally and vertically with respect to rheology. Magma with the lowest viscosity is expected in the center or the widest part the dike and more crystalline viscous magma is expected along the outer regions or the thinner parts of the dike. The lateral variation in magma properties will produce in general two different styles of expected activity upon entering a drift. Magma may be either a mixture of fragmented magma and gas characteristic of a lava fountain phase or crystallizing magma relatively depleted in volatiles characteristic of *aa* lava. The former type of magma would produce a spray of pyroclastics (scoria, spatter and ribbon bombs) into a drift thereby potentially bombarding and coating waste packages with magma (d1 in Fig. 7A-7B). Spray of magma onto waste packages is not expected to damage waste packages (EPRI, 2005). The latter type of magma would produce a slow moving crystallizing lava flow inside the drift (d2 in Fig. 7A-7B). The lava flow will have a viscosity of 10^3-10^6 Pa-s and will likely flow over or around waste packages forming a chilled margin upon contact with a waste package. Waste packages would be entombed in crystallizing magma (d3 in Fig. 7A-7B).

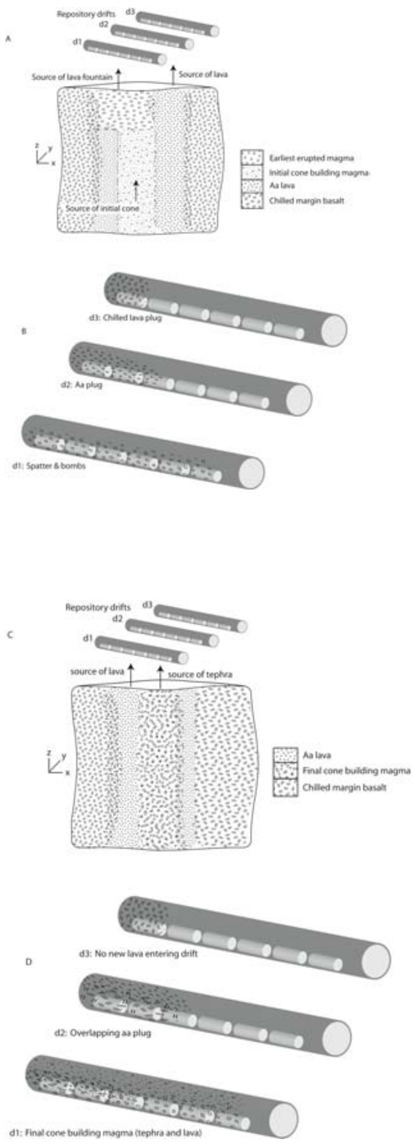

Figure 7: Conceptual model for magma-drift interaction during the (A-B) first three stages and (C-D) and last 2 stages. Not to scale. d1, d2, d3 denote three drifts located along different region of the drift. This model will be refined as new data is made available by DOE and other agencies.

Stage 3: Initial fissure eruption

Magma that is not diverted into the drift will follow the crack tip and make its way to the surface. Magma will erupt at the surface along the fissure as a curtain of lava fountains. The initial width of the dike will be that of the crack tip (< 10 cm) and will gradually increase to 4.0 m the maximum width of fissures in the YMR (OCRWM, 2003). This phase will last hours to several days (ICRP, 2003; Delaney and Pollard, 1982), then eruption activity will localize to 1-3 locations along the fissure.

Magma in the dike will be laterally and vertically gradational with respect to volume fraction of exsolved volatiles, crystallinity and liquid magma as interpreted for Lathrop Wells basalt (Figs. 3A-3B). *Aa* lava that occurred contemporaneous with the initial cone-building phase at Lathrop Wells suggests that part of the magma in the fissure-conduit system was crystallizing and volatile depleted. Therefore, a lateral temperature gradient is expected from the margin of the dike to the center. Assuming that the width of the dike varies laterally, then it is expected that the conduit or cone building part of the eruption would develop at the widest part of the dike where cooling rates are lowest. Lava is expected to erupt along thinner parts of the dike where temperatures are lower due to high rates of heat loss by contact with the wall rock. Volcanic activity is expected to cease along the thinnest (< 1 m wide) parts of the dike within 10 days when temperatures are at or below the solidus temperature due to conductive cooling for alkali basalts similar to Lathrop Wells basalts (ICRP, 2003).

TABLE 1: Summary table of dike characteristics at basaltic centers in the YMR - [ ] denotes mean values (EPRI, 2004).

