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PROBABILITY OF MAGMATIC DISRUPTION OF THE REPOSITORY

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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 and the approach and methods for estimating the probability of potential magmatic disruption of the repository and the controlled area of the proposed Yucca Mountain site. In the following discussion it is important to note that the potentially adverse condition of Quaternary igneous activity specified in 10 CFR 60.122(c)(15) appears at this time to involve processes and features associated exclusively with the basaltic volcanism that occurs sporadically across the southern Basin and Range province. For that reason, this study plan uses the term "volcanic activity" interchangeably with the term "igneous activity." The types of Quaternary igneous features known to exist in the Yucca Mountain region, including cinder cones and flows as well as shallow intrusive and other subvolcanic manifestations, are collectively referred to as "volcanic features." The term "volcanism" is not intended to refer only to those processes that result in surface eruption of magmatic products. The study is divided into four activities. The activity 8.3.1.8.1.1.1, Location and Timing of Volcanic Events, involves collation of geologic maps of the distribution of Pliocene and Quaternary basaltic volcanic centers, the geochronology of the centers, and the volume of volcanic events associated with each center. The activity 8.3.1.8.1.1.2, Evaluations of the Structural Controls of Basaltic Volcanic Activity, is concerned with two topics. First, it involves identifying the patterns of distribution of basaltic volcanism in the region, and relating the patterns to the structural and tectonic elements of the site vicinity. Second, a comprehensive set of models will be developed to describe a range of potential structural controls of past sites of basaltic volcanic activity. We will use these models to develop computational methods for determining the disruption parameter of the probability calculations. The activity 8.3.1.8.1.1.3, Presence of Magma Bodies in the Vicinity of the Site, will evaluate geophysical data from the preclosure tectonics program to test for evidence of the possible existence of anomalies that could be produced by crustal magma. Should such anomalies be identified by multiple geophysical methods, a plan will be developed to implement a detailed geophysical program to explore the anomalies. This work will be supplemented by studies of the noble gases in ground water. These geochemical studies will emphasize an examination of variations in the $^3He/^4He$ ratio of ground water to test for the presence of high ratios that could be produced by crustal magma. The activity 8.3.1.8.1.1.4, Probability Calculations and Assessment, will revise the methods used to establish volcanic recurrence rates, and the calculations of the probability of magmatic disruption or intrusion of the repository, the controlled area and the Yucca Mountain region. The outcomes of the probability calculations will be established through development of matrices of attribute values, determination of sample statistics for the matrices, simulation modeling of the probability distributions, and application of procedures of expert opinion to insure completeness of alternative models and to reduce bias in the probability distributions.

This study provides information that will be used for evaluation of performance parameters for the potential direct and indirect releases resulting from magmatic disruption of the Yucca Mountain site including releases associated with rupture of waste packages, changes in percolation flux, changes in water table elevation, and changes in rock properties along flow paths to the accessible environment.

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1.0 PURPOSE AND OBJECTIVES OF STUDIES

1.1 Objectives

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 located at Yucca Mountain. The objective of Study 8.3.1.8.1.1, Probability of Magmatic Disruption of the Repository, is to evaluate the probability of magmatic disruption of a repository at Yucca Mountain by future basaltic volcanic activity. The primary data for this evaluation are provided through Study Plan 8.3.1.8.5.1, Characterization of Volcanic Features, and from study plans of the preclosure 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). Final resolution of an evaluation of the future potential of silicic volcanism is dependent, however, on the results of drilling of planned volcanism exploration holes and on the evaluation of the significance of young (2.9 Ma) silicic volcanism at Mt. Jackson, located 100 km northwest of Yucca Mountain (Figure 1). 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). The only remaining work to be done to complete all study of silicic volcanism is to drill aeromagnetic anomalies in southern Crater Flat and the Amargosa Valley. Unless the planned exploratory drilling produces data that drastically change 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). The data justifying those assertions will be consolidated or 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. Any changes in this work will be established through Study Plan 8.3.1.8.5.1, Characterization of Volcanic Features. The potential for future basaltic volcanism is more difficult to define. Four Quaternary volcanic centers (approximately 1.2 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 two-phase approach is being used to evaluate the potential for future basaltic volcanism at the Yucca Mountain site (Crowe, Vaniman, and Carr, 1983; Crowe, 1986), with the second approach developed from the data foundation of the first. First, standard geologic studies combining field mapping, geochronologic, paleomagnetic, geochemical, and geophysical studies provide comprehensive information to decipher the history of basaltic volcanism in the Yucca Mountain region. Second, data from these studies are used to assess volcanic risk, where risk is a combined evaluation of the probability and consequences of future

basaltic volcanism affecting the Yucca Mountain site. The results of past volcanic hazard assessments using these two 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, Johnson, and Beckman, 1982; Crowe et al., 1983a, 1983b; Crowe, 1986, Crowe et al., 1986, Crowe et al., 1989; Crowe and Perry, 1990; Crowe, 1990). All work for this study plan is Quality Assurance (QA) Level I unless otherwise noted. Preexisting data from volcanism studies will be qualified to QA Level I on a case-by-case basis if the data are judged to be needed in support of a licensing 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).

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 the structural and tectonic elements of the region, and (2) computational methods for factoring the structural controls of volcanism into revised calculations of the probability of magmatic disruption of a repository and surrounding controlled area at Yucca Mountain (Activity 8.3.1.8.1.1.2, Evaluation of the Structural Controls of Basaltic Volcanic Activity).

3. A regional evaluation of the possible presence of magma bodies in the Yucca Mountain region. This activity will involve, first, an integrated evaluation of geophysical data that provides information on the subsurface structure of the Yucca Mountain region (information provided from the preclosure tectonics program). Should evidence be obtained from this evaluation that provides indications of the presence of crustal or subcrustal magma in the Yucca Mountain region, a second phase of work will be undertaken. This will include planning and obtaining of additional geophysical data that

