REVIEW OF:

DOE STUDY PLAN 8.3.1.8.1.2
Physical Processes of Magmatism and Effects on the Potential Repository (Revision 0), Dated August, 1993

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Prepared by

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1 REGULATORY BASIS FOR REVIEW

Staff at the U.S. Nuclear Regulatory Commission (NRC) are required to review and evaluate the license application of the U.S. Department of Energy (DOE) for the proposed High-Level Waste (HLW) geologic repository at Yucca Mountain, Nevada. Requirements for post-closure performance are set forth by the Environmental Protection Agency (EPA) in 40 CFR Part 191 and by the NRC in 10 CFR Part 60. Because of the possible impact of volcanism on repository performance, two conditions specifically related to volcanism are included in siting criteria in 10 CFR 60.122(c)(3), potential changes in groundwater flow as a result of igneous activity, and 10 CFR 60.122(c)(15), evidence of igneous activity in the Quaternary Period (i.e., within the last 2 m.y.).

DOE Study Plan 8.3.1.8.1.2, *Physical Processes of Magmatism and Effects on the Potential Repository*, is written to describe research intended to resolve issues related to volcanism as part of site characterization. These goals include development of data sets that will be used to assess the probability of volcanic eruptions in the region and at the HLW repository site in particular during the next 10,000 yr., and to evaluate the consequences of this potential volcanic activity on repository performance. Investigations described in Study Plan 8.3.1.8.1.2 include: eruptive effects of basaltic magmatism (activity 8.3.1.8.1.2.1); subsurface effects of basaltic magmatism (activity 8.3.1.8.1.2.2); and magma system dynamics for the Yucca Mountain Region (activity 8.3.1.8.1.2.3).

The NRC intends to provide guidance to the DOE during prelicensing activities so that technical issues related to site characterization and performance assessment (PA) can be resolved in a timely and rigorous manner. The NRC Office of Nuclear Material Safety and Safeguards (NMSS) has requested that the Center for Nuclear Waste Regulatory Analyses (CNWRA) provide a technical review of DOE Study Plan 8.3.1.8.1.2. This review concentrates on the review of technical aspects of the volcanism site characterization research program, rather than quality assurance or programmatic issues. Aspects of the technical review include:

- Assessment of the technical methods used in the characterization of volcanic features
- Analysis of the utility of the proposed research program to the resolution of technical issues related to probability and consequences of potential volcanism in and near the candidate repository site
- Identification of research areas that may provide critical information in site characterization that are not described in Study Plan 8.3.1.8.1.2

These aspects of the technical review are directly related to activities described in the License Application Review Plan (LARP). The LARP indicates that it is necessary to investigate the possible magnitude of volcanic eruptions likely to occur in the Yucca Mountain Region (YMR) in the event of future volcanic activity, the areas likely affected, the likely duration of volcanic activity (i.e, evidence of igneous activity as a potentially adverse condition, LARP section 3.2.1.9, and impact of volcanism on groundwater movement, LARP section 3.2.2.7), and to describe overall system performance (i.e., assessment of compliance with the requirement for cumulative releases of radioactive materials, LARP section 6.1). Compliance Determination Strategies (CDSs) associated with evidence of Quaternary volcanism indicate that: (i) Independent research must be conducted to evaluate Key Technical Uncertainties (KTUs) associated with volcanism; and (ii) Volcanism poses a high risk of noncompliance with 40 CFR Part 191 as set forth by the EPA and 10 CFR 60.122(c)(15) as determined by the NRC. To date, eight KTUs related to igneous activity have been identified as part of the CDSs concerned with evidence of Quaternary igneous activity. These KTUs are:

- Low resolution of exploration techniques to detect and evaluate igneous features
- Inability to sample igneous features
- Development and use of conceptual tectonic models as related to igneous activity
- Development of a conceptual groundwater flow model
- Prediction of future changes in the hydrologic system (due to tectonism)
- Conceptual model representation of the natural and engineered systems
- Variability in the model parametric values
- Prediction of future system states (disruptive scenarios)

Evaluation of these KTUs will require detailed safety reviews supported by independent tests, analyses, and related investigations. Each of these KTUs has been established independent of DOE activities and will be investigated as research programs at the CNWRA. Nonetheless, it is important to evaluate the effectiveness of DOE research with respect to these KTUs, as they must be resolved by scientific investigation in the prelicensing stage.

Most of the formal comments and questions in this review pertain to several different activities in the Study Plan, and as such are not organized with respect to specific sections of the Study Plan. In some cases, comments are directed toward research not addressed specifically in the Study Plan, for instances in which alternative investigations appear necessary. Each comment consists of:

- *Statement of Concern*. The statement of concern provides a question or comment on a specific section, or comments on the need for alternative or additional research on a specific technical issue.
- *Basis*. The technical basis for the statement of concern is described, and usually involves discussion of alternative data, models, or research that may need to be addressed.

- *Recommendation.* The recommendation is intended to offer alternative approaches or appropriate revisions that will help better address volcanism issues related to site characterization.

- *References.* A list of references cited within the comment.

Following these detailed comments, the major points raised in this review are summarized.

2 SPECIFIC TECHNICAL COMMENTS

Comment 2-1

Statement of Concern: The Study Plan does not address how volatile contents of basaltic eruptions will be determined.