Width (m)	0.3-4.0 [1.5]
Lateral extent (km)	0.5-5.0
Ascent rate (m/s)	0.04-10 [1]
# Dikes	1-10 [3]
Spacing (m)	100-690
# Vents per dike	1-10 [2-3]
Conduit diameter (m) at surface	1-50 [10]
Conduit diameter (m) at 300 m	1-4

Stage 4: Formation of conduits and central vents

Within hours to 10s days from onset the fissure eruption at the surface will cease and activity will be focused at 1 to 3 conduits (ICRP, 2003). At the repository, drifts that contain spatter and other pyroclastic deposits from an earlier stage, and are connected to the center or the widest part the dike, may be inundated by a bubble-magma mixture (Fig. 6 and d3 in Fig.7C-7D). In other drifts that contain spatter or pyroclastic material or lava and located within the narrow regions of the dike crystallizing magma may move into drifts filling space not occupied by volcanic materials (d2 in Fig.7C-7D).

At the surface, material not diverted into the drift will likely produce an ash plume capable of transporting ash > 20 km from the vent to the regulatory compliance boundary. The expected volume of scoria deposited from this phase is 0.01-0.048 km^3 (this includes the fraction of ash size material transported in the plume away from the cone, violent Strombolian event).

During this stage of the eruption, erupted magma may contain radioactive material, either as entrained UO_2 or as radionuclides dissolved into the magma, from the waste packages damaged by the initial interaction with the dike (EPRI, 2004). The mechanical processes that would result in the most damage to the waste packages include the impact of fragments of wall rock and magma from the initial intrusion of the dike into a drift. Thermal erosion of a waste package may arise if a package gets caught in the upward flow of magma. This process may affect at least 1 waste package (1.8 m diameter, 5.0 m length) and possibly two, depending on the width of the dike (0.3 - 4 m) and the location of the dike intersection relative to it.

The amount of radioactive material that may contaminate the magma depends, in part, on the size of the conduit and how magma interacts with waste packages during this prolonged stage (EPRI, 2004). The expected conduit width at future YMR basaltic eruptions is < 4 m at the repository depth (BSC, 2005) and at depths < 100 m the conduit is expected to flare to diameters > 10-50 m (e.g., Piaute Ridge and Basalt Ridge (BSC, 2005)). Waste packages cannot be transported to the surface if the conduit widths are < 2 m. The size of any intact waste package (1.8 m diameter, 5.0 m length), assuming it could be lifted by the flow of magma, will restrict magma transport through a fissure. This constriction in the fissure and sluggish flow of magma will lead to rapid solidification of the dike in this constricted region. Thus, it may be reasonable to suggest that waste packages would only be able to be transported to the surface in dikes with widths at the upper end of the range of YMR dikes (2-4 m).

Stage 5: Final stage magma-drift interaction

The final magma-drift interaction scenarios involve relatively degassed, crystallizing magma. Magma diverted into a drift may overlap earlier *aa* lava that entombed or covered waste packages if there is space otherwise the drift will be sealed off from additional magma (d2 in Fig.7C-7D). If additional magma does enter, this later lava flow is not expected to completely fill the drift. Another scenario is a drift that already is closed off to the conduit by a chilled lava plug (d1 in Fig.7C-7D). No additional lava is expected to enter these drifts.

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Attachment D:

NATURAL ANALOGS FOR FUTURE VOLCANISM IN THE YUCCA MOUNTAIN REGION

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I. INTRODUCTION

EPRI’s TSPA of the extrusive-release and intrusive-release scenarios depend strongly on identifying natural analogs for a potential future eruption [1,2]. The two release scenarios require estimates of parameters such as number of dikes, dike length and widths, conduit diameter and extent, number of conduits, and volume and duration of each eruption stage, that characterize the expected eruption. To obtain a range of values for characteristic properties representative of a future eruption, natural analogs are needed. This work presents a set of criteria for selecting natural analogs for a possible future eruption in the Yucca Mountain region.