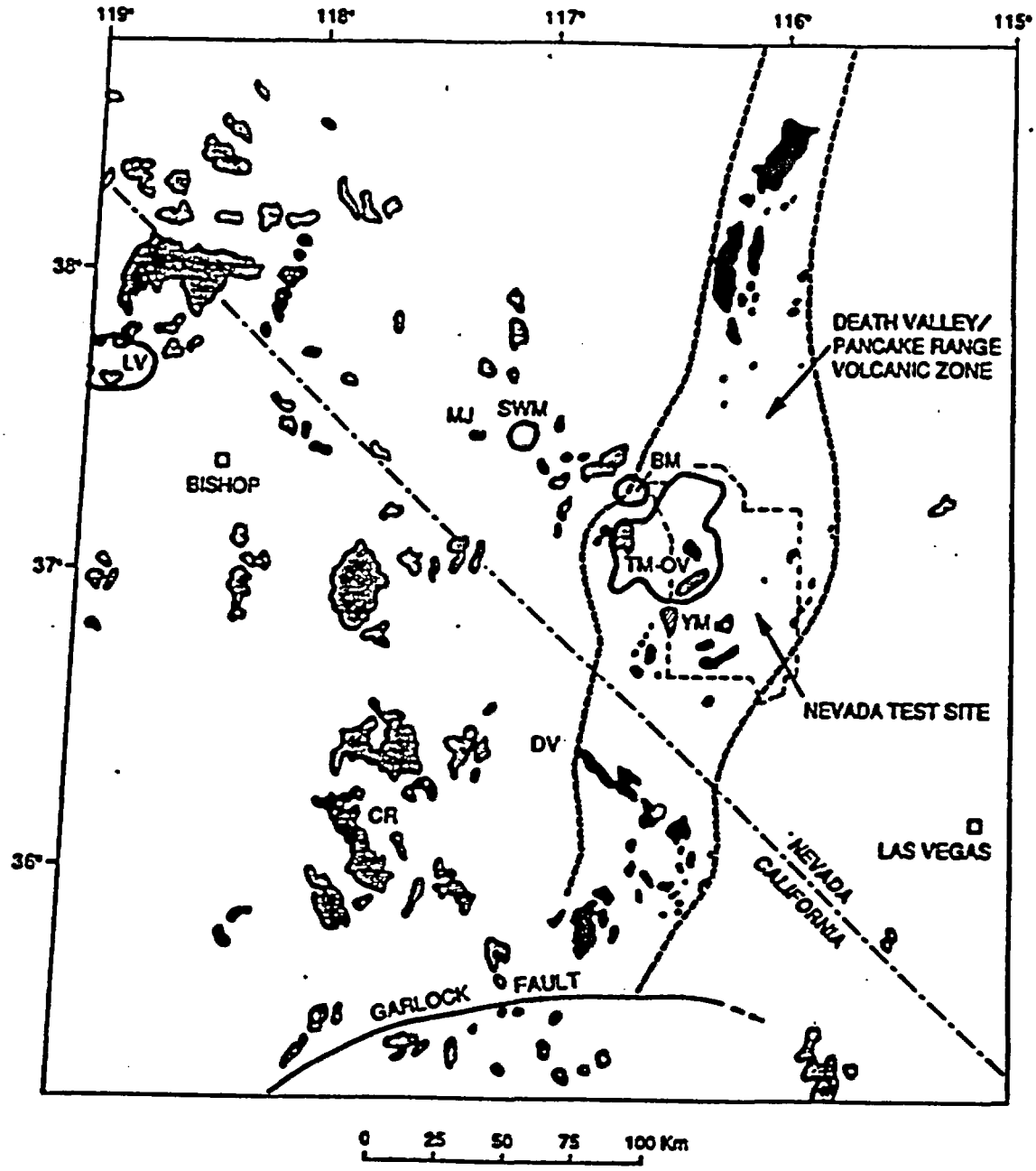


Figure 1. Distribution of post-Miocene silicic (stippled) and basaltic (black) volcanic rocks of the southern Great Basin. Basaltic rocks are inferred to be part of the Death Valley/Pancake Range volcanic zone (Crowe, Vaniman, and Carr, 1983a; Crowe, 1986). An alternative interpretation is that the zone 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; MJ: Mount Jackson dome field; LV: Long Valley caldera complex; CR: volcanic rocks of the Coso volcanic field; DV: Death Valley; YM: Yucca Mountain.

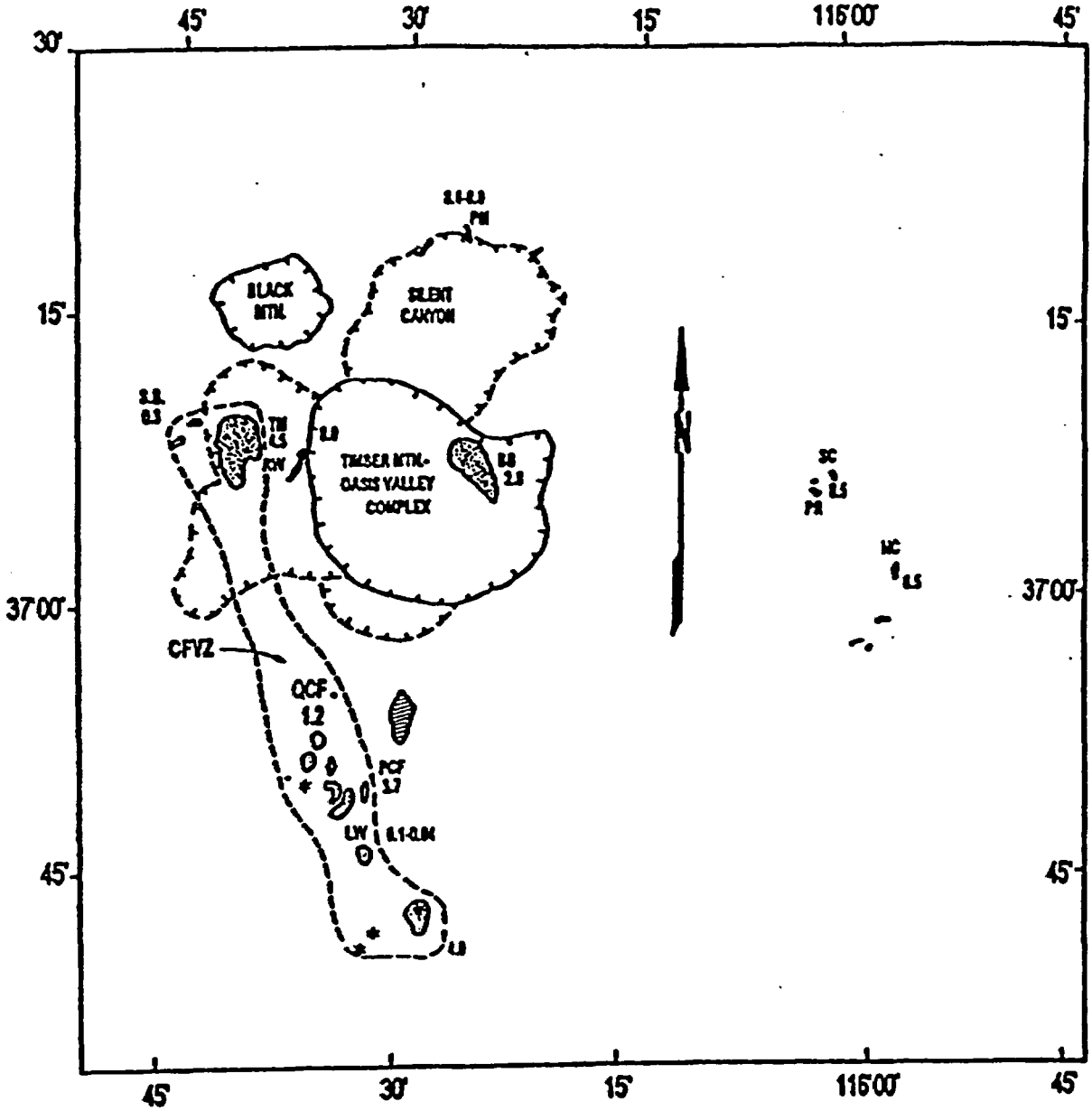


Figure 2. Post-Caldera Basalt of the Yucca Mountain region. Shaded areas are the Older Post-Caldera Basalt (OPB) including: RW: basalt of Rocket Wash, PM; basalt of Pahute Mesa; SC: basalt of Scarp Canyon; NC: basalt of Nye Canyon. Stippled areas are the Younger Post-Caldera Basalt (YPB) including: TM: basalt of Thirsty Mesa; AV: basalt of Amargosa Valley; 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).