Basis: The volatile content of basaltic magma is a critical parameter for many of the modeling activities in this study. For example, the explosivity of basaltic eruptions is significantly controlled by the volatile content of ascending magma (e.g., Wilson and Head, 1981). Models of eruption dynamics in Activities 8.3.1.8.1.2.1 and 8.3.1.8.1.2.3 thus must utilize appropriate magmatic volatile contents in order to accurately quantify the potential effects of basaltic magmatism on repository performance. In addition to eruption dynamics, variations in magmatic volatile contents can strongly affect the crystallization and evolutionary history of a magma system. For example, the addition of several percent H_2O to a generic basaltic magma will suppress plagioclase crystallization (Yoder and Tilley, 1962; Eggler, 1972; Grove and Baker, 1984). Models of magma system dynamics (Activity 8.3.1.8.1.2.3) thus must utilize appropriate volatile contents in order to accurately determine the petrogenetic history of basaltic magmas in the Yucca Mountain Region (YMR) and accurately evaluate the explosivity of eruptions.

Some Quaternary basaltic volcanoes in the YMR contain phenocrysts of amphibole in addition to olivine and possibly plagioclase (e.g., Vaniman and Crowe, 1981; Crowe et al., 1992). Knutson and Green (1975) have shown that YMR-type basalt lacks stable amphibole at 2 weight percent H_2O but contains amphibole and olivine phenocrysts at 5 weight percent H_2O. YMR basalts with amphibole phenocrysts thus may have contained an excess of 2 weight percent magmatic H_2O and possibly as much as 5 weight percent H_2O.

The Study Plan does not address the specifics of how volatile contents will be determined for basaltic magmas of the YMR. Although a range of volatile contents apparently will be considered in modeling activities, it is not stated what this range will be. From the information presented in this Study Plan (cf. comment 2), it does not appear that volatile contents appropriate for some Quaternary YMR eruptions are being considered.

Recommendation: Volatile contents should be determined accurately and precisely for YMR basaltic eruptions. Consequence models should consider the effects of magmatic volatile contents of 5 weight percent H_2O unless it can be determined that lower volatile contents are representative of YMR basaltic eruptions containing amphibole phenocrysts.

References:

Crowe, B., R. Morley, S. Wells, J. Geissman, E. McDonald, L. McFadden, F. Perry, M. Murrell, J. Poths, and S. Forman. 1992. The Lathrop Wells volcanic center: Status of field and geochronology studies. *Proceedings of the Third International High Level Radioactive Waste Management Conference.* La Grange Park, IL: American Nuclear Society: 1,997-2,013.

Eggler, D.H., 1972. Water-saturated and undersaturated melting relations in a Parícutin andesite and an estimate of water content in the natural magma. *Contributions to Mineralogy and Petrology* 34: 261-271.

Grove, T.L., and M.B. Baker. 1984. Phase equilibrium controls on the tholeiitic versus calc-alkaline differentiation trends. *Journal of Geophysical Research* 89(B5): 3253-3274.

Knutson, J., and T.H. Green. 1975. Experimental duplication of a high-pressure megacryst/cumulate assemblage in a near-saturated Hawaiite. *Contributions to Mineralogy and Petrology* 52: 121-132.

Vaniman, D., and B. Crowe. 1981. *Geology and Petrology of the Basalts of Crater Flat: Applications to Volcanic Risk Assessment for the Nevada Nuclear Waste Storage Investigations.* Los Alamos National Laboratory Report LA-8845-MS. Los Alamos, NM: Los Alamos National Laboratory.

Wilson, L., and J.W. Head III. 1981. Ascent and eruption of basaltic magma on the Earth and Moon. *Journal of Geophysical Research* 86(B4): 2971-3001.

Yoder, H.S., and C.E. Tilley. 1962. Origin of basaltic magmas: an experimental study of natural and synthetic rock systems. *Journal of Petrology* 3:342-532.

Comment 2-2

Statement of Concern: Proposed models of Hawaiian- and Strombolian-type eruptions do not encompass the range of eruption styles possible for basaltic volcanoes of the YMR and thus may underestimate the effects of basaltic eruptions on repository performance.

Basis: Hawaiian (i.e., gas-jets and magma fountains) and Strombolian (i.e., fountains and ballistic ejecta) models of eruption dynamics are used in the Study Plan as characteristic of YMR basaltic eruptions. These generalized models fail to encompass the range of explosivity observed in historical small-volume basaltic eruptions, and that potentially occurred in some YMR Quaternary eruptions. The high degree of magma fragmentation and relatively distant ejecta dispersal for these eruptions can be more accurately characterized as Plinian.

Several historically active basaltic volcanoes throughout the world have had eruptions that are considerably more explosive than Strombolian. For example, the 1992 eruption of Cerro Negro volcano in Nicaragua resulted in a convective ash-column 3.5 to 7 km high, which was sustained for about 18 hours (GVN, 1992; Connor et al., 1993). Ash from this basaltic eruption was transported in excess of 50 km, with 1 cm-thick ash beds occurring up to 45 km southwest of the volcano (Connor et al., 1993). The 1975 basaltic eruption at Tolbachik, Russia, had sustained ash-column heights in excess of 10 km, with ash transported in excess of 500 km from the volcano (e.g., Fedotov et al., 1991; Tokarev, 1983). Although these eruptions are small volume and thus not Plinian in the strictest sense (Simkin et al., 1981), they are significantly more energetic than eruptions characterized as Strombolian (Walker, 1973; Blackburn et al., 1976).