EPRI considers the Lathrop Wells basalt center, as the best example of a natural analog of a future eruption in the Yucca Mountain region, YMR. Lathrop Wells is a Quaternary basalt center located within the Crater Flat basin, an alluvial filled graben (Fig. 1). This basalt center consists of a large scoria cone and three or four sets of fissures marked by accumulations of spatter, bombs and scoria deposits that represent eroded smaller cones (possibly 3-10 small scoria cones [3]). The Lathrop Wells scoria cone is 140 m high and ~ 700 m in diameter. There is also a scoria fall layer that blankets the cone and is found several kilometers away from the cone [4]. Small volume *'A'a* flows extend from several of the fissures. The total volume of material erupted is estimated at 0.086-0.1 km^3 as listed in Table 1 along with the mass and volume totals from the various eruption phases [4].

Table 1: Data for Lathrop Wells basalt center from [4].

Magma composition	Alkali basalt	< 3 vol.% Olivine phenocrysts
Water content	1-4 wt%	
Tectonic setting	Extensional	
Dike length (km)	< 2	
	volume (km^3)	***mass (kg)***
Scoria cone	0.018	1.8×10^{10}
Tephra fall	0.039	3.9×10^{10}
'A'a lava flows	0.029	8.7×10^{10}
	0.076	1.44×10^{11}

The composition of Lathrop Wells basalt is alkali basalt (potassic trachybasalt) containing sparse (<3vol. %) olivine phenocrysts. Other basalt centers that occur within the Crater Flats basin are Little Cones, Red Cones, Black Cone and Makani (Northern) Cone. These Quaternary centers have similar magma compositions and eruption volumes as Lathrop Wells basalt center.

Published field observations (i.e. [1,6,7]) made at the Quaternary aged analog basalt centers in YMR strongly indicate that a future eruption, if it were to occur in the Yucca Mountain region, may be a monogenetic basaltic eruption. A typical eruption sequence may start with fire fountains and lava flowing out along a segment of a fissure or set of fissures (dikes), followed by Strombolian activity at conduits along the fissures [8,9]. During the Strombolian eruptive phase, multiple scoria cones may build up and scoria-fall deposits may blacket the surrounding area. The final eruptive phase of the eruption may be characterized by effusive 'A'a lava flows to possible tephra dispersal.

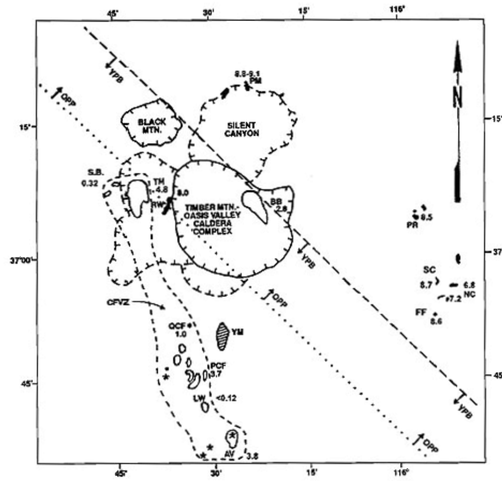

Fig. 1 Locations of basalt centers in the YMR: TM: Thirsty Mesa, AV: Amargosa Valley, PCF: Pliocene Crater Flat, BB: Buckboard Mesa, QCF: Quaternary Crater Flat, SB: Sleeping Butte, LW: Lathrop Wells, RW: Rocket Wash, PM: Pahute Mesa, PR: Pauite Ridge, SC: Scarp Canyon, NC: Nye Canyon, FF: Frenchman Flat. Dashed line encloses the Crater Flat Volcanic Zone. Asterisks mark aeromagnetic anomalies [5]. Numbers shown are the ages of the basalt centers in million of years. Taken from [5].

II. CRITERIA FOR NATURAL ANALOGS

The following quote provides the basis for defining criteria for a natural volcanic analog for a future eruption in YMR. As stated in [10], "magmas may eruption as coherent lavas and then flow coherently or fragment during flow, or the may erupt explosively to form a range of pyroclastic products. At the time of eruption the volcanic products may range in character from pure magmatic liquid to essentially solid. If the erupted material flows, either as a coherent mass or as a particulate mass flow, then the original character of the erupted material will control the form and mobility of the resulting deposit." The original character of erupted material refers to the physical state of magma in the conduit or fissure prior to erupting. The physical state of magma reflects the composition, water content, crystal content, and temperature of magma. These four properties are used as part of the criteria for defining a natural analog for future YMR volcanism.