are focused on identified anomalies that may represent magma bodies. 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 crustal magma or the operation of magmatic processes 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 calculating the recurrence rate of volcanic events and the probability of a future volcanic eruption and/or intrusion through the repository, the controlled area, and the Yucca Mountain region. The revised calculations will incorporate newly obtained information from site characterization studies (Study Plan 8.3.1.8.5.1, Characterization of Volcanic Features) in the probability calculations (Activity 8.3.1.8.1.1.4, Probability Calculations and Assessment).

1.2 Rationale for Information To Be Obtained and Use of Results

The evaluation of the Yucca Mountain site must include consideration of the potential for disruptive events that could directly or indirectly lead to the release of waste radionuclides. Volcanism has been identified as one potential disruptive event that will be evaluated for site characterization. Regulatory requirements (10 CFR 60.112 and 40 CFR Part 191) mandate that evaluation of postclosure 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 objective of this study is to evaluate the probability of magmatic activity penetrating the repository or the controlled area during the next 10 ka.

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 data supplied by this study plan are the estimated probability of a volcanic eruption and the probability of an intrusion into the potential repository site, the controlled area, and the area surrounding the Yucca Mountain site. These data will be used to make probabilistic assessments of the potential for disqualification of the site because of the presence of the potential adverse condition 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 studies of the potential cumulative radiological releases from the waste isolation system (SP 8.3.1.8.1.2).

2.0 RATIONALE

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 8.3.1.8.1.1.1)

2.1.1 Technical Rationale and Justification

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, and Section 3.1.4 of this study plan). The purpose of this activity is to collate geologic maps of the location of volcanic centers, with 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. The summarized data will provide fundamental information for the calculation of the recurrence rate of volcanic events. These data will be compiled and standardized to document the data base for probability calculations in a single, easily accessible reference. No alternative methods are known that could be used as substitutes for compiling maps and for listing geochronology 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 data for volcanic events will be obtained from this study plan (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.

2.1.2 Constraints

No measurements will be made for this activity. The maps and referenced data will not be time consuming to produce. Information will be provided on the precision and accuracy of analytical methods. There are no constraints on the activity 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 Technical Rationale and Justification

One of the parameters of the conditional probability of magmatic disruption of a repository is the disruption parameter (Crowe, Johnson, and Beckman, 1982). This parameter attempts to establish the probability that, given a future volcanic event, the event would disrupt the repository or the controlled area associated with the repository. The location of basaltic volcanic centers in the Yucca Mountain region is commonly controlled by existing structural features (Crowe and Carr, 1980; Crowe et al., 1983a, 1983b). In order to calculate the probability of magmatic disruption of the Yucca Mountain site, it is necessary to identify structural and tectonic features that may control the location of future basaltic volcanic events, and to determine how those features would affect the disruption parameter of the calculation.

The technical rationales for this activity are twofold. First, the structural and tectonic features of the Yucca Mountain region will be

examined systematically in order to determine whether or not there are associations between these features and the time/space patterns of the distribution of basaltic volcanic centers. The data for this evaluation will be obtained from Activity 8.3.1.8.5.1.1, Volcanism Drill Holes; Activity 8.3.1.8.5.1.3, Field Geologic Studies; and Activity 8.3.1.8.5.-1.4, Geochemistry of Eruptive Sequences (all from Study Plan 8.3.1.8.5-.1, Characterization of Volcanic Features). These data will be combined with data from the preclosure tectonic studies (Table 1). We will attempt to interrelate the regional tectonic framework of the site with an understanding of possible structural controls of sites of basaltic volcanic activity. Based on the results from the first part of the activity, we will also attempt to develop methods for factoring structural and tectonic controls of volcanism into the disruption parameter of the probability calculation.

We will use two major alternative approaches to developing structural models: stochastic and deterministic (see Section 3.2 for a discussion of the advantages and limitations of the two approaches). No attempt will be made to develop a single model or a set of preferred volcanic and tectonic 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 structural controls of basaltic volcanic centers. For each model, we will attempt to quantify the probability of disruption of the repository and the controlled area surrounding the repository.

We anticipate that a range of alternative models of the structural controls of basaltic volcanic activity are possible. Further, the number of models and the detailed analyses of individual models should change during the site characterization studies. The emphasis of this activity will be on continuing to develop models for the disruption parameter and on determining how various structural models will affect the numerical values of the disruption parameter.

2.2.2 Constraints

Data for an evaluation of the structural controls of basaltic volcanic activity is provided from other studies (Table 1). No direct measurements or experimental tests are planned for this activity, therefore no potential impacts on the site are identified from this work. The data parameters, calculational methods, precision, and accuracy of the calculations will be defined for each model. However, the uncertainty

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)	Field mapping of bedrock structures adjacent to basaltic volcanic fields. 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 crustal tectonic framework of the Yucca Mountain region and evaluate whether or not identified structures are associated with sites of subsurface 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.
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 area.
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 faults 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 Pliocene and Quaternary basaltic volcanic centers.

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 models of the structural 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.

of the disruption parameter will be established through the procedures for calculating the probability of magmatic disruption of the repository and the controlled area. The preliminary calculations for this activity will be completed within nine months following approval of this study plan. Revised calculations will be produced as data are obtained from the preclosure tectonics program. This work can continue through the full period of site characterization.

There are two potential constraints for this task. First, can we develop an acceptable methodology for quantifying the disruption parameter of the probability calculation 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 resolvable. First, we have already developed and defined mathematically several stochastic and deterministic models for the structural controls of basaltic volcanic activity (Crowe, Johnson, and Beckman, 1982; Crowe, 1986; Crowe et al., 1989). Additional models are being developed as new information is obtained from site characterization studies. Second, the equation for calculating the probability of magmatic disruption of the repository (Section 3.4.2) allows for flexibility in application of alternative tectonic and structural models. As new models are developed for the structural controls of surface volcanism, they can be factored into the disruption parameter of the probability calculation. These evaluations and revised calculations can continue for the full period 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 Technical Rationale and Justification

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 events and the 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 or not there is evidence of recent changes in these parameters. 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 or not 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 whether or not there is any evidence of the presence of magma in the crust beneath the Yucca Mountain region. Evidence of magma would require a reassessment of the recurrence rates of volcanic activity and processes controlling the distribution of volcanic centers. This would directly affect the assumptions used for a probabilistic approach to volcanic risk assessment.

