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YUCCA MOUNTAIN SITE CHARACTERIZATION PROJECT
STUDY PLAN APPROVAL FORM

Study Plan Number 8.3.1.8.1.1

Study Plan Title Probability of Magmatic Disruption of the Repository

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Probability of Magmatic Disruption of the Repository

ABSTRACT

Study Plan 8.3.1.8.1.1, Probability of Magmatic Disruption of the Repository, describes the purpose and objectives, the technical rationale, the constraints, the approach, and the methods for conducting probabilistic volcanic hazard assessment (PVHA) for the Yucca Mountain site. The PVHA includes an assessment of the conditional probability of the recurrence of a future magmatic event that intersects or disrupts a specified area of a repository and/or an area immediately surrounding a repository. The potentially adverse condition of the presence of Quaternary igneous activity applies to the Yucca Mountain site on the basis of criteria specified in 10 CFR 60.122(c)(15). The primary hazard of future volcanism is from the operation of eruptive and subsurface processes associated with the recurrence of future basaltic volcanism. Basaltic volcanism has occurred repeatedly in the Pliocene and Quaternary in the YMR. This study plan uses the term or phrase volcanism and volcanic activity to describe the surface processes associated with volcanoes, and the term or phrase subsurface or magmatic activity interchangeably with igneous activity as used in 10 CFR 60. The types of igneous rocks known to exist in the Yucca Mountain region, (Miocene, Pliocene and Quaternary) include tuff rings, scoria and spatter cones, pyroclastic surge and fall deposits, lava flows, and shallow intrusive rocks including dikes, plugs and sills; these are referred to collectively as volcanic and subsurface features. The probabilistic studies for this study plan are divided into four activities. The activity 8.3.1.8.1.1.1, Location and Timing of Volcanic Events, involves collation of final summary geologic maps and tables that document the distribution of Pliocene and Quaternary basaltic volcanic centers, the geochronology of the centers, the volume of each center, and the location of major eruptive vents. The activity 8.3.1.8.1.1.2, Evaluations of the Structural Controls of Basaltic Volcanic Activity, involves evaluating the distribution of basaltic centers in the region, and relating distribution patterns to the spatial, structural and tectonic elements of the site vicinity. A comprehensive set of alternative models will be developed for the spatial and structural controls of sites of basaltic volcanic centers and these models will be used to evaluate the disruption parameter of the conditional probability of magmatic disruption of a specified region. The activity 8.3.1.8.1.1.3, Presence of Magma Bodies in the Vicinity of the Site, is concerned with an evaluation of geophysical data from the preclosure and postclosure tectonics programs as part of a systematic search for evidence of the existence of anomalies that could be associated with magma bodies in the crust or upper mantle. Should anomalies be identified by multiple geophysical methods, a plan will be developed to implement a detailed geophysical program to further explore the anomalies. The activity 8.3.1.8.1.1.4, Probability Calculations and Assessment, will revise iteratively the volcanic recurrence rates for alternative types of volcanic events, the probability of magmatic disruption of the repository with accompanying eruptions, the probability of magmatic disruption of the repository system with or without penetration of the repository and accompanying eruptions, and the probability of magmatic disruption of the repository system without eruptions. The probability estimations will be established through evaluation of multiple alternative models of the recurrence rate, and spatial and structural models of event distribution. Simulation modeling will be used to establish the uncertainty of the recurrence rate, the disruption ratio, and for conducting sensitivity studies of the probability of magmatic disruption of the repository and repository system. An independent study that applies methods of expert judgment to PVHA will be undertaken separate from the studies of this study plan to ensure probability distributions adequately represent a complete range of probability outcomes, and to reduce bias in the selection and use of alternative models. A second aspect of PVHA will be the development through simulation modeling of probability distributions for data gathered from Study Plan 8.3.1.8.1.2, Physical Processes of Magmatism and Effects on the Potential Repository. Study plan 8.3.1.8.1.1, Probability of Magmatic Disruption of the Repository, provides information that will be used by the DOE for assessing the suitability of the Yucca Mountain site and will be incorporated into studies of the total system performance of a potential repository system.

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1.0 PURPOSE AND OBJECTIVES OF STUDY

The Yucca Mountain Project (YMP) is conducting volcanism studies to evaluate the possible recurrence of volcanic activity during the post-closure period of a potential repository that may be sited at Yucca Mountain. The objective of Study Plan 8.3.1.8.1.1, Probability of Magmatic Disruption of the Repository, is to evaluate the probability of magmatic disruption of a repository and/or the waste isolation system associated with a repository. Additionally, data obtained from Study Plan 8.3.1.8.1.2, Physical Processes of Magmatism and Effects on the Potential Repository, will be evaluated under activities of this study plan and formulated as probability distributions so that the data can be used in studies of the performance of the waste isolation system of a repository. We use the phrases *volcanic activity*, *eruptive activity*, or *extrusive activity* in this study plan and Study Plan 8.3.1.8.1.2 to refer to surface processes of volcanoes. The phrase *magmatic activity* is used to refer to the processes associated with magma or naturally occurring molten rock and volatile components generated within the earth. *Magmatic activity* includes both volcanic activity and the products of subsurface intrusion of magma and is intended to be used synonymously with the phrase *igneous activity* as defined in 10 CFR 60 (NRC, 1986). The phrase *repository system* refers to the geohydrologic setting that constitutes the waste-isolation system of a repository. The studies of the occurrence probability of magmatic disruption of a specified area (this study plan) are referred to as *probabilistic volcanic hazard assessment* (PVHA); studies of the probability of magmatic disruption combined with the effects or release consequences of magmatic activity are referred to as *probabilistic volcanic risk assessment* (PVRA). The primary goal of this study plan is to conduct PVHA for the range of possible eruptive and intrusive processes that could penetrate near or through a repository and/or the geohydrological setting that constitutes the repository system. The PVRA will be conducted through combining the results of PVHA, and studies of the effects of magmatic disruption of the repository, with iterative studies of the performance of the waste isolation system (Total Systems Performance Assessment or TSPA). The primary data for PVHA and volcanic effects studies will be provided through work described in Study Plans 8.3.1.8.5.1, Characterization of Volcanic Features, and 8.3.1.8.1.2 Physical Processes of Magmatism and Effects on the Potential Repository. Additional data will be provided from studies for the preclosure and post-closure tectonics program.

There are two aspects to investigations of the possible recurrence of future volcanism: (1) the potential for future silicic volcanism, and (2) the potential for future basaltic volcanism. The potential for future silicic volcanism, based on current data from site characterization studies of the Yucca Mountain region, is considered to be negligible for the post-closure period of a repository (Crowe et al. 1983a; DOE, 1988; Crowe et al. 1995). Final resolution of an evaluation for the future potential of silicic volcanism may be dependent, however, on the results of drilling of planned volcanism exploration holes in Crater Flat and the Amargosa Valley. Data from the site characterization program show that there has been no Quaternary silicic volcanism in the Yucca Mountain region. The youngest silicic volcanic center in the region is the Black Mountain caldera complex that has been dated at about 9 Ma (Noble et al. 1992). Unless the planned exploratory drilling produces data that drastically changes our understanding of the Quaternary magmatic history of the region, silicic volcanism does not appear to contribute to the potentially adverse condition of igneous activity that could impact the performance of the proposed repository. The basis for resolution of silicic volcanism is the absence of Pliocene and Quaternary silicic centers in the region, the regional decrease and cessation of silicic volcanism, and the restriction of sites of Quaternary silicic volcanism to the margins of the Great Basin (Crowe et al. 1983a; 1995). The data justifying those assertions will be consolidated and fully referenced in the license application that may be submitted to the NRC. Assessments of the importance of silicic volcanism are not based on probabilistic arguments and the data that affects these assessments is obtained through Study Plan 8.3.1.8.5.1, Characterization of Volcanic Features.

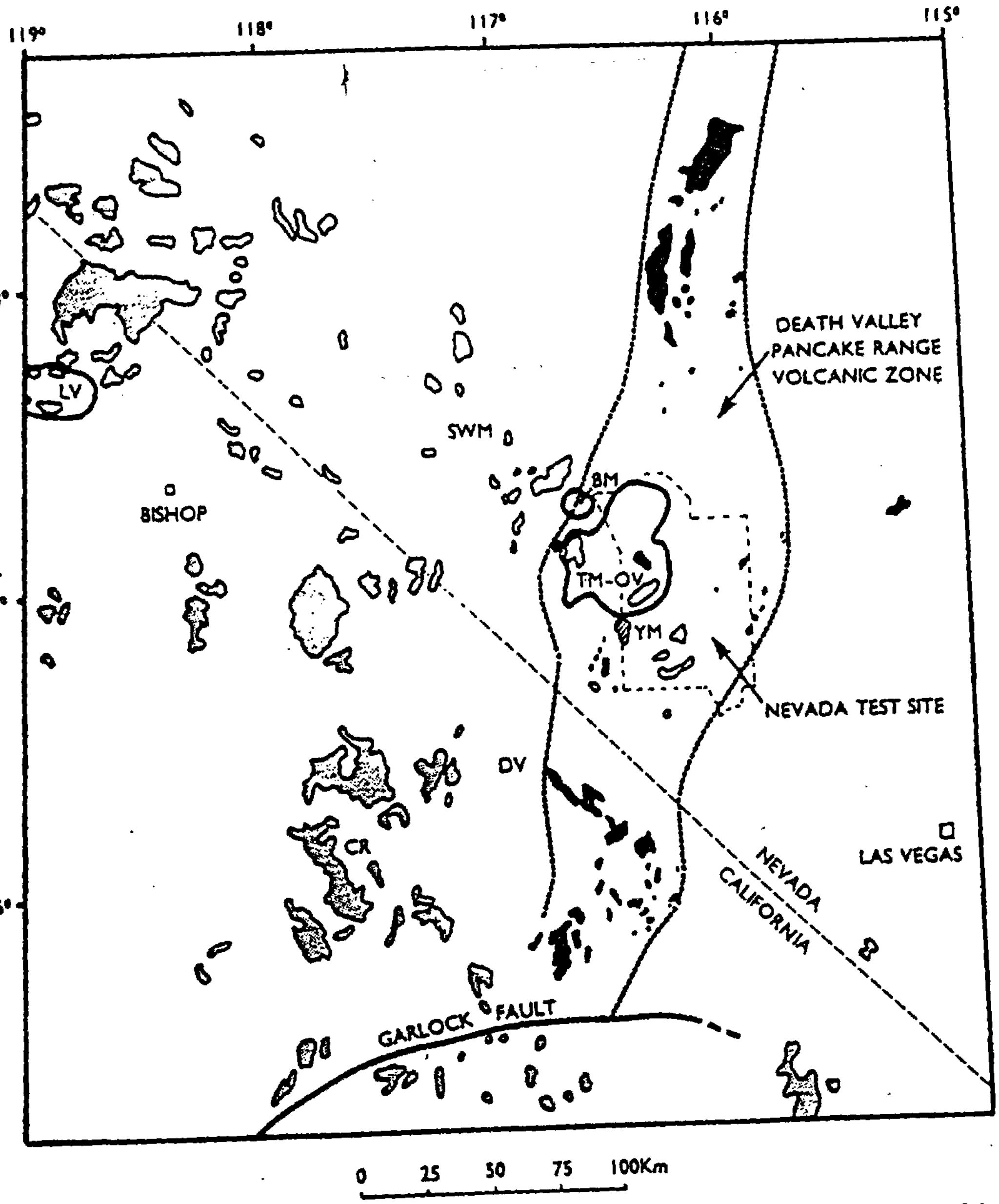

Figure 1. Distribution of post-Miocene silicic (stippled) and basaltic (black) volcanic rocks of the southern Great Basin. Basaltic rocks are inferred to be part of the Death Valley/Pancake Range volcanic zone (Crowe et al. 1983a; Crowe, 1986). An alternative interpretation is that the zone may consist of three unrelated, complex volcanic fields: (1) the Lunar Crater-Reveille range volcanic fields, (2) basaltic and silicic volcanic rocks of the Timber Mountain-Oasis Valley/Black Mountain-Stonewall Mountain volcanic fields, and (3) basaltic and silicic volcanic rocks of southern Death Valley. TM-OV: Timber Mountain-Oasis Valley caldera complex; BM: Black Mountain caldera; SWM: Stonewall Mountain caldera(caldera boundaries not shown on the figure); LV: Long Valley caldera complex; CR: volcanic rocks of the Coso volcanic field; DV: Death Valley; YM: Yucca Mountain.

Four Quaternary volcanic centers of basaltic composition (approximately 1.0 Ma) are located in Crater Flat, directly west and southwest of the exploration block of Yucca Mountain (Figure 2). Two Quaternary basaltic volcanic centers are located southwest of the Black Mountain caldera, about 45 km northwest of Yucca Mountain. The youngest recognized volcanic center in the region (<150 ka), the Lathrop Wells volcanic center, is located at the south end of Yucca Mountain, 20 km from the exploration block (Figure 2).

A three-phase approach is being used to evaluate the potential for future basaltic volcanism at the Yucca Mountain site (Crowe et al. 1983a; Crowe, 1986). The first phase involves standard geologic studies combining field mapping, geochronologic, paleomagnetic, geochemical, and geophysical studies necessary to provide comprehensive information used to decipher the history of basaltic volcanism in the Yucca Mountain region. These studies are conducted through Study Plan 8.3.1.8.5.1, Characterization of Volcanic Features. For the second phase, data from Study Plan 8.3.1.8.5.1 are used for PHVA, which is a combined evaluation of the recurrence rate and disruption probabilities for specified areas associated with the Yucca Mountain site. Data from Study Plan 8.3.1.8.1.2, Physical Processes of Magmatism and Effects on the Potential Repository, are assessed through probabilistic analyses. For the third phase, the PVHA of this Study Plan is combined with probabilistic data from the effects Study Plan and submitted iteratively to TSPA to assess the effects of magmatic processes on the cumulative radiological releases of a repository and repository system both directly through eruptions and indirectly through perturbation of the waste isolation system. The results of past volcanic hazard assessment and limited volcanic risk assessment for the Yucca Mountain site using these approaches are described in the Site Characterization Plan (SCP), Chapter 1, Sections 1.3.2.1.2 and 1.5.1 (DOE, 1988), and in separate publications (Crowe and Carr, 1980; Vaniman and Crowe, 1981; Crowe et al. 1983a, 1983b; Crowe, 1986, Crowe et al. 1986, Crowe et al. 1989; Crowe and Perry, 1990; Crowe, 1990; Crowe et al. 1993; 1995; Link et al. 1983; Valentine et al. 1992; see also Smith et al. 1990; Ho et al. 1991; Ho 1991; 1992; Connor and Hill 1993; 1995). All work for this study plan is under a fully approved Quality Assurance Program (QA) unless otherwise noted. Preexisting data from volcanism studies will be qualified to QA on a case-by-case basis if the data are judged to be needed in support of a license application for the Yucca Mountain site.