Other important criteria for a natural analog are volcano type and tectonic setting. Volcano type refers to whether the volcano is polygenetic (erupted repeatedly) or monogenetic (erupt only once) [11]. Polygenetic volcanoes (i.e. stratovolcanoes or central volcanoes) are in general, larger than monogenetic because they are built up by multiple eruptions. These volcanoes tend to have a larger and continuous supply of magma than monogenetic volcanoes. Monogenetic volcanoes (i.e. cinder or scoria cones) are small in size and supplied by small batches of magma [11]. Monogenetic cinder cones tend to occur as clusters of volcanoes forming a volcanic field in an extensional tectonic setting [12].

As previously mentioned, EPRI believes that the < 10,000 year old Lathrop Wells basalt center represents the best analog to a possible future eruption in Yucca Mountain.

OCRWM [4] also considers the Lathrop Wells center to be the best example of an analog for potential future eruptive events in the Yucca Mountain region. The OCRWM report provides abundant data on the characteristics of the deposits of this volcano and the criteria that could be useful for TSPA type calculations. In contrast to the Lathrop Wells center, the older basalt centers in the Crater Flat basin are deeply eroded and poorly-exposed [13], although they, too, provide valuable predictive data for other parts of the igneous scenario analysis. Lathrop Wells, however, is representative of the largest monogenetic basaltic eruption eruptions that might be anticipated in the future around Yucca Mountain. Features of the Lathrop Wells basalt center are used to define the criteria for selecting natural analogs to future eruptions in the YMR.

The following criteria are used to identify appropriate natural analogs in this study:

1. Magma composition is alkali basalt with 1.9-4.6 wt% H_2O and < 4 vol. % phenocrysts of olivine, amphibole and/or clinopyroxene.
2. Monogenetic scoria cone.
3. Total eruption volume < 0.1 km^3
4. Extensional tectonic setting.

In addition to magma composition, phenocryst phases and water contents are included in this list of criteria. These two parameters constrain the eruption temperature that is a governing factor of eruption style. Lathrop Wells basalts along with all basalts < 1.1 Ma in YMR (Table 2), are characterized by a crystal assemblage exclusively of olivine and some contain clinopyroxene and/or amphibole. Plagioclase phenocrysts are rare in these basalts. Plagioclase does occur in these basalts as microcrysts or groundmass crystals indicating that these grew at shallow depths during rapid decompression.

The absence of plagioclase as a phenocryst phase with olivine indicates a lower liquidus temperature or eruption temperature (975-1010^{o}C) then if plagioclase was present [14, 15]. An eruption temperature of 975-1010^{o}C yields a viscosity for basalt of 10^2-10^3 Pa-s whereas an eruption temperature of 1100-1200^{o}C yields a viscosity of 1-10 Pa-s [16, 4]. The different viscosities tend to favor different eruption styles. EPRI believes phenocryst assemblage to be vital criteria for selecting an appropriate analog to a Strombolian eruption in YMR. Therefore EPRI's analog criteria include aphyric texture (< 4 vol% phenocrysts) and phenocrysts of olivine and amphibole (or clinopyroxene).

III. NATURAL ANALOGS

We evaluate volcanic centers such as Grants Ridge, Paiute Ridge, Alkali Butte and Paricutin that have been proposed as analogs to intrusive and extrusive igneous features at YMR. Each volcanic center is discussed in terms of its limitations and YMR criteria for a good analog.

Eruption duration and power of an expected violent Strombolian eruption play key roles in ash transport calculations. Observations made during the 1944-46 eruptive phases at Paricutin volcano in Mexico and during several of the 1992 eruptive phases at Cerro Negro in Nicaragua have been used to obtain values for eruption duration and power for analog violent Strombolian eruption in YMR [17]. Eruption power (Q) is defined by the eruption column height (H): $H=8.2Q^{0.25}$ [17, 18]. Maximum durations selected by DOE for an expected violent Strombolian eruption at YMR include the 1944 and 1946 eruptions at Paricutin. These two eruptions were observed to last 75 days yielding >10^{12} kg of tephra. The 1992 violent Strombolian eruption at Cerro Negro lasted 73 days and yielded >10^{12} kg of tephra. The Lathrop Wells violent Strombolian eruption yielded 10^{10} kg of tephra. The violent Strombolian phases at Paricutin and Cerro Negro yield eruption masses that exceed the analog criteria. In addition to eruption mass, Paricutin volcano is an uncertain analog because of magma composition (Table 3). Paricutin magma is a compositionally zoned basaltic andesite. Cerro Negro is also an uncertain analog because it is polygenetic (Table 3). It has a relatively continuous supply of magma compared to Quaternary monogenetic YMR basalt systems.