The technical rationale for this activity is to review 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. First, a range of geophysical data are being obtained for the preclosure 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. Magma in the crust would be of either basaltic or silicic composition. The geophysical methods cannot discriminate the composition of bodies of magma.

The geophysical data will be reviewed by a recognized consultant in geophysics who is not involved in the preclosure tectonics program. The purpose of the review will be to determine whether or not sufficient information has been obtained to assess the potential presence of magma beneath the Yucca Mountain region. Additionally, the review will evaluate whether or not there is confirmed evidence of anomalies that can be interpreted as magma. Should such evidence be discovered, 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 models, 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 to explore 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 focus on potential magmatic 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) 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, Postclosure 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 initially planned for this activity; therefore, there are no identified site impacts from the geophysical studies for 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 Technical Rationale and Justification

The potential for future volcanic 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 surface eruption could lead to direct release of radioactive waste to the accessible environment. Intrusion or passage of magma into the controlled area surrounding the repository or the Yucca Mountain region (associated or not associated with a surface eruption) could alter the geohydrologic setting of the waste isolation system and change transport times of radioactive waste to the accessible environment. The rationale for this activity is to attempt to estimate numerically the probability of magmatic disruption of the repository, the controlled area, and the Yucca Mountain region.

There are two general approaches to assessing the risk of future volcanism. The first, more traditional, approach is to study the record of volcanism at and around a proposed facility or volcano using the standard tools of geosciences (field mapping, geochronology, petrology, geochemistry, and geophysics). These data are used to establish the nature, magnitude, and affected area of past volcanic activity to assess potential future hazards (Mullineaux, Peterson, and Crandell, 1987). Decisions with respect to the relative risk posed by future volcanic activity are made using these parameters. These analyses are best applied at active or dormant volcanoes for decisions involving land use or potential danger to property or human life from impending volcanic eruptions.

An assessment of volcanic risk for the Yucca Mountain site requires evaluation of the potential for renewed volcanic activity. Four questions must be considered. First, could an episode of volcanic activity occur during the 10 ka isolation period of a repository? Second, if there is renewed volcanism, would it disrupt the repository or the controlled area at Yucca Mountain? Third, if the potential repository or the controlled area of Yucca Mountain were disrupted by future volcanic activity, would that disruptive event lead to release of radionuclides to the accessible environment? Fourth, would the release levels from magmatic disruption exceed the regulatory requirements for licensing of a repository? These questions are much more readily answered by risk assessment (a combination of the probability and consequences of repository disruption) than by hazard assessment (a description of the nature, magnitude, and affected area of a future volcanic eruption).

A probabilistic approach to volcanic risk assessment is preferred for several reasons. First, probability assessment provides a numerical definition of the risk of future volcanism. Without a numerical definition of risk, the hazards of volcanism would be assessed through subjective judgments. These assessments are difficult to interpret within the regulatory guidance of 10 CFR 60.111. Second, the recommendations of 10 CFR 60.111 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 a probabilistic approach. There has been a uniformity in the composition, volume, and style of basaltic volcanism in the Yucca Mountain region during the last 9 Ma. 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 basalts are all straddle-type alkali basalt (classified geochemically as hawaiite; Vaniman et al., 1982). There has been a consistency in the magma effusion rate, with the exception of the Pliocene and Quaternary Periods when magma eruption rates may have declined (Vaniman and Crowe, 1981; Crowe, Johnson, and Beckman, 1982; Crowe, 1986; Crowe and Perry, 1990). Finally, probabilistic assessment of earthquake recurrence rates has become an accepted method for seismic risk assessment. There are close analogies between the methods of volcanic and seismic probabilistic assessment. Both processes may involve integrated responses of the tectonic setting of the crust and mantle of individual geologic regions (Shaw, 1980).

2.4.2 Constraints

All information for this activity are provided from other activities. No field studies or experiments are required for the probability calculations and assessments. No impacts on the site are identified. The only potential constraint with this activity is schedule. The iterative nature of the probability calculations makes it imperative to continually refine the calculations as site characterization studies proceed. However, these refinements can be readily factored into the probability calculations once the methodology of the calculations has been established. The uncertainty of the probability calculations is discussed in Section 3.4.

3.0 DESCRIPTIONS OF TESTS AND ANALYSES

3.1 Location and Timing of Volcanic Events (Activity 8.3.1.8.1.1)

3.1.1 Approach

The technical approach of this activity is to compile geologic maps and a data catalog of volume and geochronology measurements using data from Activity 8.3.1.8.5.1.1, Volcanism Drill Holes; Activity 8.3.1.8.5.1.2, Geochronology Studies; Activity 8.3.1.8.5.1.3, Field Geologic Studies of Study Plan 8.3.1.5.1, Characterization of Volcanic Features; Activity 8.3.1.8.1.4, Probability Calculations; and assessments of this study plan.

3.1.2 Summary of Test Methods

The geologic maps will be compiled on topographic quadrangle maps (1:24000 and 1:62500) from geologic maps produced from Activity 8.3.1.8.5.1.3, Field Geologic Studies. The original geologic maps will be a much larger scale (1:5000) than the compiled maps. Map units will be simplified and the information will be transferred by inspection, using geographic and topographic features on the quadrangle maps. Geochronology measurements will list the age information and a reference to the document describing the measurements and listing analytical parameters of the measurements. If no reference is available for a geochronology measurement, the analytical parameters of the measurement will be included in the data catalog. No procedures are required for this activity because the referenced data are obtained from other activities.

3.1.3 Equipment List

Topographic quadrangle maps.

3.1.4 Accuracy and Precision

No measurements are made for this activity.

3.1.5 Test Results

Compilation of geologic maps is a standard method for displaying the location and generalized geologic features of a volcanic center. The location of volcanic centers can be identified with a high degree of confidence relative to chronology and volume studies of volcanic units.

3.1.6 Description of Analyses

No analyses are required for this activity.

3.2 Evaluation of the Structural Controls of Basaltic Volcanic Centers (Activity 8.3.1.8.1.1.2)

3.2.1 Description of Tests

No tests are required for this activity. All data used in the activity will be obtained from Study Plan 8.3.1.8.5.1, Characterization of Volcanic Features, or from the preclosure tectonics study plans of Section 8.3.1.17.4 of the SCP. Investigations for this activity include only analyses of data from these sources.

3.2.2 Description of Analysis

3.2.2.1 Purpose

There are two purposes 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 data from the activities listed in Table 1. We will attempt, from this work, to develop models that describe an association between the structural features and tectonic framework and the distribution of Pliocene and Quaternary volcanic centers. The models will attempt to delineate potential structural controls that 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 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 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. Our approach will be to construct a catalog of potential structural models and calculate the values of the disruption parameter for the models and subsets of the models. For most of the models, we will not attempt to discriminate the relative merits of the models or develop a set of preferred models. The test of the significance of individual models will be how each model affects numerically the calculated data range of the disruption parameter.