The study plan is subdivided into four activities, as follows:

1. *Collation of map and reference data on the location, the geochronology, the nature, and the volume of volcanic events in the Yucca Mountain region* (Activity 8.3.1.8.1.1.1, Location and Timing of Volcanic Events). The primary interval of emphasis for the data compilation will be the last 5.0 Ma, the interval of the Younger Postcaldera basalt of the Yucca Mountain region (YMR; see Crowe, 1990).

2. *An evaluation of the structural controls of the location of sites of past basaltic volcanic activity.* This activity will involve examination of the time-space patterns of the location of basaltic volcanic centers in the Yucca Mountain region. It will focus on two topics: (1) The distribution of Pliocene and Quaternary basaltic volcanic centers in the Yucca Mountain region and their relationship to spatial, structural and tectonic elements of the region, and (2) computational methods for factoring the spatial and structural controls of volcanism into revised estimations of the probability of magmatic disruption of a potential repository and repository system at Yucca Mountain (Activity 8.3.1.8.1.1.2, Evaluation of the Structural Controls of Basaltic Volcanic Activity).

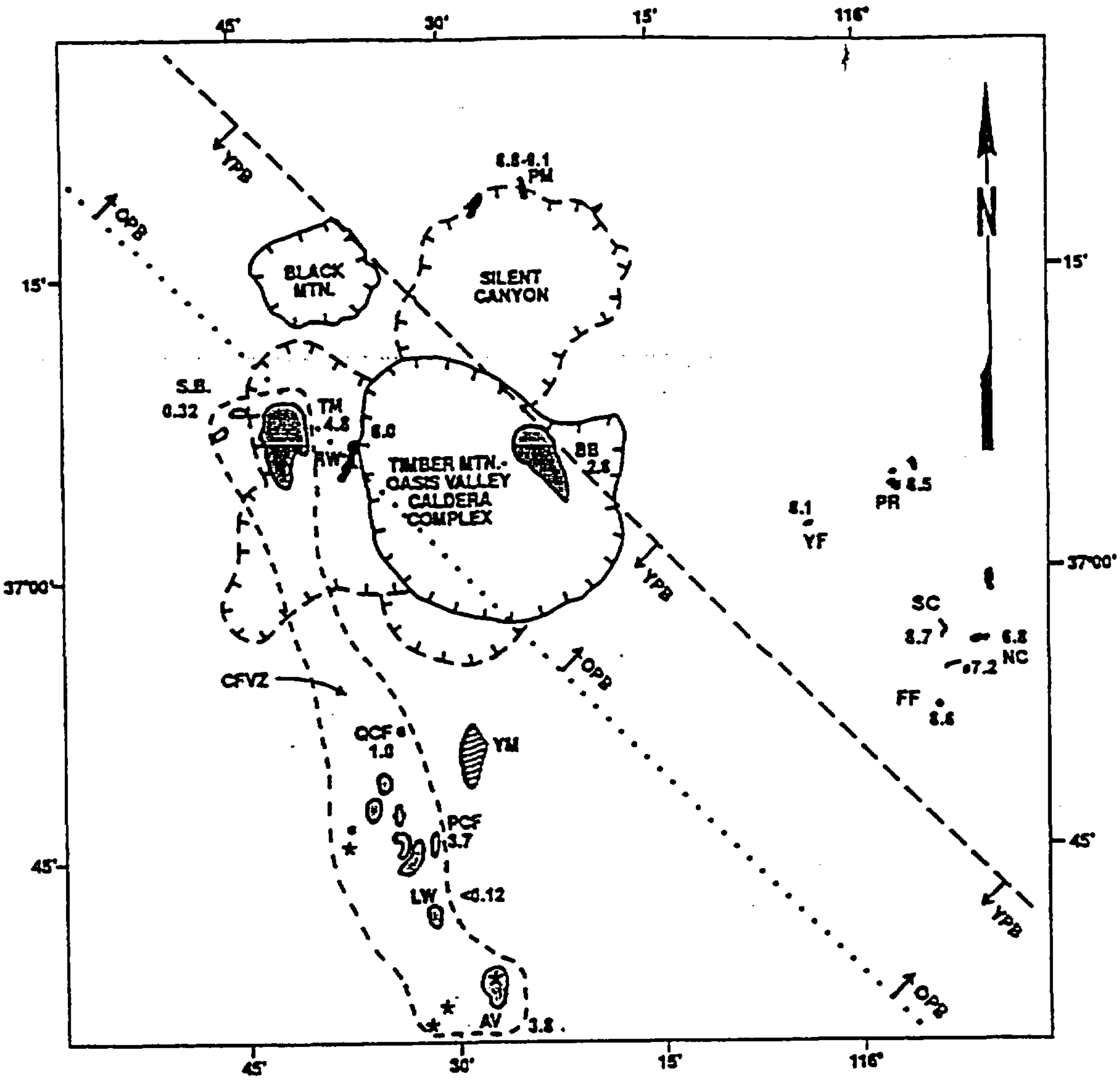

Figure 2. Post-Caldera Basalt of the Yucca Mountain region. Shaded areas are the Older Post-Caldera Basalt (OPB) including: RW: basalt of Rocket Wash, PM; basalt of Pahute Mesa; SC: basalt of Scarp Canyon; PR: basalt of Paiute Ridge; YF: basalt of Yucca Flat; NC: basalt of Nye Canyon; FF: basalt of Frenchman Flat Stippled areas are the Younger Post-Caldera Basalt (YPB) including: TM: basalt of Thirsty Mesa; AV: basalt of Amargosa Valley (confirmed by exploratory drilling); PCF: Pliocene basalt of southeast Crater Flat; BB: basalt of Buckboard Mesa; QCF: Quaternary basalt of Crater Flat; SB: basalt of Sleeping Butte; LW: basalt of Lathrop Wells. Asterisks mark aeromagnetic anomalies identified as potential buried basalt centers or intrusions (Kane and Bracken, 1983; Crowe et al. 1986). Dashed line encloses the area of the Crater Flat Volcanic Zone (CFVZ). Numbers associated with the symbols for the volcanic units of the OPB and YPB are the age of the volcanic centers in million years. Modified from Crowe and Perry (1989).

3. *A regional evaluation of the possible presence of magma bodies in the Yucca Mountain region.* This activity will involve an integrated evaluation of geophysical data that provides information on the subsurface characteristics of the Yucca Mountain region (information provided from the preclosure and post-closure tectonics program). The first phase of this evaluation has been completed (Thompson, 1994). Telseismic tomographic data for the YMR are permissive with but not conclusive that deep crustal magma chambers may be present in the YMR. These data will be tested against the results of seismic reflection/refraction surveys and new teleseismic data gathered from the upgraded Yucca Mountain seismic net. A second phase of focused geophysical work will be undertaken if collaborative evidence is obtained that supports both the existence of crustal magma bodies in the Yucca Mountain region and the interpretation that these bodies are a result of the operation of magmatic processes that are *not* represented in the volcanic record of the region. The second phase will include planning and gathering of additional geophysical data focused on resolving anomalies that could represent magma. It will also include measurements of the isotopic composition of the noble gases in ground water as an independent cross-check of the possible presence of magma in the crust beneath the Yucca Mountain region (Activity 8.3.1.8.1.1.3, Presence of Magma Bodies in the Vicinity of the Site).

4. *Estimation of the probability of future magmatic disruption of the potential Yucca Mountain site.* This activity will refine the methodology for estimating the recurrence rate of both eruptive and subsurface events, for integrating the recurrence rate with the probability of magmatic disruption, and for producing probability distributions for future eruptive and/or intrusive events and processes that could affect the repository or repository system. The PVHA and probability distributions established for data from studies of volcanic effects will be submitted to and used in performance assessment models to evaluate the long-term performance of the waste isolation system (TSPA). The revised probability estimations will incorporate newly obtained information from site characterization studies (Study Plan 8.3.1.8.5.1, Study Plan 8.3.1.8.1.2 and Study Plans for the preclosure and post-closure tectonics program) (Activity 8.3.1.8.1.1.4, Probability Calculations and Assessment) and information from an independent investigation that uses methods of expert judgment for PVHA.

2.0 SCOPE OF WORK

The following sections describe the rationale and constraints for the four activities of this study plan. For continuity, the discussions of these topics are described by individual activity.

2.1 Location and Timing of Volcanic Events (Activity 8.3.1.8.1.1

An assessment of the probability of magmatic disruption of the repository requires evaluation of data on the location, geochronology, eruptive history, and volume of Pliocene and Quaternary basaltic volcanic centers in the Yucca Mountain region (see Study Plan 8.3.1.8.5.1, Characterization of Volcanic Features).The purpose of this activity is to collate topographic and geologic maps of the location of volcanic centers, and to provide accompanying tables listing and referencing information on the geochronology of recognized volcanic events, the eruptive history of volcanic centers, and the volume of major volcanic deposits. This data will be summarized for basaltic volcanic rocks of 5.0 Ma and younger using the concept of volcanic cycles described in Crowe et al. 1995. These data will be compiled and standardized to document the data base for PVHA in a single, easily accessible reference. No alternative methods are known that could be used as substitutes for compiling maps, geochronology, eruption history and volume information.

The field and geochronology data for this activity will be obtained from Activity 8.3.1.8.5.1.1, Volcanism Drill Holes; Activity 8.3.1.8.5.1.2, Geochronology Studies, and Activity 8.3.1.8.5.1.3, Field Geologic Studies. Volume estimations for volcanic events will be obtained from work conducted for this study plan under Activity 8.3.1.8.1.1.4, Probability Calculations and Assessment. The referenced geochronology and volume data will be accompanied by a brief discussion of the precision, accuracy, advantages, and limitations of the analytical methods. The acquisition of data from these activities is an ongoing task and the data have been used iteratively in PVHA. The planned work for Activity 8.3.1.8.1.1 will be initiated when the principle investigators in charge of Study Plans 8.3.1.8.1.2, and 8.3.1.8.5.1 judge that the geochronology and field studies are nearing completion. These studies are now sufficiently advanced that the final collation of data for Activity 8.3.1.8.1.1.1 is planned to begin in FY96. If additional data needs are identified during the process of data collation and review by YMP and external review groups, these data will be obtained through further studies under the appropriate activities cited above.

Final geologic maps will be compiled on orthophotographic and topographic maps (1:24000 and 1:62500) from existing geologic maps produced from Activity 8.3.1.8.5.1.3, Field Geologic Studies. The original geologic maps will generally be at a larger scale (1:5000 to 1:12000) than the compiled maps. Map units will be simplified and the information will be transferred by inspection, using geographic and topographic features. The locations of major eruptive vents of volcanic centers, and sample-collection sites for geochronology data will be compiled on orthophotographic and topographic maps. These locations (latitude, longitude, and elevation) will also be listed in table form. The location data will be obtained through a combination of interpolation from geologic maps and surveying using a global positioning survey (GPS) instrument. Tables of geochronology data will be compiled including the ages, and the methods used for the age determinations. Documents describing the geochronologic measurements and analytical information will be referenced. If no reference is available for geochronology measurements, the analytical data will be included in a data catalog. No procedures are required for this activity because all data are obtained from other activities. The only required equipment, materials and supplies used for this activity are orthophotographic and topographic maps and GPS surveying instruments.

Compilation of geologic maps and tables of geochronology, volume and location data are standard methods for displaying information for a volcanic center. The location of volcanic centers will be shown on the geologic maps and the latitude, longitude and elevation of major vents and sample sites for geochronology measurements will be listed in data tables.

No measurements will be made and no data analyses are required for this activity. There are no constraints with respect to site impacts or schedule.

2.2 Evaluation of the Structural Controls of Basaltic Volcanic Activity (Activity 8.3.1.8.1.1.2)

2.2.1 Objectives, Methods, and Scope of the Data

There are two objectives to an evaluation of the structural controls of basaltic volcanic activity. First, the structural features and tectonic framework of the Yucca Mountain area and region will be examined on a systematic basis using constraints from data provided from the site characterization activities listed in Table 1. Not all data are expected to be significant nor will all data be used; however the range of studies summarized on Table 1 includes all information that could be important for assessing the structural controls of basaltic volcanic centers. We will attempt from this work to develop models that describe an association between structural and tectonic features, and the spatial distribution of Pliocene and Quaternary volcanic centers. The models will attempt to delineate representative volcanic zones (analogous to the identification of seismic source zones in PSHA) that may have provided or could provide pathways for the ascent of basaltic magma and therefore control the location of volcanic centers. The emphasis of this approach will be on identifying and describing a range of possible spatial and structural models that are consistent with geologic, tectonic, and geophysical data for the site region and with an understanding of the physical processes of ascent and eruption of basalt magma.

Second, once models for the spatial and structural controls of volcanism are developed, we will attempt to determine if these models can be factored numerically into the disruption parameter of the probability formula. The approach used will be to construct a catalog of spatial and structural models and to estimate the values of the disruption parameter for the models and subsets of the models. Initially, we will not attempt to discriminate the relative merits of the models or develop a set or sets of preferred models. The test of the significance of individual models will be through evaluating how specific models affect numerically the data range of the disruption parameter. Examples of estimations of the disruption parameter using multiple alternative models are described in Crowe et al. (1995).

Two methods will be used to constrain the disruptive parameter. The first method is the development of models of the distribution of Pliocene and Quaternary volcanic centers. Different age intervals and combinations of spatial patterns of volcanic centers will be used to identify volcanic zones. These zones are inferred to follow the regional structural controls of basaltic volcanism. That is the geometry of the zones should reflect the larger-scale tectonic and structural features that favor or permit ascent and eruption of magma. The source zones are constructed to outline and classify spatial differences in the probability of occurrence of future volcanic events. The probability of event recurrence should be higher *within* a zone, and lower *outside of* a zone. Further, a range of assumptions can be used to describe the distribution of volcanic centers *within* a zone. The most direct approach and one that requires the fewest assumptions is to infer that events are randomly distributed within zones. Other alternative types of preferential weighting of sites or areas within zones are possible but require additional information (Smith et al. 1990; Connor and Hill, 1993; 1995; Crowe et al. 1995). No initial preference will be given to the alternative spatial models, rather the emphasis of the estimations is on establishing ranges of values for the alternative models of the disruption ratio.