DOE describes four analogue sites to identify subsurface structures related to magmatic processes in the upper 100 m of a basalt conduit system [21]. These include East Grants Ridge in NM, Paiute Ridge, Basalt Ridge, and Basalt Ridge "East" in Nevada. East Grants Ridge is part of the Mount Taylor volcanic field. It is an erosional remnant of an alkali basalt volcano from which over 2-3 km^3 of lava was erupted [22]. The plug is 125 m wide and appears to represent a dissected scoria cone and feeder conduit [22]. DOE uses the 125 m diameter plug as a maximum value for its range of conduit diameters [22]. East Grants Ridge is an uncertain analog because of the excessive size of eruption volume of 2-3 km^3 (Table 3). The volume of material erupted from this conduit implies a long eruption duration. As magma flows through a conduit, the width of the conduit will gradually increase due to several factors that include shear-stress erosion at dike walls, thermoelastic stress on wall rock, conduit collapse due to low magmatic flow pressures or offshoot dikes, pore pressure build up, and potential hydromagmatic interaction between groundwater and magma [17]. A future eruption at YMR is not expected to exceed 0.1 km^3 in eruptive volume (Table 1) therefore conduit diameters of the order of 100 m are not expected.

Paiute Ridge is composed of alkali basalt that intruded into Miocene silicic tuffs located east of the Nevada Test Site. Dikes, sills, scoria cone remnant and lava flows are exposed at this volcanic complex and are believed to have formed from a "single, brief magmatic pulse" [21]. Features from this complex have been used by DOE to analyze conduit and fissure geometries [21]. Paiute Ridge is a good analog for future volcanism at YMR (Table 4).

Table 2: Composition and phenocryst phases in Quaternary YMR basalts. X indicates phenocrysts found in respective basalts [20, 19, 9]. Phenocryst phases: ol-olivine, pl-plagioclase, cpx-clinopyroxenes, am-amphibole, qz-quartz.

YMR BASALT TYPE	AGE (MYA)	COMPOSITION	ol	pl	cpx	am	qz
Crater Flats Basalts	Quaternary						
Little Cones (NE & SW)	0.77-1.0	Potassic trachybasalt	X			X	
Red Cones	0.92-1.1	Alkali basalt	X		X		
Black Cone	0.94-1.1	Alkali basalt	X		X		
Makani (Northern) Cone	1.16-1.17	Alkali basalt	X		X		

Sleeping Butte							
Hidden Cone	0.32-0.56	Potassic trachybasalt	X			X	
Little Black Peak	0.36-0.39	Potassic trachybasalt	X			X	
Lathrop Wells	0.074-.084	Potassic trachybasalt	X				

Basalt Ridge is another erosional remnant (well exposed) of an alkali basalt center. Exposures of dikes extend >150 m below the paleosurface. Basalt Ridge "East" is 5 km NE of Basalt Ridge. The main features of this center are exposures of parts of the feeder dike extend 800-1500 m to the north and south. Like Piaute Ridge, both Basalt Ridge and Basalt Ridge East meet the criteria to be good analogs (Table 4). Observations made at these two centers should be used for analyses of dike and conduit geometries.

Table 3: Uncertain volcanic analogs to future Yucca Mountain volcanism. E.V. eruption volume.

Volcano	Composition	E.V. (km^3)	Type	Tectonic setting
Cerro Negro [23]	Basalt	> 0.16	polygenetic	subductional
Grants Ridge [21]	Alkali basalt	2-3.0	monogenetic	extensional
Longuimay [9]	Basaltic andesite	0.33	polygenetic	subductional
Paricutin [24]	Basaltic andesites	> 2.0	monogenetic	extensional
Tolbachik [24]	Basalt	> 2.0	monogenetic	subduction

Eruptive features of the 1975 eruption at Tolbachik volcano in Kamchatka have been suggested to be analogs to YMR volcanism [25]. Conduit diameter and eruption characteristics from a violent Strombolian phase at Tolbachik volcano have been used in DOE TSPA-SR calculations. This volcano does not meet the criteria for a possible analog to future YMR volcanism. The Tolbachik eruption erupted over 2.0 km^3 of material. The scoria cone built during this eruption is 9 times the volume of Lathrop Wells cone and is located in a subduction zone. The eruption volume and tectonic setting suggest that this volcano is an uncertain analog (Table 3).