Quaternary basaltic volcanoes in the YMR have some features characteristic of eruptions that were considerably more energetic than Strombolian. For example, the cinders at Lathrop Wells are highly fragmented (Crowe et al., 1983) and lack the agglutination common for typical Strombolian eruptions (e.g., Blackburn et al., 1976; Head and Wilson, 1989). The volume of pyroclastic material at Lathrop Wells and the Sleeping Butte volcanoes is unusually large relative to the volume of associated lava flows (Crowe et al., 1983), which likely indicates relatively explosive eruptions (e.g., Wood, 1980). In addition, basaltic ash in Solitario Canyon Trench 8 may be from the eruption of Lathrop Wells, located about 20 km to the south. Basaltic ash from presumably Quaternary eruptions also occurs in Trench 14 on the east side of Yucca Mountain and in several other trenches on the west side of Yucca Crest

(H.L. McKague, pers. com., 1994). This distance of ash dispersal is not characteristic of typical Strombolian eruptions (e.g., Walker, 1973).

In addition to affecting eruption dynamics models, a significant volume of an explosive basaltic eruption may be represented by tephra that is more highly dispersed than in Strombolian eruptions (e.g., Walker, 1973; Connor et al., 1993). This dispersed tephra is poorly preserved unless it is rapidly buried by erosionally resistant deposits. Models utilizing eruption volumes (e.g., Crowe et al., 1983; Crowe and Perry, 1989) are inaccurate unless the highly dispersed tephra is incorporated into volume calculations. Although quantification of eruption explosivity is difficult for many Quaternary eruptions, preserved deposits at YMR Quaternary volcanoes indicate that these eruptions were more explosive than Strombolian.

Recommendation: Models of basaltic eruptions in the YMR should consider a range of potential explosivities, including eruptions that are more energetic than typical Strombolian eruptions. Although some of the models referred to in this Study Plan are developed for highly explosive Plinian eruptions (i.e., Valentine and Wohletz, 1989; Valentine et al., 1992), it does not appear that these models will be used to evaluate eruptions more energetic than Strombolian. Dispersed tephra volumes also need to be quantified and incorporated into eruption volume determinations, or this bias needs to be evaluated more fully.

References:

Blackburn, E.A., L. Wilson, and R.S.J. Sparks. 1976. Mechanisms and dynamics of strombolian activity. *Journal of the Geological Society of London* 132: 429-440.

Connor, C.B, L. Powell, W. Strauch, M. Navarro, O. Urbina, and W.I. Rose. 1993. The 1992 eruption of Cerro Negro, Nicaragua: An example of Plinian-style activity at a small basaltic cinder cone. *EOS, Transactions of the American Geophysical Union* 74-43: 640.

Crowe, B.M., and F.V. Perry. 1989. Volcanic probability calculations for the Yucca Mountain site: estimation of volcanic rates. *Proceedings Nuclear Waste Isolation in the Unsaturated Zone, Focus '89.* La Grange Park, IL: American Nuclear Society: 326-334.

Crowe, B., S. Self, D. Vaniman, R. Amos, and F. Perry. 1983. Aspects of potential magmatic disruption of a high-level radioactive waste repository in southern Nevada. *Journal of Geology* 91: 259-276.

Fedotov, S.A., S.T. Balesta, V.N. Dvigalo, A.A. Razina, G.B. Flerov, and A.M. Chirkov. 1991. The New Tolbachik Volcanoes. S.A. Fedotov and Yu. P. Masurenkow, eds. *Active Volcanoes of Kamchatka.* Moscow: Nauka Press: 275-279.

Global Volcanism Network (GVN). 1992. Violent strombolian activity at Cerro Negro. *Bulletin of the Global Volcanism Network* 17(3): 2-4.

Head, J.W., III, and Wilson, L., 1989. Basaltic pyroclastic eruptions: Influence of gas-release patterns and volume fluxes on fountain structure, and the formation of cinder cones, spatter cones, rootless flows, lava ponds and lava flows. *Journal of Volcanology and Geothermal Research* 37: 261-271.

Simkin, T., L. Seibert, L. McClelland, D. Bridge, C. Newhall, and J.H. Latter. 1981. *Volcanoes of the World*. Stroudsburg, PN: Hutchinson Ross.

Tokarev, P.I. 1983. Calculation of magma discharge, growth in the height of the cone and dimensions of the feeder channel of Crater I in the Great Tolbachik fissure eruption, July 1975. S.A. Fedotov and Ye. K. Markhinin, eds. *The Great Tolbachik Fissure Eruption, Geological and Geophysical Data 1975-1976*. Cambridge: Cambridge University Press: 27-35.

Valentine, G.A., and K.H. Wohletz. 1989. Numerical models of Plinian eruption columns and pyroclastic flows. *Journal of Geophysical Research* 94: 1,867-1,887.

Valentine, G.A., K.H. Wohletz, and S.W. Kieffer. 1992. Effects of topography on facies and compositional zonation in caldera-related ignimbrites. *Geological Society of America Bulletin* 104: 154-165.

Walker, G.P.L. 1973. Explosive volcanic eruptions - a new classification scheme. *Geologische Rundsche* 62: 431-446.

Wood, C.A. 1980. Morphometric evolution of cinder cones. *Journal of Volcanology and Geothermal Research* 7: 387-413.