There are two classes of spatial models. The first are models that do not include the Yucca Mountain site and the second are models that include the Yucca Mountain site. The disruption parameter can be estimated readily for the latter class of spatial models. The former class requires additional considerations and several somewhat different approaches have been used for these models including expansion of the zones to accommodate representative ranges in the dimensions of subsurface feeder systems for volcanic centers (Crowe et al. 1993; 1995), and

TABLE 1

STUDIES AND ACTIVITIES PROVIDING INFORMATION FOR ACTIVITY 8.3.1.8.1.1.2: EVALUATION OF THE STRUCTURAL CONTROLS OF VOLCANIC ACTIVITY

Study Number	Activity Description	Application to Activity 8.3.1.8.1.1.2
8.3.1.8.5.1	Field Geologic Studies (8.3.1.8.5.1.3)	Identification of bedrock structures adjacent to basaltic volcanic centers. Relationship of these structures to known faults or fault systems.
8.3.1.17.4.1	Compile Historical Earthquake Record (8.3.1.17.4.1.1)	Spatial relationship between historical seismicity and location of basaltic volcanic centers.
8.3.1.17.4.1	Monitor Current Seismicity (8.3.1.17.4.1.2)	Spatial relationship between monitored seismicity and location of basaltic volcanic centers.
8.3.1.17.4.3	Conduct and Evaluate Deep Geophysical Surveys in an East-West Transect Crossing the Furnace Creek Fault Zone, Yucca Mountain, and the Walker Lane (8.3.1.17.4.3.1)	Use geophysical studies to evaluate the tectonic framework of the Yucca Mountain region and evaluate whether or not identified structures are associated with sites of sub-surface and surface basaltic magmatism.
8.3.1.17.4.3	Evaluate Quaternary Faults Within 100 km of Yucca Mountain (8.3.1.17.4.3.2)	Relationship between sites of Pliocene and Quaternary volcanism and Quaternary faults.
8.3.1.17.4.3	Evaluate Structural Domains and Characterize the Yucca Mountain Region with Respect to Regional Patterns of Faults and Fractures (8.3.1.17.4.3.5)	Compare orientations of cluster alignments of basaltic centers and location of basaltic volcanic centers with structural domains of the Yucca Mountain region.
8.3.1.17.4.4	Evaluate the Mine Mountain Fault System (8.3.1.17.4.4.2)	Evaluate the spatial relationship between the northeast-trending faults of the Mine Mountain fault system and the location of basaltic volcanic centers, with emphasis on the location of the Lathrop Wells volcanic center.

TABLE 1

STUDIES AND ACTIVITIES PROVIDING INFORMATION FOR ACTIVITY 8.3.1.8.1.1.2:
EVALUATION OF THE STRUCTURAL CONTROLS OF VOLCANIC ACTIVITY
(continued)

Study Number	Activity Description	Application to Activity 8.3.1.8.1.1.2
8.3.1.17.4.4	Evaluate the Stagecoach Road Fault Zone (8.3.1.17.4.4.3)	Evaluate evidence of spatial association between the Stagecoach Road fault zone and the location of the Lathrop Wells volcanic center. Evaluate the relationship between the timing of volcanic events and the timing of faulting events. A particularly important observation is the recognition of two horizons of basaltic ash, presumably derived from the Lathrop Wells center, in a trench exposure of the Stagecoach Road fault.
8.3.1.17.4.5	Evaluate Postulated Detachment Faults in the Beatty-Bare Mountain Area (8.3.1.17.4.5.2)	Evaluate the spatial association between basaltic volcanic centers of Crater Flat and postulated detachment faults in the Bare Mountain and Yucca Mountain areas.
8.3.1.17.4.6	Evaluate Quaternary Geology and Potential Quaternary Faults at Yucca Mountain (8.3.1.17.4.6.1)	Evaluate the spatial association between Pliocene and Quaternary basaltic volcanic centers and known and potential Quaternary faults. Evaluate variations in the amount and nature of Quaternary faulting and the proximity to Quaternary basalt centers.
8.3.1.17.4.7	Detailed Aeromagnetic Survey of the Site Area (8.3.1.17.4.7.3)	Evaluate possible existence of and evidence for the structural orientation of subsurface feeder dikes at basaltic volcanic centers of Crater Flat from detailed aeromagnetic survey data.
8.3.1.17.4.8	Evaluate Published and Unpublished Data on Paleostress Orientation at and Proximal to the Site, and Assess the Relevance of These Data to Quaternary Tectonics (8.3.1.17.4.8.1.3)	Evaluate the effects of the stress field at Yucca Mountain on the location of individual Pliocene and Quaternary basaltic volcanic centers and on the orientation of volcanic clusters.

TABLE 1

STUDIES AND ACTIVITIES PROVIDING INFORMATION FOR ACTIVITY 8.3.1.8.1.1.2:
EVALUATION OF THE STRUCTURAL CONTROLS OF VOLCANIC ACTIVITY
(concluded)

Study Number	Activity Description	Application to Activity 8.3.1.8.1.1.2
8.3.1.17.4.11	Analyze Lateral Component of Crustal Movement Based on Historical Faulting, Seismicity, and Trilateration Surveys (8.3.1.17.4.11.1)	Evaluate the spatial relationship between areas of crustal movement and the location of Pliocene and Quaternary basaltic volcanic centers.
8.3.1.17.4.12	Evaluate Tectonic Processes and Tectonic Stability at the Site (8.3.1.17.4.12.1)	Evaluate spatial and structural models of the locations of basaltic volcanic centers in relationship to tectonic models for the Yucca Mountain site.
8.3.1.17.4.12	Evaluate Tectonic Models (8.3.1.17.4.12.2)	Integrate tectonic models for the Yucca Mountain region with models of the structural controls of sites of Pliocene and Quaternary basaltic volcanic activity.

expansion of the repository site (Crowe and Carr, 1980; Connor and Hill, 1993; 1995). Both methods have limitations and can result in somewhat arbitrary decreases or increases in the estimates of the disruption ratio. An alternative approach that we will use for this study plan is to maintain the spatial definition of a zone but to assign a geometry to a volcanic event that reflects the dimensions of the feeder systems for a volcanic event. These dimensions will be based on alternative models of basalt feeder systems, using data from the Yucca Mountain region, from analog areas, and from the geologic literature. Thus for the first class of zones (repository not included in the zone), a volcanic event will have a finite probability of disruption if the event occurs away from the repository but sufficiently close so that feeder dikes associated with the event could extend into the repository.

A second approach that will be used for studies of the structural controls of sites of basaltic volcanism is to identify alternative *structural* models for the YMR that attempt to explain the observed distribution of basaltic volcanic events ≤ 5.0 Ma. This approach will also use the data from Table 1 and attempt to develop systematic models of potential associations between structural features and the location of volcanic centers. Two constraints will be followed in assessing the data and developing structural models. First, each model will be tested against the geologic record of the Yucca Mountain area. A model will be judged unacceptable for this approach if it cannot be supported by data from the geologic record or if it is conceptually unfeasible based on an understanding of magmatic processes. Second, the structural model may not be included in probabilistic studies if the model or extrapolations of the model do not result in disruption of the repository or repository system assuming representative dimensions of subsurface feeder systems. We anticipate that there are a range of feasible models that cannot be shown, using reasonable assumptions, to result in disruption of the Yucca Mountain site. The same approaches used for the two classes of distribution models will be applied to the structural models. Structural models will be subdivided into those models that include the repository or repository system, and those models that could disrupt the repository only when the events are expanded through assignment of dimensions of feeder systems.

Examples of the application of spatial and structural models to estimations of the disruption parameter are described in Crowe et al. (1995). There are a large number of alternative methods that can be used to calculate the disruption ratio and only limited data to assess the merits of alternative models. No attempt will be made to develop a single model or a set of preferred spatial and structural models for this activity. Rather, we will systematically evaluate the structural and tectonic data from the activities listed in Table 1 to attempt to develop a data catalog of permissive models of the spatial and structural controls of the location of basaltic volcanic centers. For each model, we will attempt to constrain the probability of disruption of the repository and specified areas of the repository system. The emphasis of this activity will be on continuing to develop and test models for the disruption parameter and to test how varying spatial and structural models affect the numerical estimates of the disruption ratio.

We will use an additional and different approach, as noted above, to assessing the disruption ratio because of the previously described ambiguities in the resulting disruption ratio from expanding spatial and structural source zones (Crowe et al. 1995), or from expanding the repository area (Connor and Hill 1993; 1995). Computer simulation modeling will be used to estimate the probability of magmatic disruption of the repository and the repository system using methods developed by Sheridan (1992) and Wallmann (1993). Simulation modeling will be applied to the sets of alternative spatial and structural models described in the volcanism status report (Crowe et al. 1995). For each spatial and structural model, simulations will be run using different types of area intersections and subsurface feeder systems. These include:

1) intersection of the repository by a conduit plug and feeder dikes (*the most likely scenario for surface radiological releases from volcanic eruptions).*
2) intersection of the repository system by a conduit plug with feeder dikes extending into the repository (*a scenario with subsurface effects and a low or moderate probability of radiological releases from volcanic eruptions).*
3) intersection of the repository system by a conduit plug and feeder dikes with no penetration of the repository (*a scenario with subsurface effects and a very low or no probability of radiological releases from volcanic eruptions).*
4) intersection of the repository system by a conduit plug, feeder dikes, and sill-like intrusions (*a scenario with subsurface effects and no eruptive effects)*

The orientations of the basalt feeder systems will be established using constraints from the local stress field, observed orientations of basalt centers and cone alignments, and predictions/observations of the spatial geometry imposed by individual spatial or structural models. For estimations of the probability of magmatic disruption of the repository, the repository will be treated as a plane and the areal dimension of the plane will be established from repository dimensions used in TSPA. The dimensions will vary with alternative repository thermal loadings (for example, Wilson et al. 1994; Andrews et al. 1994). Cumulative probability distributions will be produced from the simulations for the likelihood of disruption and for the area of disruption. For estimations of the probability of magmatic disruption of the repository system, the system will be treated as a plane using dimensions from TSPA and cumulative probability distributions of the likelihood of disruption, and the areaof disruption will be produced. Data from these simulations will be used to refine the disruption ratio for specific spatial and structural models. The results of the simulation modeling will also be used as input for studies of the subsurface effects of magmatic disruption of the potential repository (Study Plan 8.3.1.8.1.2).

Discussion of the methods for incorporating the data for the disruption parameter in probability calculations is presented in Activity 8.3.1.8.1.1.4, Probability Calculations and Assessment. Any feasible spatial or structural model will be used for the location of basaltic volcanic centers in the Yucca Mountain region. We will also include alternative spatial and structural models developed by the State of Nevada, the Nuclear Regulatory Commission (NRC) and NRC contractors, and external organizations that review volcanism studies.

We originally planned to develop a detailed procedure for the studies of the structural controls of basaltic volcanism. However, the construction of individual spatial and structural models and their application to estimations of the disruption parameter varies considerably for specific models. This type of calculation is not amenable to procedural control. The development of models and their application to calculations of the disruption parameter will follow Los Alamos Quality Procedure (QP) LANL-YMP-QP-3.5, Documenting Scientific Investigations. Use of computer software for this activity will follow LANL-YMP-QP-3.20, 3.21, 3.26, and 3.27, and LANL-YMP-SQAG, Software Quality Assurance Guide.

<u>Representativeness of the Approach</u>

What is the degree of confidence for establishing correlations between the location of volcanic centers and spatial, structural, or tectonic features in the Yucca Mountain area? We will evaluate the structural controls of volcanism for all Pliocene and Quaternary small-volume basaltic volcanic centers in the Yucca Mountain region. We will also consider extending the assessment back in time to include the older Postcaldera basalt (9 Ma). These older volcanic events are not representative of expected future volcanic activity in the YMR. However, they provide more data on the spatial and structural controls of sites of basaltic volcanism and may provide a broader perspective for development of spatial and structural models. We recognize that the limited number of volcanic centers in the YMR makes it impossible to conclusively prove or disprove alternative spatial and structural models of the distribution of basaltic volcanic centers. Instead of attempting to discriminate alternative models, we will examine the effect of different models on the disruption parameter. If individual spatial and structural models do not lead to significant differences in the disruption parameter, it may not be important or necessary to discriminate models. Thus, this question can be partially resolved by developing comprehensive sets of alternative models of the spatial and structural controls of the location of basaltic volcanic centers and then establishing the range of the disruption parameter from the range of models. There can never be complete confidence that all potential spatial and structural models of the distribution of volcanic centers will be identified. However, by focusing the studies on identification of alternative models, by including all models developed by workers outside the YMP, and by examining the minimum and maximum bounds on the disruption parameter (Crowe et al. 1995), we hope to develop reasonable assurance that the problem has been adequately constrained.

How adequately can we predict the potential location of future sites of volcanic activity? This question must be addressed by examining the geologic record of volcanism in the Yucca Mountain region. The location of past volcanic activity almost certainly was controlled at least partly by existing structures in the Yucca Mountain region. Therefore, the best method for assessing the future structural controls of the location of basaltic volcanic centers is through studying the geologic record. There have been approximately 21 volcanic centers formed in the Yucca Mountain region during the last 4.8 Ma (this number assumes that the aeromagnetic anomalies in the region are younger than 4.8 Ma and represent buried volcanic centers; Crowe et al. 1986; 1995). Twenty of these centers are located in the CFVZ; one is located in the ring fracture zone of the Timber Mountain caldera (basalt of Buckboard Mesa). The geologic record of 21 volcanic centers demonstrates with a reasonable degree of confidence that future basaltic eruptions are unlikely to occur at Yucca Mountain. That is, volcanic activity during a span of 4.8 Ma **did not** penetrate the exploratory block and probably did not penetrate the controlled area surrounding the exploratory block. Based on the presumption that future volcanic centers will follow the same general patterns of past centers, it is unlikely that patterns developed over 4.8 Ma will change dramatically in the next 10,000 years (10,000 years is 0.2% of 4.8 Ma). Thus, while we are unable to define numerically the exact probability of a future volcanic center forming directly above the exploratory block of Yucca Mountain, we can apply probabilistic analyses using multiple alternative spatial and structural models to bound the likelihood and uncertainty of the disruption parameter.

An important point must be emphasized when considering spatial and structural models of the distribution of volcanic events in the YMR. An appealing assumption is that the location of past volcanic centers constrains the location of future volcanic centers. Several alternative models have emphasized this approach (the high risk zones of Smith et al. 1990; the nonhomogeneous cluster models of Connor and Hill, 1993; 1995). While these models represent reasonable alternative models of structural controls, they do not take into account two important observations from the geologic record. First, volcanic centers tend to form as coeval clusters (Crowe and Perry, 1989). Detailed chronology studies of the different centers in a cluster show that the ages of the centers *within clusters may not be resolvable* using established geochronology methods Instead the centers appear to form during emplacement of temporally related pulses of magma and the separate centers are not independent volcanic events. Models that treat each center in a contemporaneous cluster as an independent volcanic event may over-emphasize the spatial predictability of the structural controls of the location of volcanic centers. Second, if the specific location of volcanic centers and volcanic clusters are examined *in sequence*, there are no systematic patterns to the location of successive volcanic events; jump directions and distances between successive events are nonsystematic (Crowe et al. 1993; 1995). That is the location of a preceding volcanic event does not constrain the location of a succeeding volcanic events. Thus, spatial and structural models that predict the location of future volcanic events from the location of a previous event or events infer a more systematic pattern in the distribution of volcanic events than is supported by the volcanic record.