The 1988-90 eruption at Languimay volcano in Chile has been suggested as an appropriate analog for a possible future violent Stombolian eruptive phase in YMR [9]. Languimay is an uncertain analog for several reasons (Table 3). The first reason is that it is a stratovolcano and has a relatively continuous supply of magma. Second, the eruption volume is an order of magnitude greater than that expect for a future YMR eruption [9].

EPRI has proposed Red Cones and Boulder Dam dike to be appropriate analogs (Table 4). Red Cones is located near Mammoth Mountain, California. Red Cones and Lathrop Wells cone bound the scale of cone building phase of a future eruption in the Crater Flat area and buried beneath alluvium in the valleys surrounding Yucca Mountain

[1]. Boulder Dam dike located is southwest of Hoover Dam in Arizona is another good analog (Table 4). The dike is well exposed and can be traced to its source. Field observation such as geometry and physical characteristics of dikes and conduits may assist with the uncertainty associated the intrusive and extrusive scenario [1].

Table 4: Good analogs to future Yucca Mountain volcanism.

Volcano	Composition	Eruption Volume (km3)
Basalt Ridge [21]	Alkali basalt	> 0.7
Boulder Dam [27]	Camptonite	0.01
Capulin Mt [9]	Alkali basalt	1.27
Paiute Ridge [21]	Alkali basalt	0.2-0.3
Red Cones [26]	Alkali basalt	0.007

There have been numerous other analogs proposed from experts selected for the 1995-96 PVHA calculation (Table 5). Several of the analogs were not single volcanoes but volcanic fields such as Cima and Coso in California. Table 5 lists the characteristic features of these fields. The volcanic fields that do not make good analog sites are those having compositions other than alkali basalt or polygenetic meaning that the cinder cone formed from more than one eruption or the eruption was mostly phreatomagmatic. The volcanic fields that may be good analogs to the Crater Flat volcanic field are Clayton Valley, Revielle Range, and Death Valley. However, it should be noted that there is very little information available on the physical volcanology or petrology of cinder cones in Clayton Valley and Revielle Range.

Table 5: Other proposed analogs to future Yucca Mountain volcanism.

Volcano	Composition	Type	Tectonic Setting	VF Characteristics
Cima Volcanic Field (VF)		Polygenetic cinder cones	Extensional	52 vents, 65 lava flows
Clayton Valley	Alkali olivine basalt	Cinder cone	Extensional	
Coso VF	Bimodal: basalts and rhyolitic domes	Cinder cones		38 domes
El Jorollo, MX	Basalt-basaltic andesite	Cinder cone		Phreatic/phreatomagmatic phases
Lunar Crater VF	Subalkaline basalts – basanites	Maar (LC)	Extensional	95 vents , 35 flows.
Nye Canyon dikes	Most primitive basalt in YMR			
Revielle Range	Alkali olivine basalt	Cinder cones	Extensional	50 vents, lava flows. Two periods of volcanism.
SHORELINE BUTTE	basalt	Cinder cone	Extensional	(Death Valley)
Split Cone	basalt	Cinder cone	Extensional	(Death Valley)
Ubehebe Crater, CA	basalt	Tuff ring	Extensional	12 maars in area (phreatic/phreatomagmatic)

IV. CONCLUSIONS

This study provides strict criteria from which to select credible natural analogs outside the Yucca Mountain region used to constrain and define realistic range of eruptive characteristics required for dose risk calculations and probability hazard calculations. Results found that proposed analogs such as Paricutin, Grants Ridge, Tolbachik, and Longuimay are not appropriate because they do not meet at least two criteria. Use of such analogs should be restricted to understanding processes associated with an igneous event but not to quantify a characteristic property. Analogs such as Basalt Ridge, Paiute Ridge, Boulder Dam dikes, Red Cones in California fit the criteria. Field observations of eruptive characteristics at these analogs may reduce the uncertainty associated the intrusive and extrusive scenario. Volcanic fields that have been proposed as analogs to the Crater Flat volcanic field include Coso, Cima, Death Valley, Lunar Crater, Revielle Range, Nye Canyon, and El Jorollo. Based on only composition and tectonic environment, Revielle Range, Death Valley and Clayton Valley may be good analogs. The others are questionable as they include cinder cones with a wide range of composition and eruption type.

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