Comment 2-3

Statement of Concern: Thermal and degassing effects may be poorly preserved at inactive basaltic volcanoes and thus cannot be quantified adequately using the methods proposed in the Study Plan.

Basis: After the cessation of eruptive activity, heat and mass transfer to the surface and through rock surrounding shallow intrusions continues through convective degassing and heat conduction. Direct effects of volcano degassing include the movement of gas through the repository block, which may result in accelerated rates of container corrosion and deterioration of the waste packages. Indirect effects of degassing also may impact repository performance, and may include a change in the partitioning of radionuclides between aqueous and solid phases, and changes in the sorption of radionuclides. In addition, changes in movement of groundwater and gas phases in the geologic environment, and changes in the mechanical properties of the surrounding rock, may also result from degassing and thermal loading of rock by conductive and convective heat transfer. The effects of these processes can extend for some poorly constrained distance beyond the immediate area of the main vent or magma intrusion.

Most theoretical models for dike emplacement and solidification indicate that individual dikes cool rapidly to near ambient temperatures within hours or days of the cessation of rapid mass flow (e.g., Delaney and Pollard, 1982). However, the occurrence of high-temperature fumaroles at recently active cinder cones indicates that heat and mass transfer in the entire volcanic system remains elevated for considerably longer periods of time. For example, the persistence of fumaroles with temperatures in excess of 100 °C more than 200 years after the eruption of Jorullo volcano, Mexico, (J.F. Luhr, pers. comm., 1992) indicates that gas at shallow depths may remain heated for centuries following eruptive activity. Conditions responsible for the persistence of this activity must be better understood in order to determine the long-term impact of volcanism on repository performance.

Thermal and mass transfer processes that can affect repository performance may be poorly preserved in the rocks surrounding a basaltic volcano. Basaltic volcanoes rarely develop forced-convection hydrothermal systems of sufficient magnitude to result in wallrock alteration (e.g., Hardee, 1982). Although some dehydration reactions may occur in zeolites and clays at temperatures of approximately 100 °C, as noted in Study Plan 8.3.1.8.1.2, some of these dehydration and mineralogical reactions can be reversible (e.g., Smyth, 1981; Bish, 1988) or only occur at temperatures in excess of 200 °C (e.g., Bish, 1990). The presence or absence of hydrated zeolites in rock surrounding an intrusion thus may not accurately reflect the effects of a 100 °C increase in temperature associated with intrusion emplacement. Detailed zeolite and clay stability studies may provide useful constraints on wall-rock paleotemperatures. However, such studies apparently are not proposed in Study Plan 8.3.1.8.1.2. The proposed field-based investigations of subsurface alteration at analog basaltic volcanoes may thus fail to accurately delineate the region around a basaltic volcano that experienced elevated temperature and gas-flow rates.

Recommendation: The presence or absence of dehydrated zeolites will not accurately constrain paleotemperatures associated with basaltic intrusions into tuffaceous rock. Studies of active basaltic volcanoes are necessary to accurately constrain the extent and duration of thermal and degassing effects associated with small-volume basaltic intrusions and eruptions.

References:

Armstead, H.C. 1983. *Geothermal Energy*. New York, New York: E. and F.N. Spon.

Bish, D.L. 1988. *Smectite Dehydration and Stability: Applications to Radioactive Waste Isolation at Yucca Mountain, Nevada*. Los Alamos National Laboratory Report LA-11023-MS. Los Alamos, NM: Los Alamos National Laboratory.

Bish, D.L. 1990. Long-term thermal stability of clinoptilolite: The development of a "B" phase. *European Journal of Mineralogy* 2: 771-777.

Delaney, P.T., and D.D. Pollard. 1982. Solidification of basaltic magma during flow in a dike. *American Journal of Science* 282: 856-885.

Hardee, H.C. 1982. Permeable convection above magma bodies. *Tectonophysics* 84: 179-195.

Smyth, J.R. 1981. Zeolite stability constraints on radioactive waste isolation in zeolite-bearing volcanic rocks. *Journal of Geology* 90: 195-201.

Comment 2-4

Statement of Concern: Studies of eruptive effects (8.3.1.8.1.2.1 and 8.3.1.8.1.2.3) apparently will be terminated if the probability of repository release is calculated to be $\leq 10^{-8} yr^{-1}$. It is not clear how such a determination can be accurately made until the proposed studies have been completed.

Basis: Studies of eruptive effects will be concluded if at some unspecified point in the future, a probability of erupting sufficient volumes of waste is $\leq 10^{-8} yr^{-1}$. Although this tentative performance parameter goal is provided in the Site Characterization Plan (DOE, 1988), this parameter does not quantify the radiological releases possible for the disruptive event. Such a determination is necessary to evaluate the risk presented by volcanic disruption.

The Study Plan authors recognize that the quantity of repository material released can be more accurately constrained than the area of disruption (i.e., DOE, 1988). However, the models for eruption effects presented in this Study Plan (i.e., Hawaiian and Strombolian) underestimate the energetics of basaltic eruptions in the YMR. These models do not account for the hydromagmatic eruptions that occurred at Lathrop Wells (e.g., Vaniman and Crowe, 1981) and may occur during future eruptions (e.g., Crowe et al., 1986). In addition, there is evidence that some nonhydromagmatic basaltic eruptions in the YMR were considerably more energetic than Strombolian (cf. Comment 2-2). Both of these eruption scenarios are capable of dispersing significantly more repository material than those proposed for Hawaiian and Strombolian eruptions (e.g., Barr et al., 1993).