2.2.2 Constraints

Data for an evaluation of the structural controls of basaltic volcanic activity is provided from other studies (Table 1). All data used in the activity will be obtained from Study Plan 8.3.1.8.5.1, Characterization of Volcanic Features, from the preclosure and post-closure tectonics study plans of Section 8.3.1.17.4 of the SCP and from Study Plan 8.3.1.8.1.2 Physical Processes of Magmatism and Effects on the Potential Repository. Investigations for this activity include only analyses of data from other sources. Because no direct measurements or experimental tests are planned for this activity, there are no potential impacts on the site. The data parameters, estimation methods, precision, and accuracy of the estimations will be defined for each model. However, the uncertainty of the disruption parameter will be established through the procedures for estimating the probability of magmatic disruption of the repository and the repository system. The disruption parameter will be treated as a probability distribution to incorporate the uncertainty of the estimations. The first phase of revised estimations for this activity were completed and included in Chapter Seven of the volcanism status report (Crowe et al. 1995). Iterative changes in the probability estimations from revised studies for this activity will be produced as data are obtained from the preclosure and post-closure tectonics programs and when probability distributions from expert judgment studies are completed (FY96).

There are two potential constraints for this task. First, can we develop an acceptable methodology for quantifying the disruption parameter of the probability estimations within the time constraints of the site characterization studies? Second, how do we confirm that the set of volcanic and tectonic models for the structural controls of basaltic volcanic activity is acceptably comprehensive? These constraints appear significant but resolvable. First, we have already developed and defined mathematically multiple spatial models (25 spatial models or model subsets; see Table 7.13, Crowe et al. 1995) and multiple structural models (17 structural models or model subsets; see Table 7.17, Crowe et al. 1993) for the distribution of basaltic volcanic centers in the YMR (Crowe et al. 1982; Crowe, 1986; Crowe et al. 1989; 1995). Alternative models will continue to be developed as new information is obtained from the site characterization studies. These models have been used and modified by researchers affiliated with the State of Nevada and the NRC and these groups have developed independent models of the controls of the location of basalt centers. We have evaluated and adopted nearly all of the modified or independent models used by these workers in our probabilistic assessments (Crowe et al. 1995). Additionally, the approaches used to develop and assess controls of the distribution of basaltic volcanic centers is similar to approaches used for the spatial distribution of earthquakes in probabilistic seismic hazard assessment (PSHA). Thus, the relatively widespread usage and acceptance of our spatial and structural models and the acceptance of similar approaches in PSHA for siting of nuclear facilities is viewed as an acceptance of the probabilistic approach to developing models for the disruption parameter. Second, the equation for calculating the probability of magmatic disruption of the repository (Section 3.4.2) allows for flexibility in assessing alternative spatial and structural models for the disruption parameter. As new models are developed, they can be factored readily into the disruption parameter of the probability estimations. Thus while there are no existing standards for testing or assessing "comprehensiveness" in development of models for the structural controls of basaltic volcanic centers, we will attempt to minimize this constraint through the use of multiple alternative models that are developed over the time span of site characterization studies.

2.3 Presence of Magma Bodies in the Vicinity of the Site (Activity 8.3.1.8.1.1.3)

2.3.1 Objectives, Methods and Scope of Work

An evaluation of the probability of magmatic disruption of the repository is based primarily on an assessment of the past record of volcanism in the Yucca Mountain region. Assessments of the recurrence rate of volcanic and intrusive events and the spatial and structural controls of volcanic activity are dependent on the assumption that past recurrence rates and patterns of volcanic activity can be used to forecast future recurrence rates and patterns of volcanic activity. It is therefore important to consider whether there is evidence of recent changes in any of these processes. These questions are evaluated partly in Activity 8.3.1.8.5.1.5, Evolutionary Cycles of Basaltic Volcanic Fields (Study Plan 8.3.1.8.5.1, Characterization of Volcanic Features) and in Activity 8.3.1.8.1.1.4, Probability Calculations and Assessment. However, an equally important question is whether processes have occurred in the recent geologic past or are now occurring that could modify future patterns of volcanic activity? The major identified concern is evidence of the presence of magma in the crust beneath the Yucca Mountain region. Evidence of the operation of processes that recently or could now be producing magma would require a reassessment of the future recurrence rates of volcanic activity and processes controlling the distribution of volcanic centers. This would directly affect the assumptions used for PVHA.

The technical rationale for this activity is to review periodically geophysical data collected in the vicinity of the Yucca Mountain site to determine if there are any indications of the presence of subsurface magma. This evaluation will follow a twofold approach. A range of geophysical data are being obtained for the preclosure and post-closure tectonics studies (Section 8.3.1.8.17, Preclosure Tectonics). The first approach of this activity is to review the results of the framework geophysical studies to determine if there is any evidence that is suggestive of the presence of magma beneath the Yucca Mountain region. Geophysical data for this activity will be collected from three activities. The activity 8.3.1.17.4.3.1, Conduct and Evaluate Deep Geophysical Surveys, will provide data from a reflection/refraction seismic survey across Crater Flat and Yucca Mountain. Other proposed geophysical methods in this activity include seismic reflection, seismic refraction, gravity, magnetic, and magnetotelluric surveys. In addition, the curie temperature isotherm will be mapped using large-scale aeromagnetic data. Heat flow data will be evaluated from Activity 8.3.1.1 5.2.2.1, Surface-Based Evaluation of Ambient Thermal Conditions. Finally, Study 8.3.1.17.4.1, Historical and Current Seismicity, will provide enhanced teleseismic data that can be used to further evaluate evidence of magma bodies.

These geophysical data will be analyzed as part of the individual activities that cover a range of topics. We will evaluate the results of data reduction and interpretations from the studies for these activities to make three decisions for volcanism studies. First, are the data obtained sufficient to resolve questions of the possible existence of crustal magma bodies? Second, is evidence present from the geophysical studies that is indicative of the presence of crustal magma bodies? Third, is there any relationship between possible magma bodies and the surface record of volcanism? If the answer to any or all questions is yes, we will develop a document describing additional geophysical and noble gas studies that may be required to resolve the issue of the possible presence of crustal magma in the Yucca Mountain region.

The existing geophysical data has been reviewed by an external consultant in tectonics and geophysics. The purpose of the review was to determine whether sufficient information has been obtained to assess the possible presence of magma beneath the Yucca Mountain region. Additionally, the review evaluated whether there is confirmed evidence of geophysical anomalies that can be interpreted as magma bodies. Permissive but not conclusive evidence was obtained that magma bodies could be present beneath the Yucca Mountain region (Evans and Smith 1992). The presence of these bodies will be evaluated further from the results of ongoing or planned geophysical studies. The following geophysics studies were identified as providing potential benefit to the volcanism studies (Thompson, 1994):

1) extension of aeromagnetic coverage to the Paiute Ridge area of the Half Pint range for assessment of detection depths of basaltic intrusions (new activity of Study Plan 8.3.1.8.2.1).
2) continued magnetization studies of basalt, tuff and basement rock (Study Plan 8.3.1.8.2.1).
3) seismic reflection and refraction studies particularly across the Crater Flat basin (preclosure and post-closure tectonics program; see Table 1).
4) refined earthquake tomography (preclosure and post-closure tectonics program; see Table 1).
5) strain-rate studies including long-term geodetic studies (proposed studies in the Exploratory Studies Facilities).
6) in situ stress measurements (preclosure and post-closure tectonics program; see Table 1).

If evidence of the existence of magma bodies in the crust is verified through these or related studies, the second approach to this activity would be undertaken. This approach would involve two efforts. First, because reduction and interpretation of geophysical data often results in nonunique interpretations, it is possible, perhaps probable, that some data may be obtained that is permissive with the presence of subsurface magma. If magma is present in the crust beneath Yucca Mountain, it should be confirmed through application and evaluation of the results of multiple geophysical methods. Based on an evaluation of the results of geophysical data from the first approach, we would undertake a second phase of geophysical studies focused on exploring any identified anomalies that could be attributed to subsurface magma. We would employ many of the same techniques used in the first approach, but scale the second phase of geophysical investigations to provide maximum resolution of the potential magma anomalies. Second, we would obtain ground water samples from existing wells in the Yucca Mountain region. These samples would be used to measure the isotopic composition of the noble gases, with emphasis on the $^3He/^4He$ ratios. Torgersen et al. (1987; see also Kennedy et al. 1985) have shown that high ratios of $^3He/^4He$ may be used to identify zones of subsurface magma.

2.3.2 Constraints

Geophysical data for this activity will be obtained from Sections 8.3.1.8, Post-closure Tectonics, and 8.3.1.17, Preclosure Tectonics (see SCP Table 8.3.1.17-9 for a summary of geophysical methods). No direct geophysical measurements are planned initially for this activity; therefore, there are no identified site impacts from this activity. Samples of ground water for measurement of the isotopic composition of the noble gases can be obtained from surface springs, and from existing and planned drill holes in and around Yucca Mountain and in the Amargosa Valley. There are no anticipated impacts on the site from the noble gas studies. The descriptions of geophysical data--including advantages, limitations, precision, and accuracy are discussed in the study plans for the preclosure tectonics program.

2.4 Probability Calculations and Assessment (Activity 8.3.1.8.1.1.4)

2.4.1 Objectives, Methods, and Scope of Data

The possibility of future magmatic activity has been identified as a potentially adverse condition for the Yucca Mountain site (DOE, 1986, 1988). Disruption of a repository at Yucca Mountain by ascending magma followed by eruption could lead to release of radioactive waste to the accessible environment. Intrusion or passage of magma into the repository or the repository system of the YMR (associated or not associated with an eruption) could alter the geohydrologic setting of the waste isolation system and could change transport times of radioactive waste to the accessible environment. The objective this activity is to attempt to estimate: (1) the probability of magmatic disruption of the repository and the repository system for a range of magmatic events (Crowe et al. 1995) and (2) the probability distributions for data obtained from Study Plan 8.3.1.8.1.2 Physical Processes of Magmatism and Effects on the Potential Repository.

The PVHA for the Yucca Mountain site requires evaluation of the potential for renewed volcanic activity (Crowe et al. 1995). Two questions must be considered. First, could an episode of volcanic activity occur in the Yucca Mountain region during the 10 ka isolation period of a repository? Second, if there is renewed volcanism (eruptive or subsurface activity), could it disrupt or affect the repository or the repository system?

These questions are best answered by PVHA. A probabilistic assessment provides a numerical definition with defined uncertainty of the hazards of future volcanism. Without a numerical definition, the hazards of volcanism would have to be assessed through subjective judgments. Subjective assessments are difficult to interpret within the regulatory guidance of 10 CFR 60.112. Second, the recommendations of 10 CFR 60.112 with respect to tectonic processes are disposed toward probabilistic assessment. Third, the geologic record of basaltic volcanism in the Yucca Mountain region is compatible with the requirements of application of a probabilistic approach. There has been a regularity in patterns through time of the composition, volume, and style of basaltic volcanism in the Yucca Mountain region during the last 9 Ma (Crowe 1990). At about 9 Ma, there was a transition from large volume (>1 km^3) basaltic volcanism associated with the waning stages of the Timber Mountain-Oasis Valley caldera to small volume basaltic volcanism (<1 km^3; see Crowe, 1990). The small volume basalt are all alkali basalt (Vaniman et al. 1982). There has been an approximate consistency in the magma-output rates, with the exception of the Pliocene and Quaternary when output rates may have declined (Vaniman and Crowe, 1981; Crowe et al, 1982; Crowe, 1986; Crowe and Perry, 1989; Perry and Crowe, 1992). Eruptive processes at basalt centers have been of intermixed hawaiian and strombolian style with minor to significant hydrovolcanic activity. The eruptive classifications are used after Walker (1973) and Cas and Wright (1988), and are based on general characteristics of the pyroclastic deposits that are inferred to reflect eruption dynamics. Third, experience has shown that probabilistic assessment of earthquakes has become a powerful tool for seismic risk assessment, particularly for siting of nuclear facilities. There are close analogies between the methods of volcanic and seismic probabilistic assessment. Both processes involve integrated responses of the tectonic setting of the crust and mantle of individual geologic regions (Shaw, 1980). The above considerations suggest that PVRA can be conducted for the Yucca Mountain site by combining PVHA (this study plan) with studies of the total system performance assessment of a repository system. Finally, the isolation period for containment of radioactive waste may change under the revised recommendations of the National Academy of Sciences (NRC 1995). The probabilistic approach used in this study plan is flexible and the probability models used in the assessment can be readily adapted to any isolation period selected under future regulatory requirements.

The probability of magmatic disruption of a repository or the repository system (Pr_{dr}) is defined as a conditional probability:

$$Pr_{dr} = Pr(E2 \text{ given } E1)Pr(E1),$$

where *E1* denotes the recurrence rate of volcanic events in the Yucca Mountain region, and *E2* denotes the probability that the future magmatic event intersects a specified area. This probability can be expressed mathematically as (Crowe et al. 1982):

$$\Pr[\text{no eruptive event before time } t] = \exp^{(-\lambda tp)},$$

where λ is the recurrence rate of volcanic events, and p is the probability that an event is disruptive. The λ is defined differently for specific volcanic and magmatic events (Crowe et al. 1995). For most cases it is defined is the rate of formation of new volcanic centers, the event that represents the greatest risk to a potential repository. The p is defined as a/A where a is the area of concern and A is the area of the established volcanic rate or λ. The probability model assumes both homogeneous and nonhomogeneous Poisson distributions of the volcanic events through time and space (Crowe et al. 1982; Crowe 1986; Ho et al. 1991; Ho 1991; 1992; Connor and Hill 1993; 1995; Crowe et al. 1993; 1995).

Several assumptions are required to apply the probability formulas. First, the past record of basaltic volcanic activity in the Yucca Mountain region is used for probabilistic assessment because it is judged to be the best estimator of the recurrence rate and to a lesser extent the distribution of future volcanic events. This assumption is supported by the consistency of the record of volcanism in the region for the last 9 Ma (Crowe 1990). Basaltic volcanic eruptions formed spatially isolated centers comprising scoria and spatter cone(s), local tuff rings (two, possibly three centers) and associated aa lava flows. Pliocene and Quaternary volcanic activity has occurred within an approximate 2000 km^2 area designated as the Yucca Mountain Region [YMR; this area is almost identical to the Area of Most Recent Volcanism (ARMV) of Smith et al. 1990 but is expanded slightly to include aeromagnetic anomalies confirmed or suspected to represent buried volcanic centers]. We assume future volcanic events will exhibit the same general patterns of temporal and spatial variability as past volcanic events but will not necessarily occur at the same sites (Crowe et al. 1993; 1995). Further, we assume future volcanic events will occur in the YMR.