3.2.2.2 Method

Two approaches will be used in developing data for the disruptive parameter. The first approach (stochastic approach) will follow the methods developed by Crowe, Johnson, and Beckman (1982). We will assume a random spatial distribution of volcanic activity and develop minimum area circles and ellipses that enclose the volcanic centers used to establish the recurrence rate and the Yucca Mountain site. The only modification to the earlier work will be to examine a more comprehensive range of combinations of volcanic centers for the Yucca Mountain area.

The second approach will apply deterministic methods in formulating the disruption parameter. The basis for this approach will be to develop systematic models of potential associations between structural features and the location of volcanic centers using data from the preclosure tectonics program (Table 1). We will attempt to describe causative relations between existing structure, structural settings, and the location of volcanic centers. Two constraints will be followed in applying the 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 must provide some logical means by which the model can be extrapolated to result in disruption of the repository or controlled area. We anticipate that a range of feasible models exist that cannot be shown,

using reasonable assumptions, to result in disruption of a repository at Yucca Mountain.

The two approaches used in the development of models of the structural controls of basaltic volcanic activity can best be shown by presenting examples of calculations. We note that the methods for calculating the disruption parameter are iterative. We will continue to develop and refine structural/tectonic models for the location of basaltic volcanic centers throughout the process of site characterization, particularly as new information becomes available from the preclosure tectonics studies (8.3.1.17.4). The examples used in this study plan may or may not be used in final calculations.

The methods for calculating the disruption parameter are iterative. We will continue to develop and refine structural/tectonic models for the location of basaltic volcanic centers throughout the process of site characterization. New information will be incorporated in the calculations, particularly as data becomes available from the preclosure tectonics studies (8.3.1.17.4).

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. Iterative structural models will be developed for this activity as more data are available from the preclosure tectonics program (Activity 8.3.1.17.4). We anticipate that different types of calculations will be used for he disruption parameter, dependent on the type of structural model proposed for the location of volcanic centers. We will attempt to develop structural models of the location of basaltic volcanic centers and attempt to apply the models to calculations of the disruption parameter. This approach can be used for any supportable structural model for the location of basaltic volcanic centers for the Yucca Mountain region. The emphasis of the analysis for this activity will be to develop, through the site characterization processes, a comprehensive set of structural models and respective sets of disruption parameters. This information will be analyzed further in Activity 8.3.1.8.1.1.4, Probability Calculations and Assessment.

3.2.2.3 Detailed Technical Procedures

One detailed procedure will be developed for this activity.

- Methods for Calculating the Disruption Parameter for Calculation of the Probability of Disruption of the Repository by Magmatic Activity. This is a standard procedure and describes QA Level I data analyses. The procedure will be completed in September of 1990.

- Use of computer software for this activity will follow TWS-QAS-QP-3.17, 3.18, 3.19, 3.20, 3.21 and 3.22 (see Table A-1)

3.2.2.4 Representativeness of Analytical Approach

There are two key questions for assessing the structural controls of volcanic activity. The first is: What is the degree of confidence possible for establishing correlations between the location of volcanic centers and structural or tectonic features in the Yucca Mountain area? We intend to evaluate this question using two approaches. First, we will evaluate the structural controls of volcanism for all small-volume basaltic activity in the Yucca Mountain region (back to 9 Ma), and for basaltic centers of the Cima and Lunar Crater volcanic fields. Expanding the age span and number of basaltic volcanic centers studied for this activity may increase the confidence in the developed structural models. Second, we will examine the effect of various

structural models on the disruption parameter. If various structural models do not lead to significant differences in the disruption parameter, it is not important to develop sufficient confidence to discriminate between models. Thus, this question can be partially resolved by developing multiple models of the structural controls of the location of basaltic volcanic centers and then establishing the range of the disruption parameter based on those models. The second question is: How adequately we can 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 by existing structures in the Yucca Mountain region. Therefore, our best assessment of the future structural controls of the location of basaltic volcanic centers is through studying the geologic record. There have been approximately 18 volcanic events in the Yucca Mountain region during the last 3.7 Ma [an event is defined as the formation of a new volcanic center; this number assumes that the aeromagnetic anomalies in the region (Crowe et al., 1986) are younger than 3.7 Ma and represent buried volcanic centers]. Seventeen of these events 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 18 past events demonstrates that future basaltic eruptions are unlikely to occur at Yucca Mountain. We are unable to define numerically the exact probability of a future volcanic event occurring through the exploratory block of Yucca Mountain. However, we intend to examine multiple structural models to attempt to define the disruption parameter for each model. There is a relatively high degree of confidence that using this approach the probability of an eruption at Yucca Mountain can be bounded.

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

3.3.1 Approach

We will follow a two-phased approach for this activity. The first approach will involve review of geophysical data for the Yucca Mountain region. The second approach is dependent on the results of the first approach. If evidence is obtained that indicates or is permissive (using multiple geophysical methods) with the presence of magma beneath Yucca Mountain, the second approach will be followed. This second approach involves focused geophysical studies to obtain detailed data to test the location, nature, and geologic credibility of anomalies that may represent magma. In parallel with this work, we will sample ground water from existing wells and surface springs in the Yucca Mountain region. The isotopic composition of the noble gases, with an emphasis on the $^3He/^4He$ ratios, will be measured to test for evidence of magma.

Geophysical data for this activity will be collected from three activities, all involving geophysical investigations. Activity 8.3.1.17.4.3.1, Conduct and Evaluate Deep Geophysical Surveys, will contribute data from an east-west transect crossing the Furnace Creek fault zone, Yucca Mountain, and the Walker Lane. Geophysical methods include seismic reflection, seismic refraction, gravity, magnetics, 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 8.3.1.15.2.2.1, Surface-Based Evaluation of Ambient Thermal Conditions. Finally, Study 8.3.1.17.4.1, Historical and Current Seismicity, will provide data that can be used to evaluate evidence of magma bodies.

These geophysical data will be analyzed as part of the individual activities. We will evaluate the results of data reduction and interpretations from the studies of these activities to make two

decisions. 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? If the answer to either question is positive, we will develop a document describing the additional geophysical and noble gas studies that are required to resolve the issue of the possible presence of subcrustal magma in the Yucca Mountain region. Such a document will become an appendix of this study plan.

3.4 Probability Calculations and Assessment (Activity 8.3.1.8.1.1.4)

3.4.1 Description of Tests

No tests will be undertaken for this activity. All information for the activity is provided from Study Plan 8.3.1.8.5.1, Characterization of Volcanic Features, and from Activity 8.3.1.8.1.1.2, Evaluation of the Structural Controls of Basaltic Volcanic Centers. The work for this activity involves analysis of existing data and is described in Section 3.4.2.