Determining the amount of repository material that can potentially be erupted will require the data from both activities 8.3.1.8.1.2.1 (eruptive effects) and 8.3.1.8.1.2.3 (magma system dynamics) in this Study Plan, in addition to input from Study Plans 8.3.1.8.1.1 (Probability of Magmatic Disruption) and 8.3.1.8.5.1 (Characterization of Volcanic Features). Any calculation about the amount of repository material erupted is clearly preliminary, unless all of these studies are completed. Thus, the proposed limitations to activities 8.3.1.8.1.2.1 and 8.3.1.8.1.2.3 is inappropriate until the proposed studies are completed.

Recommendation: Activities 8.3.1.8.1.2.1 and 8.3.1.8.1.2.3 should be amended to incorporate the detailed studies alluded to in the Study Plan, regardless of a preliminary release determination.

References:

Barr, G.E., E. Dunn, H. Dockery, R. Barnard, G. Valentine, B. Crowe. 1993. *Scenarios Constructed for Basaltic Igneous Activity at Yucca Mountain and Vicinity*. Sandia National Laboratory Report SAND 91-1653. Albuquerque, NM: Sandia National Laboratory.

Crowe, B.M., K.H. Wohletz, D.T. Vaniman, E. Gladney, and N. Bower. 1986. *Status of Volcanic Hazard Studies for the Nevada Nuclear Waste Storage Investigations*. Los Alamos National Laboratory Report LA-9325-MS, Vol. II. Los Alamos, NM: Los Alamos National Laboratory.

U.S. Department of Energy (DOE). 1988. *Site Characterization Plan (Postclosure Tectonics)*. DOE/RW-0160. Washington, DC: U.S. Department of Energy. V, Chapter 8.3.1.8.

Vaniman, D., and B. Crowe. 1981. *Geology and Petrology of the Basalts of Crater Flat: Applications to Volcanic Risk Assessment for the Nevada Nuclear Waste Storage Investigations*. Los Alamos National Laboratory Report LA-8845-MS. Los Alamos, NM: Los Alamos National Laboratory.

Comment 2-5

Statement of Concern: Studies of subsurface effects (8.3.1.8.1.2.2) apparently will be terminated if preliminary models show that insignificant sorption effects are associated with alteration zones around basaltic intrusions. The effects of alteration on radionuclide sorption cannot be robustly evaluated until hydrologic and geochemical studies, which are independent of and beyond the scope of this Study Plan, are completed. In addition, it is not clear how such a determination can be accurately made until the proposed studies have been completed.

Basis: Studies of the subsurface effects of basaltic intrusions apparently will be terminated if groundwater transport calculations indicate that insignificant radionuclide release could result from alteration effects. The basis for these calculations is that most zeolites are unstable at temperatures above about 100 °C. Although some dehydration reactions may occur in zeolites and clays at temperatures below 100 °C (Knowlton, et al., 1986), some dehydration and mineralogical reactions can be reversible (e.g., Smyth, 1981; Bish, 1988) or only occur at temperatures in excess of 200 °C (e.g., Bish, 1990). In addition, the kinetics and composition of the solution surrounding the zeolite also can control these dehydration reactions (e.g., Smyth and Caporuscio, 1981). The stability of zeolites around basaltic intrusions thus cannot be determined by simply calculating the zone around an intrusion that exceeds 100 °C, as proposed in the Study Plan. The significance of this alteration zone on groundwater transport of radionuclides also cannot be evaluated, until groundwater transport and geochemical models have been developed (e.g., DOE, 1988). Although the Study Plan recognizes that hot groundwater and volatiles released from degassing intrusions may increase waste-package corrosion, these effects apparently will not be studied if zeolite dehydration is not found to be "significant." The apparent decision to not fully investigate the effects of alteration on rock surrounding an intrusion, unless some undetermined level of significance is achieved, appears to be premature.

Recommendation: The Study Plan should be revised to reflect the detailed field and modeling studies needed to better constrain alteration processes associated with basaltic intrusions into silicic tuffs, regardless of the preliminary calculations proposed in the Study Plan.

References:

Bish, D.L. 1988. *Smectite Dehydration and Stability: Applications to Radioactive Waste Isolation at Yucca Mountain, Nevada.* Los Alamos National Laboratory Report LA-11023-MS. Los Alamos, NM: Los Alamos National Laboratory.

Bish, D.L. 1990. Long-term thermal stability of clinoptilolite: The development of a "B" phase. *European Journal of Mineralogy* 2: 771-777.

Knowlton, G.D., T.R. White, and H.L. McKague. 1981. Thermal study of types of water associated with clinoptilolite. *Clays and Clay Minerals* 29: 403-411.

Smyth, J.R. 1981. Zeolite stability constraints on radioactive waste isolation in zeolite-bearing volcanic rocks. *Journal of Geology* 90: 195-201.

Smyth, J.R., and F.A. Caporuscio. 1981. *Review of the Thermal Stability and Cation Exchange Properties of the Zeolite Minerals Clinoptilolite, Mordenite, and Analcime: Applications to Radioactive Waste Isolation in Silicic Tuff.* Los Alamos National Laboratory Report LA-8841-MS. Los Alamos, NM: Los Alamos National Laboratory.