Second, we assume there has been a sufficiently detailed study of the YMR to identify all Quaternary volcanic centers. This assumption is based on a variety of evidence. Quaternary volcanic landforms are conspicuous surface topographic features in arid regions of the southwest United States. They can and have been identified through simple visual inspection of aerial photographs and even satellite photographs (Wood and Kienle 1988). Detailed geologic mapping has been completed in the near vicinity and in the region surrounding the Yucca Mountain site.

The presence and location of Quaternary volcanic centers in the YMR has been known, and their identifications have remained unchanged for several decades. Third, detailed drape aeromagnetic surveys have been completed for the Yucca Mountain region (Kane and Bracken 1983; Langenheim et al. 1992). Basaltic volcanic rocks have high magnetic susceptibility and are identified easily among the Paleozoic rocks and the alluvial fill of the basins around Yucca Mountain. Surface Pliocene and Quaternary volcanic centers are identified with high confidence on aeromagnetic data (Crowe and Carr 1980; Kane and Bracken 1983; Crowe et al. 1986; Langenheim et al. 1992). Studies of the depth of detection of basalt intrusions in tuff, alluvium and Paleozoic rocks are in progress to assess the possibility of undetected Quaternary basalt centers in the YMR, particularly in volcanic country rock (tuff). We do not assume that there are *no* undetected sites of Quaternary magmatic activity but instead argue using a variety of geologic and geophysical data that the number of undetected centers must be *small* relative to the number of *known* Quaternary centers. Therefore the uncertainty introduced by the possibility of undetected volcanic centers can be incorporated through probabilistic assessments that incorporate minimum, maximum, and most likely models of the recurrence rate.

We assume that the observations and interpretations of the volcanic deposits of the past record of volcanism are reliable, an assumption that is difficult to quantify. Here there are two sources of uncertainty. The primary method for dating of Quaternary basaltic volcanic rocks is the K-Ar method. The method becomes increasing less precise with decreasing age of volcanic rocks. However, we have constrained this problem by using multiple chronology methods for volcanic rocks of late Pleistocene age (Crowe et al. 1992; 1995). Additionally, we use multiple models for the age of volcanic events where there is uncertainty in age assignments.

The third area of uncertainty is the potential loss of the observational record for basalt centers older than a few hundred thousand years. This is primarily from erosional loss or from cover of the centers by alluvium. We have attempted to reconstruct original volumes, have drilled exploratory holes, and used aeromagnetic and ground magnetic data to estimate the areal extent of buried basalt units (Crowe et al. 1983b). Again, we accommodate this uncertainty by varying the assumptions used for volume calculations for the probability estimations. The volume-predictable, homogeneous and nonhomogeneous Poisson models use the age and erupted magma volumes to calculate magma-output rates. Because the volume of erupted magma has declined significantly through time in the Yucca Mountain region, the volume-predictable models are not strongly affected by the uncertainty of the determinations in the ages or eruptive volumes of the centers.

Finally, we assume that alternative eruptive models for the youngest Quaternary volcanic centers (monogenetic and polygenetic) could apply to the Pliocene and Quaternary volcanic centers. These two models differ primarily in their resulting assessments of the consequences of volcanic activity. The monogenetic model is generally regarded as the established model for the eruptive behavior of small volume basaltic volcanic centers whereas the polygenetic model is regarded as controversial and is not accepted by most volcanologists. The most likely future volcanic event based on the monogenetic model is the formation of a new volcanic center; the most likely future volcanic event based on the polygenetic (polycyclic) model is the recurrence of a small volume volcanic eruption at an i volcanic center (the Hidden Cone or Lathrop Wells center). This latter event has a relatively high probability of occurrence compared to a monogenetic model but the effects of a polygenetic (polycyclic) event at either of the centers would be virtually insignificant on a repository at Yucca Mountain (a high probability, low consequences event; see Crowe et al. 1995). Because of the limited acceptance of the polygenetic model for small volume basalt centers of the Yucca Mountain region, and the low *risk* of the event, we will not evaluate the polygenetic model for PVHA in this study plan. Instead we will focus our PVHA on the formation of a new volcanic center (Crowe et al. 1995). However, we have been unable to *disprove* the polygenetic model at two volcanic centers (Lathrop Wells, Hidden Cone; see Crowe et al. 1995) and it may be permissive at several other Quaternary volcanic centers (Bradshaw and Smith, 1994). Therefore, we will retain the option of assessing the polygenetic model for Study Plan 8.3.1.8.1.2. By evaluating the effects of both models, we are attempting to ensure that all potential effects of magmatic disruption of a repository are considered.

Volcanism studies have decision points that determine whether different scenarios can be eliminated from concern on the basis of a low occurrence probability, or whether magmatic effects or radiological releases must be assessed to determine the *risk* to the potential site with respect to volcanism. The logic for these decision points is described in Study Plan 8.3.1.8.2.1. The main application of probability data from this study plan is in assessments of the suitability or potential disqualification of the Yucca Mountain site by the DOE. If volcanism scenarios are eliminated from concern for a suitability decision by the DOE, they *may or may not* be eliminated from performance assessment studies of the repository system. That decision will be made by the DOE largely on the basis of continuing TSPA.

The primary basis for decision points in this Study Plan and in Study Plan 8.3.1.8.2.1 is established by an assessment of whether the initiating volcanic events have a probability of occurrence of less than 1 in 10,000 in 10,000 years (10^{-8} yr^{-1}). If the events have an occurrence probability of < 10^{-8} yr^{-1}, they will be judged **not** to be an issue that could lead to disqualification of the potential Yucca Mountain site. If the events have an occurrence probability of > 10^{-8} yr^{-1}, a two-step logic will be used to assess the significance of the events. First, the occurrence probability will be evaluated that the event will occur and will result in eruptive releases. If the occurrence probability of eruptive releases is < 10^{-8} yr^{-1}, the event will be judged **not** to be an issue that could lead to disqualification of the potential Yucca Mountain site. If the occurrence probability of eruptive releases is > 10^{-8} yr^{-1}, detailed studies will be undertaken to establish the contributions of eruptive and subsurface releases to the cumulative releases from the waste isolation system (TSPA). The studies of magmatic processes that may contribute to radiological releases are described in Study Plan 8.3.1.8.1.2. The assessment of the cumulative releases of the repository system, including the potential contributions from eruptive and subsurface magmatic activity is assessed through TSPA.

There are a sequence of key questions that must be answered for PVHA. The first is whether igneous activity is a concern for the potential Yucca Mountain site? We have established already that the presence of at least seven, possibly eight, Quaternary volcanic centers in the vicinity of Yucca Mountain is a potentially adverse condition and requires assessment through site characterization activities (DOE 1986; 1988). The second question is what is the probability of a future igneous event during the 10,000-yr isolation period of a repository for disposal of high-level waste? This is subdivided into two questions. What is the probability of a volcanic eruption and what is the probability of intrusive activity? These probabilities are dependent because each volcanic eruption must be accompanied by an intrusive event. Logic requires therefore that Pr_i is greater than or equal to Pr_v, where Pr_i is the probability of an intrusive event and Pr_v is the probability of a volcanic event. Assessment of current site data has not revealed any examples in the Yucca Mountain region where an intrusive event has occurred at or near the depths of a potential repository without an accompanying volcanic eruption. Moreover, basalt magmas are likely to actively exsolve volatiles at repository depths and the volume expansion from volatile release provides a strong driving force to produce an eruption. Current data thus suggest that $Pr_i \approx Pr_v$. However, we recognize that the supportive data from the volcanic record for these conclusions are limited because of the limited record of Quaternary and Pliocene volcanic events in the YMR. Therefore, we will continue to assess evidence of any possible conditions where Pr_i could be > Pr_v. For either case, existing data (Crowe and Carr 1980; Crowe 1986; Crowe et al. 1982, 1989; Crowe and Perry 1989; Ho et al. 1991; Ho 1992; Crowe et al. 1992; Connor and Hill 1993; Crowe et al. 1993; 1995) show that the 50 percentile value of the probability of a volcanic event *in the Yucca Mountain region* is slightly greater than 10^{-8} yr^{-1}(see Crowe et al. 1995). Therefore the probability of an eruptive and/or intrusive event must be assessed for the Yucca Mountain site (*Note: Because* $Pr_i \approx Pr_v$, *the remaining discussion will only mention* Pr_v. *We* *recognize implicitly that the described assessments apply to both events and we will continue to assess any conditions where $Pr_i > Pr_v$).*

We have established that the probability of a future volcanic eruption somewhere in the Yucca Mountain region is > 10^{-8} yr.$^{-1}$ The next question is where could the event occur? There are three options: 1) the YMR, 2) the repository system, and 3) the repository.

The likelihood of the first option, a future volcanic event in the Yucca Mountain region is:

$$Pr_o = 1 - exp^{(-\lambda tp)}$$

where Pr_o is the probability of intrusion or eruption outside of the repository and the repository system. The attribute p is significant for the equation only for events close to the boundary of the repository system. This attribute drops out of the equation because $a/A \approx 1$ as a approaches A. In this case, the annual probability of an event occurring in the Yucca Mountain region approaches λ, the recurrence rate of volcanic events. We have already established that λ is > 10^{-8} yr^{-1}. Therefore Pr_o is > 10^{-8} yr^{-1} for many cases of the probability estimations and this option must be assessed through evaluation of radiological releases.

The second option is that a future volcanic event or intrusion can occur within the repository system. Here the likelihood of the event is:

$$Pr_{Ca} = 1 - exp^{(-\lambda tp)}$$

where Pr_{Ca} is the probability of intrusion or eruption through the repository system, and p is the a/A where a is the area of the repository system and A is the area of the established volcanic rate. The repository system is larger than the repository by more than a factor of ten. Therefore, it is likely that Pr_{Ca} > 10^{-8} yr^{-1} and this option will require an evaluation of the effects of eruptive and subsurface activity.

The third option is a future volcanic event penetrates the repository. The likelihood of a volcanic event penetrating the repository is:

$$Pr_d = 1 - exp^{(-\lambda tp)}$$

where Pr_d is the probability of intrusion or eruption through the repository, and p is a/A where a is equal to the area of the repository and A is the area of the volcanic recurrence rate. If the probability of this conditional event exceeds some presently unspecified value, the site should be disqualified because of the hazards of future volcanism. Additionally, the site would be disqualified if the radiological releases associated with disruption of a repository or the repository system (TSPA) exceed the regulatory requirements.

If Pr_d is < 10^{-8} yr^{-1}, the direct effects of repository disruption and eruption at the surface are not important issues for site suitability. Volcanism studies of the effects of an eruption through a repository would be ended.

If Pr_d is > 10^{-8} yr^{-1}, assessments will be conducted of the cumulative contribution of radiological releases for TSPA from volcanic or subsurface magmatic activity. This will be accomplished by combining, through iterative studies, the PVHA from this study and the effects of eruptive and subsurface studies from Study Plan 8.3.1.8.1.2 with TSPA.

Estimations of the PVHA will follow three steps. First, methods for calculating λ, the recurrence rate of future volcanic events (extrusive or intrusive) in the Yucca Mountain region will be refined from previous studies (Crowe and Carr, 1980; Crowe et al. 1982; Crowe et al. 1993). The first iteration of these refinements are described in Crowe et al. 1995. The emphasis of these refined probability estimations was and will continue to be to identify and estimate numerically multiple alternative models of the recurrence rate of eruptive and intrusive events (E1) and the disruption ratio (E2). Cumulative probability distributions will be defined through simulation modeling using most likely, minimum, and maximum estimates of E1 and E2 (Crowe et al. 1993; 1995). Multiple alternative models of E1 will be defined in Activity 8.3.1.8.1.1.4. These data will be treated as probability distributions using the same approach applied in evaluating E2 (Crowe et al. 1993; 1995).

Sensitivity analysis will be conducted for the respective attributes (E1 and E2) of the conditional probability. This will be accomplished through simulation modeling. First, the effects of alternative models of E2 on E1 will be assessed. A spreadsheet matrix of estimates of E1 will be developed for all viable alternative models of E2. Simulation modeling will be conducted using the spreadsheet model as the input data to define modified probability distributions for E1. Failure to modify E1 for specified spatial and structural models of E2 can result in *overestimation* of the recurrence rate (Crowe et al. 1993; 1995; Wallmann, 1993).

Second, the variability of simulation output for the conditional probability will be assessed in two stages:

1) Multiple alternative models for E1 using mean or median values for E2 (sensitivity analysis for E1).
2) Multiple alternative models for E2 using mean or median values for E1 (sensitivity analysis for E2).

Results to date of sensitivity analyses shows that alternative models of E1 have limited affects on the conditional probability whereas alternative models of E2 have greater affects on the conditional probability (Crowe et al. 1993; 1995).

The probability of magmatic disruption of the repository and specified areas of the repository system from future volcanic events (PVHA) will be estimated for the following scenarios: 1) the probability of formation of a new volcanic center, 2) the probability of formation of a new volcanic intrusion, and 3) the probability of formation of a new volcanic cluster. Scenarios one through three will also be assessed as part of Study Plan 8.3.1.8.1.2 for all cases where the disruption and/or intrusion probability is greater than 10^{-8} yr^{-1}.

The investigation descriptions, the performance parameters, the tentative parameter goals, and the needed confidence for investigation requiring annual probability calculations are listed in Table 2. The definition of *high confidence* for the parameter goals described in Table 2 is that the *90 percentile value* from a cumulative probability distribution meets the parameter goals. The definition of *moderate confidence* for the parameter goals described in Table 2 is that the *mean or most likely values* of a cumulative probability distribution meet the parameter goals.