3.4.2 Description of Analysis

3.4.2.1 Purpose

The probability of magmatic disruption of a repository and release of radionuclides to the accessible environment through an eruption (Pr_{dr}) is defined as a tripartite probability:

$$Pr_{dr} = Pr(E3 \text{ given } E2,E1)Pr(E2 \text{ given } E1)Pr(E1),$$

where *E1* denotes the recurrence rate of volcanic events in the Yucca Mountain region, *E2* denotes the probability that the future magmatic event intersects the repository, or waste isolation system, and *E3* denotes the probability that magmatic disruption of the repository leads to rapid releases of radionuclides to the surface (accessible environment) in quantities that exceed the regulatory requirements. This probability can be expressed mathematically as (Crowe et al. 1982):

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

where λ is the recurrence rate of volcanic events, p is the probability that an event is disruptive, and r is the probability that the radionuclide releases to the accessible environment exceed the regulatory requirements for licensing a repository. The λ is defined as the rate of formation of new volcanic centers. 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 a simple or homogeneous Poisson distribution of the volcanic events through time (Crowe et al. 1982; Crowe 1986). Crowe et al. (1992a) reviewed recurrence models for volcanic events and discussed the rationale for choosing a simple Poisson model. Briefly, the model is conceptually simple, assumptions using this model are defined and potential errors can be constrained. The Poisson model is particularly appropriate and even conservative for the case of the Yucca Mountain region where multiple lines of evidence indicate volcanism is waning (Vaniman and Crowe, 1981; Crowe et al 1982; Crowe et al 1992a, Perry and Crowe 1992). The simple Poisson model does not introduce unwarranted complexities that are not justified or required by the time-distribution properties of a small data set. Moreover, by virtue of the small data set, models incorporating other parameters do not yield results that differ significantly using other distribution models (for example, Ho 1991; Ho 1992). Finally, there is ample justification in both the seismic and volcanological literature for application of a simple Poisson model (Crowe et al. 1992a).

Several assumptions are required to apply the probability formula. First, the past record of basaltic volcanic activity in the Yucca Mountain region is judged to be the most reliable indicator of the rates of future volcanic events. This assumption is supported by the consistency of the record of volcanism in the region for the last 10 Ma. All post-late Miocene volcanic centers formed from the eruption of small volumes (< 1 km^3) of basaltic magma (Crowe 1990). The activity

formed spatially isolated centers comprising scoria cone(s) and associated aa lava flows.

Second, we assume there has been a sufficiently detailed study of the Yucca Mountain region 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 potential Yucca Mountain site. The presence and location of Quaternary volcanic centers in the region 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). Any subsurface basaltic rocks of significant volume that are present above depths of several kilometers should be identifiable from aeromagnetic data. Intrusions below the depth of detection by aeromagnetic studies are not of concern to a repository for most anticipated conditions.

Finally, we assume that the observations and interpretations of the geologic record 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. However, we have constrained this problem by using multiple chronology methods (Crowe et al. 1992). Additionally, we use multiple models for the age of volcanic events where there is uncertainty in age assignments. The simple Poisson model requires only the recognition of Quaternary volcanic centers. The second 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 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 1983). Again, we accommodate this uncertainty by varying the assumptions of the volume calculations for the probability calculations. The volume-predictable, simple Poisson models use the age and erupted magma volumes to calculate magma output rates. Because the volume of erupted magma has declined through time in the Yucca Mountain region, the volume-predictable model is not strongly affected by the uncertainty of the determinations in the ages or eruptive volumes of the centers. Finally, we assume that both competing eruptive models for the youngest Quaternary volcanic centers (monogenetic and polycyclic) apply to the Pliocene and Quaternary volcanic centers. The two models are not different for establishing the rate of formation of volcanic events but are different in assessing the consequences of volcanic activity. By evaluating the effects of both models, we are assured that the complete range of potential effects of repository disruption by magmatic activity is considered carefully.

Volcanism studies have a decision point that determines whether different scenarios can be eliminated from concern on the basis of a low occurrence probability, or whether magmatic effects or releases must be assessed to determine the suitability of the potential site with respect to volcanism. If the site is not found to be unsuitable, there must be an evaluation of the consequences of volcanic events in terms of the cumulative release calculation required for licensing.

For the site suitability determination, there are additional decision points. The primary basis for these decision points is established by an assessment of whether the initiating volcanic events can or cannot be shown to 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 immediate releases to the accessible environment that exceed regulatory requirements. If the occurrence probability of exceeding allowable 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.

For the cumulative release calculation, if the occurrence probability of exceeding allowable releases is > 10^{-8} yr^{-1}, detailed studies will be undertaken to establish the contributions of direct and indirect magmatically-driven releases to cumulative releases from the waste isolation system. Quantifying magmatically-driven radiological releases is not the subject of this Study Plan. Volcanism studies from Study Plan 8.3.1.8.1.2 provide the information needed to identify effects of magmatic activity on the waste isolation system. Calculation of the radiological releases from direct, indirect, or coupled magmatic effects will be undertaken as part of performance assessment studies.

There are several key questions that must be answered to assess the risk of future volcanism. The first is whether igneous activity is a concern for the potential Yucca Mountain site? We have established already that the presence of five Quaternary volcanic centers in the vicinity of Yucca Mountain is a potentially adverse condition and requires assessment as a part of 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 broken into two questions. What is the probability of a volcanic eruption and what is the probability of an intrusive igneous 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 evidence in the Yucca Mountain region that 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 be exsolving 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 $Pr_i \approx Pr_v$. Nonetheless, we will continue to assess data through ongoing site characterization studies to determine if there are any likely conditions where Pr_i could be > Pr_v. For either case, existing data (Crowe and Carr 1980; Crowe 1986; Crowe et al 1982, 1988; Crowe and Perry 1989; Ho et al. 1991; Ho 1992; and Crowe et al. 1992) show that the probability of a volcanic event in the Yucca Mountain region is > than 10^{-8} yr^{-1}. Therefore these events must be assessed for the potential Yucca Mountain site (*Note: Because $Pr_i \approx Pr_v$, the remaining discussion will only mention Pr_v recognizing that the described assessments apply to both events).*

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 does the event occur? There are three options: 1) the Yucca Mountain region, 2) the controlled area of a repository, 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 Pt_o is the probability of intrusion or eruption outside of the repository and the controlled area. The attribute p is significant for the equation only for events close to the boundary of the controlled area. 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 Pt_o is > 10^{-8} yr^{-1} for many cases of the probability estimations and requires that this option be assessed through evaluation of secondary radiological releases.

The second option is that a future volcanic event or intrusion can occur within the controlled area. 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 controlled area, and p is the a/A where a is the area of the controlled area and A is the area of the established volcanic rate. The controlled area is larger than the area of the repository by slightly greater 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 secondary effects of magmatic 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 risk of this event exceeds some presently unspecified value, the site should be disqualified because of the risk of volcanism. A suggested realistic value is 10^{-6} yr^{-1}. Studies to date indicate it is physically implausible for Pr_d to be less than 10^{-6} yr^{-1} (Crowe et al 1982; 1992b; Ho 1991; 1992; Ho et al. 1991). If this were to occur, it would require either a major change in λ, or the discovery of some unrecognized structural control of the site of future volcanism that directly focuses future volcanism at the potential Yucca Mountain site. Additionally, the site would be disqualified if the radiological releases associated with magmatic disruption of a repository 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 an important licensing issue. Volcanism studies of the effects of eruption through a repository would be ended. This is a distinct possibility based on current site data.