U.S. Department of Energy (DOE). 1988. *Site Characterization Plan (Geochemistry).* DOE/RW-0160. Washington, DC: U.S. Department of Energy. II, A, Chapter 8.3.1.3.

Comment 2-6

Statement of Concern: There are five Quaternary volcanic centers located in Crater Flat, not four as stated in the Study Plan.

Basis: There are five spatially discrete Quaternary basaltic vents in Crater Flat: Northern Cone, Black Cone, Red Cone, Little Cone North (LCN), and Little Cone South (LCS). LCN lacks an associated lava flow, but LCS apparently is associated with a buried flow that extends at least 0.5 km south of the cinder cone (e.g., Crowe and Carr, 1980). LCN contains phenocrysts of amphibole, but amphibole is absent from LCS (e.g., Vaniman and Crowe, 1981). The geochemical data presented in Vaniman and Crowe (1981) and Crowe et al. (1986) also show that LCS and LCN have some compositional distinctions. The discrete locations, different eruptive styles, and mineralogical and geochemical differences clearly show that LCN and LCS are discrete volcanic centers.

Recommendation: The Little Cones represent two discrete volcanic centers and should not be counted as one event. The Quaternary Crater Flat volcanic field contains five discrete volcanoes. Calculations utilizing cone or vent counts should be modified to reflect the presence of two discrete volcanoes at the Little Cones.

References:

Crowe, B.M., and W.J. Carr. 1980. *Preliminary Assessment of the Risk of Volcanism at a Proposed Nuclear Waste Repository in the Southern Great Basin.* U.S. Geological Survey Open-file Report 80-357. Reston, VA: U.S. Geological Survey.

Crowe, B.M., K.H. Wohletz, D.T. Vaniman, E. Gladney, and N. Bower. 1986. *Status of Volcanic Hazard Studies for the Nevada Nuclear Waste Storage Investigations.* Los Alamos National Laboratory Report LA-9325-MS, Vol. II. Los Alamos, NM: Los Alamos National Laboratory.

Vaniman, D., and B. Crowe. 1981. *Geology and Petrology of the Basalts of Crater Flat: Applications to Volcanic Risk Assessment for the Nevada Nuclear Waste Storage Investigations.* Los Alamos National Laboratory Report LA-8845-MS. Los Alamos, NM: Los Alamos National Laboratory.

Comment 2-7

Statement of Concern: Planned lithic fragment studies in the YMR will inadequately characterize the ability of Quaternary basaltic volcanoes to fragment and erupt subsurface material, unless all Quaternary volcanoes are examined.

Basis: In the YMR, the only lithic fragment studies apparently planned are at Red and Black Cones in Crater Flat. These vents are selected due to their proximity to the USW VH-2 and VH-1 drill holes, which will be used to provide stratigraphic control. However, the proposed studies likely will not provide the data necessary to evaluate the ability of Quaternary basaltic volcanoes to fragment and erupt subsurface material at repository depths.

Drill hole VH-2, which is located between Red and Black Cones, penetrated 360 m of alluvium and 30 m of Miocene basalt before intersecting the top of the Ammonia Tanks member of the Timber Mountain

Tuff (Carr and Parrish, 1985). The upper 100 m of alluvium consists of Cenozoic volcanic clasts with subordinate amounts of Paleozoic clasts, whereas the lower 260 m is dominated by Paleozoic clasts (Carr and Parrish, 1985). It is not clear how tuffaceous lithic fragments will be attributed to pyroclastic units $>$390 m deep or to epiclastic units $<$390 m deep. In addition, alluvium dominated by Paleozoic clasts also occurs between 535 and 595 m, which could further complicate the stratigraphic relationships of these lithic fragments.

Red and Black Cones are characterized by large volumes of lavas relative to the volume of the associated cinder cones (Crowe et al., 1983). However, the Sleeping Buttes and Lathrop Wells volcanoes are characterized by relatively large cinder cone volumes (Crowe et al., 1983), which may indicate that these vents are more explosive than Red or Black Cones. In addition, Lathrop Wells lacks prominent beds of agglutinated scoria. Red and Black Cones contain prominent agglutinated scoria deposits, which may indicate that these deposits were less fragmented (i.e., less explosive) than Lathrop Wells. By observation, Lathrop Wells also contains significantly more xenoliths than either Red or Black Cones.

Recommendation: Xenolith studies should examine all of the Quaternary basaltic volcanoes of the YMR, not just Red and Black Cones. Although precise stratigraphic correlation may not be possible for xenoliths from many of these volcanoes, some depth constraints should be possible for each of these vents. In addition to depth of origin, the abundance and characteristics of xenoliths may be significantly different for each Quaternary volcano of the YMR. All Quaternary volcanoes should be examined to provide robust constraints on the ability of YMR basaltic magmas to fragment and erupt subsurface material.

References:

Carr, W.J., and L.D. Parrish. 1985. *Geology of Drill Hole USW VH-2, and Structure of Crater Flat, Southwestern Nevada.* USGS Open-File Report 85-475. Reston, VA: U.S. Geological Survey.

Crowe, B., S. Self, D. Vaniman, R. Amos, and F. Perry. 1983. Aspects of potential magmatic disruption of a high-level radioactive waste repository in southern Nevada. *Journal of Geology* 91: 259-276.