TABLE 2

INVESTIGATIONS REQUIRING INFORMATION ON THE PROBABILITY OF MAGMATIC DISRUPTION OF THE REPOSITORY

Investigation	Performance Parameter	Parameter Goal	Needed Confidence
Direct releases resulting from volcanic activity (8.3.1.8.1)	Annual probability of magmatic activity penetrating the repository	$<10^{-6}\ yr^{-1}$	High
Rupture of waste packages due to tectonic events (8.3.1.8.2)	Annual probability of magmatic activity penetrating the repository	$<10^{-5}\ yr^{-1}$	High
Changes in unsaturated and saturated zone hydrology due to tectonic events (changes in average percolation flux) (8.3.1.8.3)	Annual probability of volcanic eruption within the controlled area	$<10^{-5}\ yr^{-1}$	High
Changes in unsaturated and saturated zone hydrology due to tectonic events (changes in average percolation flux) (8.3.1.8.3)	Annual probability of major igneous intrusion within the controlled area	$<10^{-5}\ yr^{-1}$	High
Changes in unsaturated and saturated zone hydrology due to tectonic events (changes in water table elevation) (8.3.1.8.3)	Annual probability of major igneous intrusion within the controlled area	$<10^{-5}\ yr^{-1}$	Moderate
Changes in unsaturated and saturated zone hydrology due to tectonic events (changes in rock properties along transport paths) (8.3.1.8.3)	Annual probability of major igneous intrusion within the controlled area	$<10^{-5}\ yr^{-1}$	Moderate

TABLE 2

INVESTIGATIONS REQUIRING INFORMATION ON THE PROBABILITY OF MAGMATIC DISRUPTION OF THE REPOSITORY
(concluded)

Investigation	Performance Parameter	Parameter	Needed Confidence
Changes in rock geochemical properties resulting from tectonic processes (8.3.1.8.4)	Annual probability of major igneous intrusion within the controlled area	$<10^{-5}$ yr^{-1}	Moderate

Methods for Calculating the Rate of Occurrence of Volcanic Events

The first attribute of the Pr_{dq} is E1, the rate of occurrence of future volcanic events. Three approaches will be used to estimate E1 (Crowe et al. 1995): 1) time-series analysis of volcanic events, 2) homogeneous and nonhomogeneous Poisson models using event counts per time, and 3) magma-output rates. Multiple iterations of each approach will be undertaken to attempt toprovide a range of estimations that conform to various geologic assumptions for processes of basaltic volcanism in the Yucca Mountain region. These estimations will be based primarily on the patterns of basaltic volcanic activity recorded in the geologic record of the Yucca Mountain region. This record provides the best "predictor" of the recurrence rate. We will also attempt to evaluate any evidence that is suggestive of possible changes in the nature of future basaltic volcanic activity consistent with an understanding of magmatic processes using data inputs from Activity 8.3.1.8.1.2.4, Magma system dynamics and Activity 8.3.1.8.5.1.5 Evolution of Basaltic Volcanic Fields. The emphasis of this activity will be on evaluating the possible range of values of the recurrence rate of future volcanic activity. If additional methods for estimating recurrence rates of volcanic activity are developed during site characterization studies, they will be included in revised recurrence rate estimations.

Time-Series Analyses: Past studies showed that there are no distinct patterns or periodicity to the time distribution of Quaternary basaltic volcanic events in the Yucca Mountain region. Moreover, the limited number of volcanic events was judged to be insufficient for formal time-series analyses (Crowe et al. 1982, p. 178). We will continue to reevaluate this conclusion using new data provided by Activity 8.3.1.8.5.1.2, Geochronology Studies. Results of the first iteration of revised estimates of E1 (Crowe et al. 1995) show that attempts to apply time-series analyses are limited by the small number of Pliocene and Quaternary volcanic events in the YMR. The only realistic application of data from this analyses is the recognition of a **minimum** repose interval. This interval is currently estimated to be 200 ka or equivalent to an eruption recurrence rate of 5.2×10^{-6} yr^{-1} (Crowe et al. 1995).

Homogeneous and Nonhomogeneous Poisson Models of Event Counts Through Time: There are advantages and disadvantages to counts of volcanic events through time for establishing volcanic recurrence rates (volcanic events are defined as individual volcanic vents or clusters of vents where field, and chronology studies show the vents are time synchronous; see Crowe et al. 1995 for an expanded discussion of the definition of volcanic events in probabilistic assessments).

Advantages: Volcanic events are relatively easy to recognize in the field, particularly for Quaternary volcanic centers. The calculations are direct and easily understood. The recurrence rate is established by dividing the number of vents by a specified period of time. This is based on assumptions of a random distribution of volcanic events through time, and no time dependence of events (homogeneous Poisson distributed events). The recurrence rate is also established using a Weibull-modified distribution where the event return period may be non-stationary (Ho, 1991; 1992). Connor and Hill (1993) and Crowe et al. (1993; 1995) have shown that there are not significant differences between estimations of the recurrence rate using homogeneous or nonhomogeneous Poisson distribution models. We will continue to evaluate both homogeneous and nonhomogeneous Poisson models to ensure E1 is not under-estimated in any of the calculations.

Disadvantages: Volcanic events are almost certainly not randomly distributed through time; they occur episodically and exhibit volume-predictable behavior indicating they are affected by previous events. Counts of volcanic events weight equally each event and do not account for the magnitude of events (volume of eruptive events or spatial scattering of time-related eruptive vents). The method is somewhat insensitive to changes in rates of volcanic activity. Finally, because volcanic events occur episodically, counts of volcanic events can be biased arbitrarily toward either high or low rates by varying the length of time of the vent counts (Crowe and Perry, 1989). Crowe et al. (1995) showed that this disadvantage can be constrained by using time intervals that correspond to volcanic cycles for event counts.

We intend to continue to use homogeneous and nonhomogeneous Poisson models of event counts for estimating the rate of occurrence of volcanic events, but with several constraints that attempt to minimize the disadvantages of the method. First, we will restrict the time of vent counts to intervals corresponding to volcanic cycles. These periods will be the time since the onset of the Younger Post-Caldera basalt (4.8 million years) and an interval during the Quaternary period that may represent a period of accelerated recurrence rates (Connor and Hill, 1993; 1995; Crowe et al. 1993; 1995). Optionally, we may consider examining E1 using the range of models for the interval of the Postcaldera basalt (9.0 Ma and younger). Second, we will use the results of geochronology and field studies (Activities 8.3.1.8.5.1.2 and 8.3.1.8.5.1.3) to identify volcanic events and clusters of volcanic events. Closely spaced or aligned volcanic vents with similar ages, geochemistry and field magnetic directions will be treated as single volcanic events. Spatially separate volcanic vents (> 5 km) requiring multiple feeder dikes or vents with different ages or geochemical data will be treated as separate events. We will use homogeneous and nonhomogeneous Poisson models for estimating the probability of formation of a new volcanic center, the formation of a cluster of volcanic centers, the recurrence rate of subsurface intrusions (including tests of whether this rate is different from the recurrence rate for formation of a new volcanic center), and the probability of intracluster events in a cluster of centers.

Magma-Output Rates: We will continue to reexamine the data used to establish a regression-fit model that yielded magma-output rates for past volcanic activity in the Yucca Mountain region (Crowe et al. 1982). This method is based on an observed association between cumulative erupted magma volume and time. A number of workers (Wadge, 1982; Bacon, 1982; Kuntz et al. 1986; Shaw, 1980, 1987; King, 1989; Crowe and Perry, 1990) have shown that the slope of a curve of a plot of cumulative magma volume versus time for a volcanic center or a volcanic field can be used to establish a magma-output rate (the term is used following the definition of Kuntz et al. 1986). It is the surface-extrusion rate of volcanic deposits (corrected to magma density) from volcanic eruptions through time. For episodic volcanic events it is the integrated rate of surface eruption of magma during periods of eruptive and non-eruptive activity. The probability revisions of Crowe et al. (1995; see Chapter 7) show that magma volume is not a sensitive parameter in PVHA primarily because of a sharp decline in eruptive volumes during the last 5.0 Ma. We will continue to assess magma-output rates in future studies but the results of these studies will not be emphasized in PVHA.

Advantages: The rate is established from a measurable variable, the magma volume of individual eruptive units. For this activity, the magma-output rates are estimated for different combinations of Pliocene and Quaternary centers of the Yucca Mountain region. The estimated rates are therefore specific to the Yucca Mountain region, and provide a consistent basis for forecasting future rates of volcanic activity. Changes in the slope of a magma volume/time plot can be used as a sensitive indicator of changes in magma effusion rates through time (Wadge, 1982; Kuntz et al. 1986).

Disadvantages: Magma-output rates have been established primarily at active volcanic centers or volcanic fields with numerous volcanic centers (20 to > 100 cones). There is minimal experience at evaluating magma-output rates at small-volume volcanic fields with scattered centers and episodic activity. However, several considerations suggest this approach may be valid. Bacon (1982) has demonstrated time-predictable behavior of episodic basaltic volcanic activity in the Coso volcanic field of eastern California. Shaw (1987) has shown that there is a self-similarity in magma-volume/time behavior of Hawaiian volcanoes at scales of specific vents, individual shield volcanoes (Kilauea, Mauna Loa), individual islands of Hawaii, and the growth and propagation of the Hawaii-Emperor Island chain. Surface basaltic volcanic centers are fed mostly by basalt feeder dikes (Crowe et al. 1983b). An unknown and potentially significant volume of magma is present in the feeder dikes and is not extruded at the surface. This volume is not accounted for by an evaluation of magma-output rates. This second disadvantage is acknowledged but not considered to be significant for calculating the probability of magmatic disruption of the Yucca Mountain site. For a magmatic event to be significant, it must affect the waste isolation system or penetrate the repository. Magma-output rates measure magma volumes that intrude the crust and are erupted. It is less likely that significant quantities of magma will ascend to repository depths (300 m) and not reach the surface. We also note that published estimates of magma-output rates in the volcanological literature are almost always established from the estimates of the erupted volume of magma (an important exception however, is for the eruptions of Kilauea volcano, Hawaii). Additionally, the effects of magma flux and volumes of magma in shallow intrusions is assessed through Study Plan 8.3.1.8.2.1 and TSPA. A magma-output rate is not a direct indicator of volcanic recurrence rates. It must be used as a variable in a separate equation that relates output rates to representative volumes of volcanic events. Selection of representative volumes of volcanic events is difficult in the YMR because of a decline in erupted magma volumes through time. The decline in erupted volumes of magma through time can lead to *underestimates* of recurrence rates of volcanic events (see Crowe et al. 1995; their table 7.9). Regression fits using a range of fitting models are generally unsatisfactory for magma-volume versus time for the volcanic events of the YMR (Crowe et al. 1995). The regression models have outliers and residual plots show linearity and curvilinear structure. Log normalized regression models give improved regression fits but still contain outliers and structure to the regression residuals. The only geologically reasonable recurrence rates using magma-output models are obtained using the mean volume of the *smallest* volume of Quaternary eruptive events (Crowe et al. 1995).

We will establish magma-output rates for multiple alternative combinations of the Pliocene and Quaternary volcanic record of the Yucca Mountain region. The emphasis of these calculations will be on establishing the range of calculated magma-output rates. To do this, we will examine multiple approaches for constructing plots of cumulative magma volume versus time. Alternative models for constructing these estimations are described in the following section.

1. Rate of Formation of Volcanic Clusters: The magma-output rate will be calculated by plotting the cumulative volume of clustered volcanic events. Individual clusters will be treated as a composite of synchronous volcanic events, and plotted as a single point on the cumulative magma-volume/time plot. Points will include the basalt of Thirsty Mesa, aeromagnetic anomalies of Amargosa Valley and Crater Flat, the cluster of basalt centers of southeast

Crater Flat, the basalt of Buckboard Mesa, the Quaternary basalt cluster of Crater Flat, the Sleeping Butte cluster, and the Lathrop Wells center. Additional centers may be added to existing clusters, or new clusters may be defined dependent on the results of exploratory drilling of aeromagnetic anomalies. The Buckboard Mesa basalt center will be used in some but not all estimations because it is not part of the Crater Flat volcanic zone. It will, however, be treated as an alternative model in volcanic cluster models. A major advantage of the cluster-rate estimation is that it establishes the magma-output rate for the episodic formation of new groups of volcanic centers. This event is the main identified volcanic scenario that could result in magmatic disruption of the repository or repository system.

2. Rate of Center Formation Within Volcanic Clusters: The magma-output rates will be calculated for the case of formation of individual centers within clusters of volcanic centers. This calculation will require successful completion of the geochronology studies of Study Plan 8.3.1.8.5.1, Characterization of Volcanic Features, to establish the detailed chronology of individual centers. This calculation will attempt to determine if rates of formation of volcanic centers are higher during cluster episodes. The geometry of past clusters (cluster length, cluster width, number of centers) will be used to evaluate the spatial application of the magma-output rate for volcanic centers formed as cluster events. The spatial distribution of this rate is specific to the individual volcanic cluster. It defines the rate of formation of volcanic centers within an existing cluster. Existing data (Crowe et al. 1995) show that this approach may be impossible because the uncertainty of geochronology age determinations may exceed the recurrence rate of the formation of centers within volcanic clusters. This method will not be emphasized in probability revisions.

3. Event Recurrence Models: A variety of models have been used for predicting time-volume behavior of volcanic centers and fields. The most widely applied model is the volume-predictable model (Kuntz et al. 1986; Crowe and Perry, 1989; steady-state model of Wadge, 1982). Bacon suggested that the basalt and rhyolite centers of the Coso volcanic field of California showed time-predictable behavior. Crowe and Perry (1989) suggested that time-volume behavior of a volcanic field should vary through the evolutionary cycle of the field. They used data from the Springerville volcanic field to illustrate time-evolutionary patterns. A wealth of information is available from the seismic hazard literature on earthquake occurrence models that provides useful analog information for PVHA. Schwartz and Coppersmith (1986) and Anagnos and Kiremidjian (1988) reviewed earthquake models and classified them into several groups: (1) stochastic or Poisson models (random occurrence of events in space in time), (2) Markov and semi-Markov models (unique event dependence in a sequence of events), (3) renewal models (the process restarts after the occurrence of events; this includes the slip-predictable model, which is analogous to the volume-predictable model for volcanism), and (4) trigger or branching models (initiating events within a Poisson process). We will examine a range of potential volcanic and seismic models and test them with the data from the Yucca Mountain region.

4. Volume-Predictable Model: At present, we plan to evaluate volume-predictable models for the Yucca Mountain region. Multiple approaches will be used to provide curve fits for plots of cumulative magma volume versus time. The regression fit provides an average approximation of magma-output rate. It is relatively insensitive to changes in magma-output but offers the advantage of providing regression confidence levels for estimating uncertainty. Moreover, the regression fit can be evaluated for goodness of fit (note, however, that artificially high values of R are obtained for regression fits of cumulative curves. This effect can be minimized by plotting magma volume, not cumulative volume, versus time). Crowe et al. (1995) obtained poor regression fits for most regression models treating time as the independent variable and magma volume as the dependent variable. This model limitation may be overcome by application of nonlinear regression or multiple regression. However

while these approaches will be tried, they may be of marginal use because of the limited number of volcanic events in the YMR.

If a magma-output rate is established, it can be used to calculate the time of the next volcanic event using the formula

$$Tp = (Vm/Em) - Te, \tag{4}$$

where Tp is the predicted time of the next volcanic event, Vm is a representative eruption volume for a volcanic event, Em is the calculated magma effusion rate, and Te is the time since the last volcanic eruption.