If Pr_d is > 10^{-8} yr^{-1}, assessments will be conducted of the probability of direct releases of radioactive waste to the accessible environment by a volcanic eruption. This relationship is modeled as:

$$Pr_{dr} = 1 - exp^{(\lambda - tpr)}$$

where Pr_{dr} is the probability of disqualification of the repository from future volcanic eruptions and r is the probability that volcanic eruptions release radionuclides to the accessible environment in quantities that exceed the regulatory requirements. This relationship

does not apply to the probability of volcanic intrusion because this event does not result in direct releases of radionuclides to the accessible environment. The proposed studies to investigate this topic are described in Study Plan 8.3.1.8.1.2.

Calculation of the probability of magmatic disruption will follow three steps. First, methods for calculating , the recurrence rate of future volcanic events (extrusive or intrusive) in the Yucca Mountain region will be refined from previous calculations (Crowe and Carr, 1980; Crowe et al. 1982). Second revised methods for assembling the calculations for the probability of magmatic disruption of the repository Pr(E2 given E1)Pr(E1) will be undertaken. Data for scenario cases of the probability attributes will be compiled as matrices, sample statistics, and simulation modeling will be used to establish probability distributions. Third, formal procedures involving application of expert opinion will be used to increase assurance that all alternative volcanic models have been considered. Expert opinion will be used to weight uniformly the inclusion of alternative models in the probability distributions relative to the applicability of alternative models to the setting of the Yucca Mountain region and processes of magma dynamics.

The probability of magmatic disruption of the repository and surrounding area from future volcanic events will be calculated for the following scenarios: 1) the probability of recurrence of a small-volume eruption at the Lathrop Wells or Hidden Cone volcanic centers (Crowe et al., 1989), 2) the probability of formation of a new volcanic center or intrusion in the Yucca Mountain region, 3) the probability of formation of a new volcanic event or intrusion in the controlled area, and 4) the probability of formation of a new volcanic center or intrusion in the repository. Because the first scenario has no direct effect on the potential repository and is considered only for the cases of existing volcanic centers, only the recurrence rate of future events will be calculated or bounded. The probability of magmatic disruption for scenarios two and three will be established for areas defined by two constraints. Scenario two will be assessed for an area where a/A is < 1. The probability of disruption approaches , the recurrence rate, when $a/A=1$. The probability of the third scenario will be considered for both intrusive and eruptive events. The probability of intrusive events may be slightly higher for intrusions versus eruptive events for scenarios three and four. The calculations for these cases will examine a range of geometric constructions of the disruption ratio where either the repository or controlled area will be intruded but waste will not be carried to the surface. Scenarios one through four will be considered as part of Study Plan 8.3.1.8.1.2 for all cases where the disruption/intrusion probability is less 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 *bounds* of the probability estimations meet the parameter goals. The definition of **moderate confidence** for the parameter goals described in Table 2 is that the *likely values* of the probability estimations 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	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 Goal	Needed Confidence
travel paths) (8.3.1.8.3)			
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

3.4.2.2 Method

The methods of analysis for this activity are described for the three approaches listed in Section 3.4.2.1. These include: (1) methods for determining the recurrence rates of future basaltic volcanic events, (2) methods for summarizing the recurrence rate probabilities and for combining recurrence rate data and the disruption parameter to obtain statistical data for the probability of magmatic disruption of a repository or surrounding controlled area at Yucca Mountain, and (3) methods for weighting probability statistical data using expert opinion.

Methods for Calculating the Rate of Occurrence of Volcanic Events

The first parameter of the Pr_{dq} is E1, the rate of occurrence of future volcanic events. Three methods will be used to calculate E1 for the two defined cases: (1) examination of recurrence intervals of volcanic events, (2) counts of volcanic vents through time (stochastic approach), and (3) evaluations of magma effusion rates (deterministic approach examining magma eruption volume versus time). The intent of this activity is to use an approach similar to that used for Activity 8.3.1.8.1.1.2, Evaluations of the structural controls of basaltic volcanic activity. We will use three methods for calculating the rate of recurrence of future volcanic events. Multiple iterations of each method will be undertaken to attempt to provide a range of calculations that conform to various geologic assumptions for basaltic volcanism in the Yucca Mountain region. These calculations will be based primarily on the patterns of basaltic volcanic activity recorded in the geologic record of the Yucca Mountain region. This record is considered to provide the best indication of the most likely type of future volcanic activity. We will also attempt to evaluate any evidence suggestive of possible changes in the nature of future basaltic volcanic activity consistent with an understanding of magmatic processes. 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 calculating recurrence rates of volcanic activity are developed during site characterization studies, they will be included in revised recurrence rate calculations.

Recurrence Intervals: Past studies showed that there were 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 to analyze for

interval patterns (Crowe et al., 1982, p. 178). We will reevaluate this conclusion using new data provided by Activity 8.3.1.8.5.1.2, Geochronology Studies. Two new observations will be considered in a revised assessment of evidence for recurrence patterns. These include formation of new volcanic centers associated with clustered volcanic events (Crowe and Perry, 1990), and recurrence patterns of small-volume scoria eruptions at polycyclic centers (Crowe et al., 1989; Wells et al., 1990).

Counts of Volcanic Events 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 paleomagnetic data show the vents are time synchronous).

Advantages: Volcanic vents 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 the assumptions of a random distribution of volcanic events through time, and no time dependence of events (Poisson distributed events).

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 weigh 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 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, 1990).

We intend to continue to use counts of volcanic vents for calculating the rate of occurrence of volcanic events, but with several constraints. These constraints attempt to minimize the disadvantages of the method. First, we will restrict the time of vent counts to set periods. These periods will be the time since the onset of the Younger Post-Caldera basalt (4.5 million years) and the Quaternary period (corresponding to guidance in 10 CFR 60). 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 group volcanic events. Closely spaced or aligned volcanic vents with similar field magnetic directions will be treated as single volcanic events. Spatially separate volcanic vents (requiring multiple feeder dikes) or vents with different field magnetic directions will be treated as separate vents and counted as multiple events.

Magma Effusion Rates: We will reexamine the data used to establish a highly correlated regression-fit model that yielded magma eruption rates for past volcanic activity in the Yucca Mountain region (Crowe, Johnson, and Beckman, 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, 1984, 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 effusion rate. The term magma effusion rate is used following the definition of Wadge (1982) and is similar to the term magma output rate of Kuntz et al. (1986). It is the surface extrusion rate (corrected to magma density) of volcanic eruptions through time. For episodic volcanic events it is the integrated rate of surface eruption of magma during periods of eruptive and noneruptive activity.