Comment 2-8

Statement of Concern: The proposed studies for wall-rock fragmentation and subsurface effects apparently do not account for the ascending magma encountering a repository zone where confining pressure is not lithostatic. Analog studies at subsurface depths of around 300 m will not accurately represent the dynamics of magma interaction with the proposed repository.

Basis: An inherent assumption in all the proposed analog studies of subsurface magmatic effects is that the lithostatic confining pressure represents the pressure on the ascending magma. However, the repository will represent a zone 300 m below the surface that has a confining pressure that is not lithostatic. Although repository design is in an initial stage, drifts likely will be backfilled with noncompacted, crushed tuff (e.g., DOE, 1988). The confining pressure of the backfilled drifts will thus be less than lithostatic, but greater than atmospheric pressure. Thus, additional exsolution of volatiles will likely occur as the ascending magma encounters the repository.

In addition to the confining pressure within the repository, the state of stress in the vicinity of the repository will be complex. Stress anisotropy will likely develop as a result of the underground openings, heating of the rock by the waste packages, and possible degradation of wallrock properties with time. Although repository design is in a preliminary stage, it is possible to model the effects of repository construction on the surrounding stress field and thus determine what subsurface conditions best represent emplacement of basaltic intrusions at or near the repository.

Analog studies are focused on determining the amount of wall rock that can be fragmented and erupted from subsurface depths of around 300 m. This approach can potentially underestimate the amount of repository material incorporated into ascending basaltic magma, because the lower confining pressure of the repository horizon will likely enhance volatile exsolution and result in more extensive magma and wall-rock fragmentation (cf. Wilson and Head, 1981). Thus, the mechanisms of magma and wall-rock fragmentation from depths <300 m at analog volcanoes may be more representative of magma-repository interactions than those at around 300 m. Although it is stated in the Study Plan (p. 21) that an attempt will be made to locate dikes that intersected poorly consolidated rock at 300 m depth, it is not clear how the potential absence of such dikes will be accommodated in the planned studies.

Recommendation: Calculations should be made to determine what subsurface depth beneath analog volcanoes best represents the confining pressure and wall-rock characteristics of the backfilled repository horizon and adjacent areas. Although dikes that intersect poorly consolidated material at 300 m may be located in analog areas, the Study Plan should address how the absence of suitable intrusions will be accommodated in models of dike-repository interactions.

References:

U.S. Department of Energy (DOE). 1988. *Site Characterization Plan Overview.* DOE/RW-0198. Washington, DC: U.S. Department of Energy.

Wilson, L., and J.W. Head III. 1981. Ascent and eruption of basaltic magma on the Earth and Moon. *Journal of Geophysical Research* 86(B4): 2,971-3,001.

Comment 2-9

Statement of Concern: Many of the planned studies are directed only at volcanoes of the Crater Flat Volcanic Zone (CFVZ), especially in activity 8.3.1.8.1.2.3. However, the CFVZ does not include the 2.8 Ma Buckboard Mesa volcano. Not including Buckboard Mesa into petrogenetic models will result in an incomplete understanding of the range of magmatic processes possible in the YMR, and may lead to erroneous conclusions regarding magma system dynamics.

Basis: The CFVZ (Crowe and Perry, 1989) includes all basaltic volcanoes in the YMR younger than about 5 Ma, with the exception of the 2.8 ± 0.1 Ma Buckboard Mesa volcano. Buckboard Mesa represents one of the largest basaltic eruptions of post-caldera basalt (Crowe and Perry, 1989) in the YMR (e.g., Crowe et al., 1983a). Buckboard Mesa basaltic lavas contain xenoliths of partially melted and disaggregated granitic rock and xenocrysts of rounded quartz, both of which likely indicate crustal contamination (e.g., Crowe et al., 1983b). Buckboard Mesa also is compositionally distinct from other CFVZ basalts (e.g., Crowe et al., 1986). Although Buckboard Mesa is not located in the NW-trending CFVZ, Smith et al. (1990) considered it a fundamental part of the YMR magmatic system.

Buckboard Mesa is spatially and temporally part of the YMR volcanic system. The relatively large volume of apparently crustally contaminated basalt at Buckboard Mesa appears unique for < 5 Ma basaltic rocks of the YMR. Determining the petrogenesis of Buckboard Mesa would yield critical information of how mantle-derived melts may stagnate or interact with the crust in this magma system. These features may not be readily discernable at CFVZ volcanoes. It is not clear why Buckboard Mesa is not being considered in any of the activities in this Study Plan.

Recommendation: Include the Buckboard Mesa volcano in models of post-5 Ma volcanism in the YMR.

References:

Crowe, B.M., and F.V. Perry. 1989. Volcanic probability calculations for the Yucca Mountain site: estimation of volcanic rates. *Proceedings Nuclear Waste Isolation in the Unsaturated Zone, Focus '89.* La Grange Park, IL: American Nuclear Society: 326-334.

Crowe, B.M., D.T. Vaniman, and W.J. Carr. 1983a. *Status of Volcanic Hazard Studies for the Nevada Nuclear Waste Storage Investigations.* Los Alamos National Laboratory Report LA-9325-MS. Los Alamos, NM: Los Alamos National Laboratory.

Crowe, B., S. Self, D. Vaniman, R. Amos, and F. Perry. 1983b. Aspects of potential magmatic disruption of a high-level radioactive waste repository in southern Nevada. *Journal of Geology* 91: 259-276.