The Vm is the most sensitive parameter of this equation. For calculating the probability of formation of a new volcanic center, it is the representative volume of the initiating events associated with formation of a new volcanic center. The Vm is the volume of clustered volcanic events used in calculating the recurrence rates of the cluster model. Because data for Vm for the Yucca Mountain region is limited, we planned initially to use data from the Cima and Lunar Crater volcanic fields to increase the statistical data base for Vm. Field studies have shown however, that the volcanic events of the YMR (particularly Quaternary volcanic events) are of unusually small volume. Use of data from the Cima and Lunar Crater volcanic fields would produce mean estimates of Vm that are considerably larger than those established from the mean volume of Quaternary volcanic events in the YMR. This would tend to give unrealistically long recurrence intervals (see Crowe et al. 1995) and the results from magma-output studies will be examined primarily as a tool to evaluated probability bounds

Volume Calculations: Calculations of volcanic recurrence rates are dependent on producing plots of cumulative magma-volume/time for Pliocene and Quaternary volcanic centers. Because of the importance of the volume data, we have developed several refinements for calculating the magma volume of volcanic events. These refinements include:

1. The reproducibility and uncertainty of volume calculations are not commonly considered in volcanism field studies. To limit uncertainty and determine the reproducibility of calculations, we have developed multiple approaches to calculating the volume of volcanic events. Two approaches will be followed. The first is to use detailed geologic maps of volcanic centers developed from Activity 8.3.1.8.5.1.3, Field Geologic Studies. These maps will be digitized. A computer program will be used to contour the top and bottom surfaces of volcanic units and calculate the volume of representative eruptive events. The second approach is to use conventional methods for estimating magma volumes assuming average unit thickness and obtaining areal estimations of units from geologic maps. For both approaches, volumes will be calculated from outcrop maps and from maps that attempt to reconstruct the original distribution of volcanic events. These reconstructions will use results from trenching studies, field mapping and geophysical data. Estimated volumes will be corrected using appropriate density corrections for converting the different types of volcanic deposits to magmatic densities (DRE).

2. A significant volume of magma of basaltic volcanic centers can be erupted and deposited in the scoria-fall sheet. This material is rapidly eroded and removed from the geologic record. Different assumptions about the volume of magma in the scoria-fall sheet of a center can significantly affect calculations of magma-output rates (Crowe and Perry, 1989). To reduce the uncertainty of this component in the volume calculations, we will obtain thickness of scoria-fall units where possible from Activities 8.3.1.8.5.1.2 and 8.3.1.8.5.1.3. These thicknesses will be used to calculate the volume of scoria-fall sheets using the models of Pyle (1989) and Fierstein and Nathenson (1989). If it is not possible to obtain thickness data

of scoria-fall deposits, we will estimate the missing volume of the pyroclastic component by assessing the size and fragmentation characteristics of near-vent deposits (constrain eruption models) and comparing these data with examples of well studied scoria-fall deposits in the volcanological literature (see Crowe et al. 1983b).

3. Aeromagnetic anomalies will be drilled as part of Study Plan 8.3.1.8.5.1, Characterization of Volcanic Features. Should Pliocene basaltic volcanic rocks be encountered in the drill holes, it will be important to estimate the volume of the units for modifying magma-output rates (see Activity 8.3.1.8.5.1.1, Volcanism Drill Holes). If silicic intrusions or buried silicic centers are encountered, we would follow the strategy described in Activity 8.3.1.8.5.1.1, Volcanism drill holes, of Study Plan 8.3.1.8.5.1, Characterization of Volcanic Features. The volume estimations will be based on the results of exploratory drilling and detailed gravity and magnetic modeling of the anomaly sites. The drill holes are currently planned for fiscal year 1996. We will document the geophysical investigations and the modeling used for the volume calculations in scientific notebooks following quality assurance requirements for the Los Alamos and the US Geological Survey.

Methods for Estimation of the Probability of Magmatic Disruption (Pr(E2 given E1)Pr(E1))

Multiple alternative models of the probability of magmatic disruption of specified areas E2 will be assembled in a spreadsheet matrix using data input from this activity and from Activity 8.3.1.8.1.1.2 of this Study Plan. Individual variables in the data will be plotted on probability diagrams (see Crowe et al. 1995) and standard statistical methods will be used to assess the data distributions and identify outliers. The recurrence rate (E1) will be summarized first for specific spatial and structural models to avoid overestimating recurrence rates (Crowe et al. 1993, 1995; Wallmann 1993). The range of values for E2 will be obtained from studies for activity 8.3.1.8.1.1.2.

The variables E1 and E2 will be combined through simulation modeling using Latin hypercube sampling. This combining of variables will assume uniform weighting of both the alternative recurrence models, and the multiple structural and spatial models. We will also examine alternative methods of assembling the data using primarily an emphasis on alternative spatial and structural models, which have the greatest effect on the probability of magmatic disruption (Crowe et al. 1995). The purpose of this work will be to assess the range of variation in the PVHA produced through applying different scientific perspectives during data assemblage. The range of different probability estimates will be emphasized not the results of any single approach. Our goal is to provide documentation of the effects of alternative models of PVHA to assist the DOE in the development of probabilistic assessments that will be applied to the regulatory requirements for licensing a potential site for storage of high-level radioactive waste.

Methods for Producing Cumulative Probability Distributions for Data from Study Plan 8.3.1.8.1.2

Data from Study Plan 8.3.1.8.1.2 will be assembled in a spreadsheet matrix. The data will be divided into two categories corresponding to the Study Plan activities (eruptive and subsurface process). Key data identified from Study Plan 8.3.1.8.1.2 will be assessed using probabilistic analyses to fully represent the uncertainty of the data. Simulation modeling will be used to produce cumulative probability distributions for variables from the two data categories using data constraints from a combination of minimum, maximum, and most likely estimations and identifying natural bounds in data from analog studies, evaluations of the geologic literature, and constraints from the dynamics of magmatic processes. These data, represented as probability distributions, will be submitted to TSPA studies. Based on the results of the TSPA, we will refine the data using one or a combination of three approaches. First, If the TSPA results show that the data do not significantly affect release estimations, we will not consider further refinements in the probability distributions. Second, if the TSPA results show that a parameter has a significant affect on release estimations, we will evaluate whether more data can be gathered and if these data could be used to further constrain the probability distributions. Third, we will assess the results of the TSPA to attempt to determine if we need to gather new data (through Study Plan 8.3.1.8.1.2) and produce probability distributions (through this activity) for variables that were not considered in the initial studies.

Expert Judgment

An important issue for PVHA is the requirement that the resulting probability distributions adequately represent the complete range of probability outcomes. This can be addressed by several processes through the application of expert judgment studies. First, the assembly of multiple volcanological, tectonic, and petrologic experts on an expert judgment panel provides for a spectrum of opinions on data and models used in probabilistic assessments. Models developed for the Yucca Mountain region by external experts will be documented in the workshop proceedings, and in the elicitation reports by the individual experts. The expert judgment assessments will be controlled and documented under DOE controls and procedures (see appendix A of this study plan). The detailed goals of the expert judgment studies will be described in a strategic plan that will be submitted to the DOE (see appendix A of this study plan). Second, the exchange of data and the process of questioning and examining data that occur in expert judgment workshops serves to expand the scope of information used in probabilistic assessment. Current to the final revision of this study plan, the expert judgment panel on volcanism has completed three workshops, conducted two field trips and were conducting individual elicitations for the PVHA. The ongoing expert judgment studies are being conducted as a part of regulatory interactions; the studies do not fall directly under this study plan and they are not being controlled under the planning guidance contained in this study plan.

A second issue for PVHA is the relative weights applied to alternative models used in assessments. The initial compilation of probability matrices and the development of probability distributions for this study plan will be based on equal weighting of all models. However, different models have different geologic credibility based on the applicability of the model to the tectonic setting of the YMR and established concepts of magmatic processes. A recognized concern or area of possible bias is that equal weighing of all models does not guarantee representative or unbiased probability distributions (see Meyer and Booker, their Chapter 16). Bias can be introduced in the probability data through the process of selection of alternative models. For example, it is possible to skew a probability distribution by selectively emphasizing development of large numbers of alternative models that yield high or low values of the disruption probability. A second key area of emphasis for implementation of expert judgment studies of volcanism studies will be on an assessment of the suitability and weighting of alternative models used in probabilistic volcanic hazard assessment. The rigorous process of probabilistic elicitations of experts, the application of established techniques for analysis of data from expert judgment, and the methods of combining responses from expert judgment are all designed to reduce bias in data assessments (Meyer and Booker, 1991; see appendix A of this study plan for a description of the application of expert judgment to PVHA).

2.4.2 Constraints

All information for this activity are provided from other activities with the exception of volume calculations. These calculations are completed through this activity but the data used for the calculations are obtained through other studies. No field studies or experiments are required for the probability calculations and assessments and thus no impacts on the site are identified. The only potential constraint with this activity is schedule. The iterative nature of the probability estimations makes it imperative to continually refine the probabilistic data as information is obtained from site characterization studies. However, these refinements can be readily factored into the probability estimations because the methodology of the estimations has been established. The uncertainty of the probability calculations is discussed in Section 3.4.

2.4.3. Detailed Technical Procedures, Equipment and Software for Data Analysis

One detailed procedure was developed for this activity.

- Use of the Garmin GPS 100 for the Location of Volcanic Features; Detailed procedure LANL-ESS13-DP-611,R0

- Computer software for probability calculations will follow the requirements of TWS-QAS-QP-3.20, 3.21, 3.26, and 3.27.

We planned originally to write a detailed technical procedure describing the methods for estimating magma volumes of basalt centers in the YMR. However the methods have proven to be variable for individual volcanic centers and therefore are not amenable to procedural control. We will document the methods for volume estimations under Los Alamos Quality Assurance Procedure LANL-YMP-QP-03.5, Documenting Scientific Investigations.

- Windows compatible computers with numeric coprocessors.
- SYSTAT statistical software, Systat Inc.
- SPSS for Windows, statistical software, SPSS Inc.
- @RISK computer software, risk analysis and simulation add-in for Microsoft Excel, Palisade Corporation.
- BestFit, distribution fitting software for Windows, Palisade Corporation
- EXCEL, spreadsheet for Windows, Microsoft Corporation

2.4.4 Accuracy and Precision

The only measurements made for this activity are the latitude, longitude and elevation of major volcanic vents. The accuracy and precision of these measurements are dependent primarily on the configuration of GPS satellites relative to the sampling site during the acquisition of surveying data. Generally the data for location of volcanic features and sample sites does not need to be more accurate than ± 100 meters, which is easily obtainable even without postprocessing to remove the effects of selective availability. Data on the count times and precision of individual GPS measurements are recorded during data acquisition. The data are downloaded to computer and the data files are stored in computer systems and archived periodically in the volcanism residence file located in Suite 820, Bank of America building, in Las Vegas, Nevada.

2.4.5 Representativeness

Several questions must be assessed concerning the suitability of PVHA for the Yucca Mountain site. First, is the approach valid for assessing the hazards of future volcanic events for subsurface disposal of high-level radioactive waste? Second, are the data for probability estimations sufficient to meet the requirements of reasonable assurance?

First, the major strengths of probabilistic approaches to site characterization studies for the Yucca Mountain site were described in section 2.4.1. Second, a probabilistic approach to volcanism studies should be acceptable if it can be demonstrated that the assessment does not underestimate volcanic hazards. We have attempted to meet these requirements by using multiple models in probabilistic assessments and comparing the significance of the alternative models. For example, Crowe et al. (1995) showed that there are not significant differences in estimates of the volcanic recurrence rate (E1) for homogeneous versus nonhomogeneous

Poisson models if the period of time for the analysis is established using volcanic cycles. Seismic studies have shown that homogeneous Poisson models differ from nonhomogeneous Poisson models only when the time between events approaches or exceeds the mean recurrence time (Cornell and Winterstein, 1988). For most cases, homogeneous Poisson models provide an adequate approach to probabilistic modeling and the analysis can be structured to **not** underestimate PVHA (Crowe et al. 1995).

The second question, the quantity of data sufficiency for PVHA, is somewhat difficult to answer. The Yucca Mountain site is caught in a logic paradox. If more Quaternary volcanic events were present in the site vicinity, there would be increased data for estimating the recurrence rate of volcanic events and the structural controls of those events. Consequently, there would be increased confidence (decreased uncertainty) in forecasts of future volcanic activity. However, by virtue of the increased data (more volcanic events), there would be an increased likelihood that the site might be affected by future volcanic activity. The question of data sufficiency for probability estimations is answered by two parts of this study plan. First, permissible data ranges are assessed in the probabilistic estimations and multiple data approaches are applied to the data used in the probability equations. Further, these data ranges and model assumptions are evaluated continually throughout the duration of the study plan activities. A critical constraint on data uncertainty is the status of volcanic processes in the Yucca Mountain region. While the data are not completely definitive, the decreasing volume of erupted basalt in the Pliocene and Quaternary and the pattern of waning tectonism in the YMR suggest that the causative processes of volcanism are waning If this is the case, then the PVHA, which is based on an assumed steady-state model of volcanic activity, can be demonstrated to be conservative.

3.0 APPLICATION OF RESULTS

The evaluation of the Yucca Mountain site must include consideration of the potential for a range of disruptive events that could directly or indirectly lead to the release of waste radionuclides. Igneous activity, including both eruptive and subsurface magmatic activity, has been identified as one class of potentially disruptive events that needs to be evaluated for site characterization studies. Regulatory requirements (10 CFR 60.112 and 40 CFR Part 191) mandate that evaluation of post-closure performance must consider events and processes that can occur within 10 ka of repository closure, including estimates of the probabilities of events and processes.

The performance allocation process has been used by the YMP to establish appropriate strategies of issue resolution (issues to be resolved are listed in SCP Section 8.2.1). A general discussion of the performance allocation approach is provided in SCP Section 8.1. Issue resolution strategies and details of performance allocation for each design and performance assessment issue are summarized in SCP Section 8.2, and expanded in SCP Sections 8.3.2 through 8.3.5.

The specific data supplied by this study plan are the estimated probability of a volcanic eruption near or through a repository, the probability of an eruption or intrusion in the repository system, and the development of probability distributions for processes of eruptive or subsurface magmatic events. These data will be used to make probabilistic assessments of the potential for disqualification of the site because of the potentially adverse condition of the presence of Quaternary igneous activity. Additionally, the probabilistic data for a future volcanic eruption or an intrusion and the processes accompanying these events will be used to aid performance assessment studies of the potential cumulative radiological releases from the waste isolation system during 10 ka (TSPA). The information from this Study Plan will be used by the DOE to assess the suitability of the Yucca Mountain site for isolation of radioactive waste. The information from this Study Plan will also be combined with information from Study Plans 8.3.1.8.1.2, 8.3.1.8.2.1, and 8.3.1.8.5.1 and incorporated in studies of total system performance of a potential repository system.

The primary goals of Study Plan 8.3.1.8.1.1 are to assist the DOE in assessing the suitability of the Yucca Mountain site and to ensure that adequate information for volcanism is submitted to continuing studies of the total system performance assessment (Wilson et al. 1994; Andrews et al. 1994). The results of probabilistic assessments from this study are focused on evaluating **unbiased** probability distributions (the distributions are derived from an emphasis on the most current scientific understanding of volcanic and tectonic processes in the YMR). These distributions may or may not be used by the DOE in formal assessments of site suitability and in formal licensing documents. Further, the DOE may choose to modify the methods of assembling probability distributions to respond to site suitability or regulatory requirements.