Crowe, B.M., K.H. Wohletz, D.T. Vaniman, E. Gladney, and N. Bower. 1986. *Status of Volcanic Hazard Studies for the Nevada Nuclear Waste Storage Investigations.* Los Alamos National Laboratory Report LA-9325-MS, Vol. II. Los Alamos, NM: Los Alamos National Laboratory.

Smith, E.I., T.R. Feuerbach, and J.E. Faulds. 1990. The area of most recent volcanism near Yucca Mountain, Nevada: implications for volcanic risk assessment. *Proceedings of the First International High Level Radioactive Waste Management Conference.* La Grange Park, IL: American Nuclear Society: 81-90.

Question 2-1

Statement of Concern: The terms "Crater Flat Volcanic Zone" and "Crater Flat" are used extensively in the section on magma system dynamics. Are these terms synonymous?

Basis: Specific tests and analyses in section 8.3.1.8.1.2.3 on magma system dynamics refer to either volcanoes of the "Crater Flat Volcanic Zone" or "Crater Flat". Will activities directed at "Crater Flat" volcanoes only examine the Quaternary and Pliocene basalts physically located in Crater Flat, or is this term synonymous with the "Crater Flat Volcanic Zone", as shown on figure 2? If these terms are not synonymous, then the planned activities at "Crater Flat" volcanoes will not examine the full range of eruptive styles present in the YMR.

Recommendation: Clarify the usage of the term "Crater Flat". If this term is used correctly as written, provide a justification as to why only the volcanoes physically located in Crater Flat will be studied as part of 8.3.1.8.1.2.3 activities.

3 SUMMARY

Study Plan 8.3.1.8.1.2 proposes numerous investigations that will yield important insights and constraints on how basaltic magmas can interact with the proposed high-level nuclear waste repository at Yucca Mountain, Nevada. These studies will investigate surface release mechanisms of basaltic eruptions, subsurface effects associated with basaltic intrusions, and physical mechanisms of magmatic activity in the Yucca Mountain Region (YMR). The proposed studies focus on numerical modeling, and examination of analog areas to both constrain numerical models and develop conceptual models of basaltic magmatism.

The potentially most contentious issue in this Study Plan is that certain studies will be terminated if preliminary or tentative performance goals are attained. Eruptive effect studies will be terminated unless calculations show that a certain amount of repository material can be erupted (Comment 2-4). However, accurately calculating the amount of material released requires that a range of eruption styles and release mechanisms are considered in detail, which can only be accomplished by completing the proposed studies. A similar determination is made to decide if alteration of wall rock around a basaltic intrusion will result in "significant" groundwater transport of waste (Comments 2-3, 2-5). All such determinations appear premature until the results of the proposed studies in this and other Study Plans have been evaluated.

Most of the proposed detailed studies focus on volcanoes at either Crater Flat or in the Crater Flat Volcanic Zone (e.g., Crowe, 1990). These studies consistently fail to include the 2.8 Ma Buckboard Mesa volcano, which may represent an unusually large eruption of crustally contaminated basaltic magma. In addition, studies restricted to Crater Flat volcanoes (e.g., 8.3.1.8.1.2.1) will not examine the Lathrop Wells and Sleeping Butte volcanoes, which are the three most recently active volcanoes in the YMR. These volcanoes also may represent the most explosive eruptions in the YMR. All of the proposed studies in the YMR should be modified to include Buckboard Mesa, Lathrop Wells, and the Sleeping Butte volcanoes (Comments 2-7, 2-9).

Analog studies are a prominent component of the proposed research. As was noted in the review of Study Plan 8.3.1.8.5.1 by Connor and Hill (1993), none of the proposed analog volcanic centers are in the Western Great Basin (WGB) tectonic-magmatic province (e.g., Fitton et al., 1991), which includes the YMR. Study Plan 8.3.1.8.1.2 also does not document how potential differences in magma composition, crustal structure, and magma flux between WGB and proposed analog areas will be accommodated, or if sufficient data exists for these analog areas to support accurate comparisons with the YMR.

Finally, several of the proposed investigations on eruption mechanics are not explained in sufficient detail to evaluate how this research will provide the data necessary to constrain these processes. For example, determining the volatile content of the magma is critical to understanding eruption dynamics (Comments 2-1, 2-2). Although examination of pyroclastic deposits is part of the Study Plan, details are not provided as to how these studies will result in accurate determinations of volatile contents. Such relationships are not readily available in the geologic literature and will likely be difficult to determine. However, the Study Plan only states that such relationships "will be developed (e.g., p. 16)" and does not provide details on how these relationships will be quantified.

<u>References</u>:

Connor, C.B, and B.E. Hill. 1993. *Review of DOE Study Plan 8.3.1.8.5.1, Characterization of Volcanic Features (Revision 1).* IM-5702-001-310-003. San Antonio, TX: Center for Nuclear Waste Regulatory Analyses.

Crowe, B.M. 1990. Basaltic volcanic episodes of the Yucca Mountain region. *Proceedings, First International High Level Radioactive Waste Management.* La Grange Park, IL: American Nuclear Society: 65-73.

Fitton, J.G., D. James, and W.P. Leeman. 1991. Basic magmatism associated with late Cenozoic extension in the western United States: Compositional variations in space and time. *Journal of Geophysical Research* 96: 13,693-13,711.