4.0 SCHEDULE AND MILESTONES

The milestones for Study Plan 8.3.1.8.1.1, Probability of Magmatic Disruption of the Repository, are listed in this section by activity. The schedule for this study is dependent on the overall site characterization program and is also dependent on data from Study Plan 8.3.1.8.5.1, Characterization of Volcanic Features, and geologic and geophysical data from the preclosure tectonics program (8.3.1.17).

The highest priority goals for this study plan are to establish the revised methodology for probability estimations and to begin the estimations using the revised methodology. Because volcanism is judged to be a potential disqualifying issue, these goals were met in FY95 with the completion of the volcanism status report (Crowe et al. 1995). We anticipate that revisions and additions to these probability estimations will continue throughout the site characterization process. We have established the procedures for studies using formal methods of expert judgment and these procedures are described in appendix A of this Study Plan. However, the implementation of the expert judgment studies for volcanism are being carried out under activities that are not a part of this study plan. Activities 8.3.1.8.1.1.2 and 8.3.1.8.1.1.3 require timely evaluation of data from the preclosure tectonics program. For the latter, we will examine new models of the structural controls of volcanic activity whenever new data reports are released from the preclosure tectonics program. For the former, we will make a decision on the need for a second phase of geophysical and noble gas studies with the completion and assessment of seismic reflection/refraction studies across Crater Flat and Yucca Mountain, the upgrade and acquisition of data from the seismic net, and assessment of the depth of detection of basaltic intrusions using aeromagnetic data. Current to the final revision of the Study Plan, the seismic reflection/refraction experiment had been completed and the data were being reviewed and evaluated.

4.1 Location and Timing of Volcanic Events (Activity 8.3.1.8.1.1.1)

This activity is dependent on completion of Activity 8.3.1.8.5.1.2, Geochronology Studies, and Activity 8.3.1.8.5.1.3, Field Geologic Studies, of Study Plan 8.3.1.8.5.1, Characterization of Volcanic Features. Current plans are to start this activity at the beginning of FY96.

(B) Location of Volcanic Centers

Report with compiled maps of the location of volcanic centers and tables with vent locations, magma volumes, and referenced geochronology data.

4.2 Evaluation of the Structural Controls of Basaltic Volcanic Activity (Activity 8.3.1.8.1.1.2)

This activity is dependent on completion of data from the preclosure tectonics program and from Activity 8.3.1.8.5.1.3, Field geologic studies.

(E) Disruption Parameters, Preliminary Calculations

Report on preliminary calculations of the disruption parameter. This work was completed in FY95 and is summarized in the volcanism status report (Crowe et al. 1995).

Disruption Parameters, Annual Updates

Yearly reports will be produced to update the calculations of the disruption parameter, commencing one year after the first report on preliminary calculations. The next scheduled update is at the end of FY95 and will included the results of simulation modeling of E2.

Figure 3. Schedule and Milestones.

(Final version to be provided by DOE)

4.3 Presence of Magma Bodies in the Vicinity of the Site (Activity 8.3.1.8.1.1.3

This activity requires data from Section 8.3.1.17, Preclosure tectonics.

(G) Decision Point: Geophysical and Noble Gas Isotopic Studies

A decision will be made on whether a second phase of detailed geophysical and noble gas isotopic studies will be required. Based on information contained in a summary report by an external consultant in geophysics the decision was made in FY95 that implementation of a second phase of studies is not assigned a high priority.

Decision Document: Amend Study Plan

If the second phase of studies are judged to be required, a report will be completed 6 months after the decision and will be added as an appendix to this study plan. The report will follow the study plan format and will describe the required plans for the second phase of focused geophysical studies.

4.4 Probability Calculations and Assessment (Activity 8.3.1.8.1.1.4)

The major data for this activity are provided by all activities of Study Plan 8.3.1.8.5.1, Characterization of Volcanic Features and Study Plan 8.3.1.8.1.2 Physical Processes of Magmatism and Effects on the Potential Repository. Data for the disruption parameter are provided from Activity 8.3.1.8.1.1.3, Evaluation of the Structural Controls of Basaltic Volcanic Activity. Should data from Activity 8.3.1.8.1.1.3, Presence of Magma Bodies in the Vicinity of the Site, reveal the presence of magma in the crust in the Yucca Mountain region, the probabilistic analysis based on the geologic record of the region will be reexamined.

Report: Methodology for Calculation of Probability of Magmatic Disruption

The studies on the methodology of estimation of the probability of magmatic disruption of the repository were completed in FY95 (volcanism status report; Crowe et al. 1995).

(D) Report: Revised Calculations of Probability of Magmatic Disruption

A report on the results of revised calculations of the probability of magmatic disruption of the repository will. be completed at the end of each fiscal year following the completion of the volcanism status report. The first milestone report under this planning was completed at the end of FY95.

Decision Point: Studies on Magmatic Disruption

The probability of repository disruption was estimated to be less than the parameter goal ($<10^{-6}$ for repository disruption, $<10^{-5}$ for intrusion of the repository system) in the volcanism status report (Crowe et al. 1995).

Report: Plan for Using Expert Judgment

The plan for applying expert judgment to volcanism studies was completed and is attached as an appendix to this Study Plan.

(H) Report: Evaluation of Probability Models by Expert Judgment

An independent report (independent of this study plan) will be issued in the winter of FY96 on the results of the expert judgment studies. The information in this report will be assessed and incorporated in the Volcanism Synthesis Report scheduled for completion at the end of FY96.

Annual Reports: Probability Calculations

Yearly updates will be issued for the probability calculations as results of data from site characterization become available for the probability calculations. The first milestone report under this planning was completed at the end of FY95.

APPENDIX A:

THE USE OF EXPERT JUDGMENT FOR VOLCANIC HAZARD ASSESSMENT

1.0 Introduction

Study Plan 8.3.1.8.1.1 identifies the application of expert judgment to probabilistic volcanic hazard assessment (PVHA) for the proposed Yucca Mountain site. This appendix to the Study Plan describes the general procedures to be followed for the expert judgment elicitation process. Details of the process will be provided in a Strategic Plan that will be developed as the project progresses. A review of the available data pertaining to volcanic hazards, and the models used to make probability estimates and conduct simulation analyses, are described in Crowe et al. (1995).

Expert judgment of the confidence in, and adequacy of, the available data base and the models for assessing volcanic hazards is a necessary step toward achieving an integrated assessment of the volcanic hazards, and, ultimately, volcanic risk at the site. For this study, volcanic *hazard is* defined as the probability of disruption of the potential repository site; volcanic *risk* is defined as PVHA combined with consequences of the disruption expressed generally as the release of radionuclides to the accessible environment. Members of an expert panel will be asked to evaluate the available data, develop and apply appropriate models to assess the future volcanic hazards, and to quantify the uncertainties in their assessments. A probabilistic approach will be used to describe the current state of knowledge and to incorporate explicitly the uncertainties.

The three major goals for the use of expert judgment are as follows: 1) to review all data and develop or refine models for evaluating the future locations and recurrence of volcanism; 2) to assign weights to the various models to arrive at representative cumulative probability distributions for probabilistic variables; and 3) to evaluate all the appropriate variables for each model and to quantify the uncertainties associated with each parameter value. The integration of the assessments from all of the experts will provide a full representation of the probability of disruption of the potential repository from volcanic processes (eruptive and subsurface).

2.0 Methodology

In the study of any complex technical problem, expert judgment is used; however, this judgment is generally implicit and the basis for the judgments are undocumented. In recent years, formal studies have been conducted that explicitly include expert judgment by incorporating the judgments of multiple experts, and providing various levels of documentation of the reasoning on which the judgments are based. The process and procedures of obtaining and using expert judgments in complex technical problems have evolved in the course of these studies, so that the accountability and defensibility of the analyses is high.

The use of expert judgment provides a mechanism for quantifying and documenting scientific knowledge and bringing all available knowledge into the decision-making process. For certain analysis and design applications, the values of geotechnical parameters must be estimated. Since these parameters are often complex (varying with space and time) and the available data base may be statistically limited, estimates of parameter values must incorporate subjective interpretations and judgments. Decision-makers do not rely on data alone, but on the interpretations of data. Data and expert judgment should not be considered interchangeable, since data must always be interpreted and it is the interpretation of data that results in scientific understanding. The degree of uncertainty in a body of data can be quantified, resulting in useful information for prioritizing future data collection efforts. Sensitivity studies can be performed to indicate parameters with the strongest influence on the outcome being assessed.

The formal process for conducting the expert judgment elicitation can be divided into five basic steps, as follows:

1) selection of specialists
2) selection and refinement of issues
3) training for elicitation
4) elicitation
5) analysis and aggregation

Descriptions of each of these five steps, and their anticipated use in the assessment of volcanic hazard at Yucca Mountain, are described below. For the volcanic hazard assessment, a project team will be assembled to plan and conduct the expert elicitation process; this *"Methodology Development"* team will refine the procedures in the steps described below.

2.1 Selection of Experts

Experts who are widely recognized by their peers as experts in their particular field will be selected as members of an expert panel. A broad search for experts will be conducted to emphasize the ranges of expertise relevant to the issues, and differences in interpretations. The selection of multiple experts for a particular discipline, particularly individuals with strongly differing opinions, enhances the credibility of a panel. The optimum number of experts selected for an expert panel is related to the complexity of the issues to be evaluated, and the importance of the parameters to be estimated.

Experts selected to participate on the expert panel will be geologists with extensive experience relevant to assessment of volcanic hazards. It is anticipated that approximately 8 to 10 experts will be needed to cover comprehensively the important issues. A list of potential panel members will be compiled by obtaining recommendations from organizations and individuals that are familiar with volcanic hazard assessments. Consideration will be given to each panel member's technical qualifications and to the ultimate composition and balance of the panel as a whole, in accordance with guidelines to be developed by the Methodology Development team. The following guidelines will be used:

1) Geologist with good professional reputation and widely recognized competence based on academic training and relevant experience. Tangible evidence of expertise, such as written documentation of research in refereed journals and reviewed reports is required.

2) Understanding of the general problem area through experience collecting and analyzing research data for relevant volcanic studies in the southern Great Basin or similar extensional tectonic environments; prior familiarity with the data available for the Yucca Mountain site will be an asset, but not a requirement for participation.

3) Availability and willingness to participate as a named panel member, including a commitment to devoting the necessary time and effort to the project and a willingness to explain and defend technical positions.

4) Personal attributes that include strong communication and interpersonal skills, flexibility and impartiality, and the ability to simplify; individuals will be asked specifically not to act as representatives of technical positions taken by their organization, but rather to provide their own technical interpretations and uncertainties.

5) Help to provide a panel balanced to include experts with diverse opinions, areas of technical expertise, and institutional/organizational backgrounds.

2.2 Selection and Refinement of Issues

The purpose or goals of a project indicate the issues to be selected and assessed. The selected issues should be discussed and refined so that the events and quantities to be elicited are clearly defined. It is generally useful to decompose the events or quantities into smaller units (e.g., using logic tree format) that can be assigned discrete values and probabilities then these values and probabilities can be combined mathematically .

A key part of the volcanic hazard project will be the interactions and communications among the experts. Four workshops will be conducted whose purposes are to: 1) define data needs to address key technical issues, 2) review and discuss alternative methodologies, 3) review various interpretations of data related to volcanic hazard, and 4) provide feedback and discussion of preliminary results prior to finalization of the experts assessments. In addition, two field trips will be held to review field relationships at volcanoes in the Yucca Mountain region. The workshops and field trips are important opportunities for the experts to review available data and ask questions of those conducting the work, and gain an understanding of important PVHA issues through an iterative process of challenge and defense of studies.

Alternative models for evaluating volcanic hazard at Yucca Mountain, including models presented by the State of Nevada and by the US Nuclear Regulatory Commission and its contractors, have been reviewed by Crowe et al. (1995). These models and other published models, and the variables that must be considered for each model, will provide a starting point for the panel members. Each expert, however, may identify their own significant variables, and develop their own models and inputs, as desired. Data and interpretations relevant to the basic issues will be presented and discussed in detail during workshops. The purpose of these discussions will be to ensure a common understanding of the issues being addressed and provide a forum for the discussion of alternative models and variables. Decomposition of the assessment issues, or structuring the analysis so that a series of simpler assessments can be made instead of one complex assessment, will be a major objective of the discussions.

2.3 Training for Elicitation

Training experts in elicitation methods, concepts of probability, and biases in probability assessments is an important part of expert judgment elicitation. For the volcanic hazard assessment, it is anticipated that a one-half day training session will be held at an initial workshop. The training session will be conducted by an elicitation expert, trained in subjective probability and decision analysis. The training will include an introduction to the elicitation and analysis methods (including the assessment process and documentation of probabilities), a discussion of probability and the techniques used in assessing probabilities (e.g., assessing probabilities for discrete events and for continuous events), complexities that affect probability assessment (e.g., unstated assumptions, motivational bias, and cognitive biases such as overconfidence and anchoring), and aggregation of probability assessments.

2.4 Elicitation of the Experts

For the volcanic hazard assessment, it is anticipated that elicitations of the judgments of the experts will be conducted in private, individual sessions. The sessions will be attended by an analyst with broad experience in hazard modeling, a generalist with geologic experience, and an elicitation expert: the analyst will have the primary responsibility for understanding and characterizing the models and parameters being elicited from the expert; the generalist will lead the expert through the assessment, ask the technical questions, and ensure that the technical reasoning or basis for each judgment is described and recorded in writing; and the elicitation expert will assist in the description of uncertainties and ensure that the expert's judgments are properly represented. The format of the elicitations will follow the logic specified by the expert. At each major step in the assessment, the expert will be asked to provide the technical basis for the assessment being made, and to express the uncertainty in each assessment (e.g., as a range of discrete alternatives each having a relative weight, or by a cumulative probability distribution for continuous variables.) Written documentation of the elicitation will be prepared for inclusion in the project report. Following a feedback workshop, the experts will have an opportunity to revise their assessments before they are finalized.

2.5 Analysis and Combination

The results of the elicitations will be a range of judgments on volcanic hazards at Yucca Mountain. These judgments will be in the form of individual distributions of the probability of disruption. These probability distributions will be combined to develop an integrated probability of volcanic hazard.

Sensitivity analyses will be conducted to determine the most important contributors to the final results. Each expert will be provided with the sensitivity analyses, assessments made by other experts on the panel, and aggregated results across all experts. The panel will convene at a workshop to discuss these results and their uncertainties. There will be an opportunity for each expert to make revisions, and any changes made will be recorded and documented.

2.6 Implementation

The results of the expert judgment elicitation to assess volcanic hazards will be fully documented and summarized in a report to DOE. Documentation will include: criteria used to select specialists and the qualifications of each of the experts serving on the panel; summaries of each workshop or panel meeting; results of each of the individual elicitations, including the technical bases for each judgment; and the aggregated results and the range of uncertainty.

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