Advantages: There are major advantages to using magma effusion rates for establishing volcanic recurrence rates. First, the rate is established from determinations of magma volumes of individual eruptive units. For this activity, the effusion rates are determined for the Pliocene and Quaternary centers of the Yucca Mountain region. The calculated rate is therefore specific to the Yucca Mountain region, and provides a definable basis for forecasting future rates of volcanic activity. Second, 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: There are several potential disadvantages to calculating a magma effusion rate for the Yucca Mountain region. First, magma effusion rates have been established primarily at active volcanic centers or volcanic fields with numerous volcanic centers (20 to > 100 cones). There is less experience at evaluating magma effusion rates at small-volume volcanic fields with scattered centers and episodic activity. However, several considerations suggest this approach is 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. Crowe, Johnson, and Beckman (1982) and Crowe and Perry (1990) have shown that the Pliocene and Quaternary volcanic centers of the Crater Flat Volcanic zone exhibit volume-predictable behavior. Second, surface basaltic volcanic centers are fed by basalt feeder dikes. An unknown and potentially significant volume of magma is present in the feeder dikes and is never extruded at the surface. This volume is not accounted for by an evaluation of magma effusion 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 effusion rates measure magma that intrudes the crust and is erupted at the surface. We consider it unlikely that significant quantities of magma will ascend to repository depths (300 m) and not reach the surface. Moreover, should basaltic magma form a shallow intrusion, it should be readily detected by aeromagnetic data. Third, an effusion rate is not a direct indicator of volcanic recurrence rates. It must be used as a variable in a separate equation to calculate recurrence rates.

Effusion Rate Calculations: Approaches

We will establish magma effusion rates for the Pliocene and Quaternary volcanic record of the Yucca Mountain region. The emphasis of these calculations will be on establishing the range of calculated effusion rates. To do this, we will examine multiple approaches for constructing a plot of cumulative magma volume versus time for calculating magma effusion rate.

1. Rate of Formation of Volcanic Clusters: The magma effusion 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 3.7 Ma cluster, the 1.2 cluster, the Sleeping Butte cluster, and 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 not be plotted in most calculations because it is not considered to be part of the Crater Flat volcanic zone. It will, however, be treated as a cluster point for some calculations to evaluate how addition of this point affects calculated effusion rates. A major advantage of the cluster-rate calculation is that it establishes the magma effusion 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 controlled area.

2. Rate of Center Formation Within Volcanic Clusters: The magma effusion rate 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 effusion rate calculated 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.

3. Volcanic 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 (Kurtz et al., 1986; Crowe and Perry, 1990; 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 (1990) 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 probabilistic assessment of volcanic recurrence models. 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 emphasize volume-predictable models for the Yucca Mountain region. Several approaches will be used to provide curve fits for plots of cumulative magma volume/time. Planned curve fit models include regression fit, rate bound fit, and first and second derivative fits. The regression fit provides an average approximation of magma effusion rates. It is relatively insensitive to changes in magma effusion rates 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, which can be eliminated by plotting magma volume, not cumulative volume, versus time). The rate bound fit corresponds to a physical model of volcanic process that has been developed for Hawaiian volcanoes (Shaw, 1982, 1987). This model assumes that the maximum magma effusion rate is bounded by the magma supply rate. Effusion rates at volcanic vents or the growth of volcanic centers can approach but not exceed the magma supply rate. The magma supply or maximum effusion rate can be approximated by graphically fitting a curve on a cumulative magma volume/time plot that forms an upper limit (rate bound) on the magma volume points (see maximum effusion rate of Wadge, 1982). The first and second derivative fits can be used to calculate the magma effusion rate at specified points in time. The first derivative yields the magma effusion rate, and the second derivative is the rate of change of the magma effusion rate. This calculation is sensitive to time changes in magma effusion rates, and can be used to calculate magma effusion at time 0 (the most appropriate rate to extrapolate into the future).

5. One of the difficulties of applying effusion rate models to the Yucca Mountain data is the limited number of Pliocene and Quaternary volcanic centers or clusters of volcanic centers in the region. This limitation will make it difficult to test the suitability of various models. Because of this, we will use two approaches to test models. First, we will assess the range of values obtained for various effusion rate models to determine if the selection of models leads to marked changes in effusion rates. Second, we will use data from published studies of volcanic fields in the southwest United States to evaluate the application of magma effusion models to volcanic fields. We will obtain and emphasize data from the Cima and Lunar Crater volcanic fields, which are geographically close to, and may provide the most appropriate analogies for comparison with, the Yucca Mountain region. This information will be obtained from Study Plan 8.3.1.8.5.1, Characterization of Volcanic Features.

Recurrence Rate Calculations: Once a magma effusion rate is established, it can be used to calculate the time of the next volcanic event using

$$Tp = (Vm/Em) - Te, \qquad (4)$$

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.

Vm is the most sensitive parameter of this equation. It can be substituted to produce two separate probability calculations, and becomes the representative volume of a small-volume scoria eruption for calculating the probability of recurrence of small-volume scoria eruptions. 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. 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 will use data from the Cima and Lunar Crater volcanic fields to provide statistical data for Vm. These volcanic fields contain over 100 Quaternary volcanic centers.

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 is not commonly considered in volcanism field studies. To limit uncertainty and determine the reproducibility of calculations, we have developed a computer-based approach to calculating the volume of volcanic events. Two procedures 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 using an image processing system. Elevation data will be added to the digitized maps from topographic maps and from local measurement of unit thicknesses. A computer program will be used to contour the top and bottom surfaces of volcanic units and calculate the volume of each unit. The second approach is to complete detailed surveying of selected volcanic centers using a laser theodolite. The survey data will be contoured and a three-dimensional topographic map of the center will be developed using the contouring and plotting procedures (multiple contouring and three-dimensional plotting routines are available in the program) of the computer program. A geologic map of the center will be overlaid on the contoured map, and the computer program will be used to calculate the volume of individual volcanic units.

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 effusion rates (Crowe and Perry, 1990). To reduce the uncertainty of this component in the volume calculations, we will obtain thickness of ash fall units 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).

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 determine the volume of the units for modifying magma effusion 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 1992. We will describe the geophysical investigations and the modeling to be used for the volume calculations in a report that will be released six months before the start of the exploratory drilling. The report will be added as an appendix to this study plan.

Assembling Probability Calculations

Data from the recurrence rate calculations will be assembled in matrix form using a computer spreadsheet. Data will be assembled for three sets. Set one will include calculations of the probability of recurrence of small-volume scoria eruptions at an existing volcanic center. Set two will include calculations of the recurrence probability for formation of a new volcanic center on a cluster of volcanic centers. Set three will include the calculations for the probability of magmatic disruption of the repository. Set three will include the calculations of the probability of intrusion or eruption of magma through the Yucca Mountain region, the controlled area, or the repository. This calculation will be determined by combining data set two with the data on the disruption ratio (p) established from Activity 8.3.1.8.1.1.2.

These combined calculations will, in some cases, require modifying the rate parameter, because some of the structural models are formulated for areas that do not include all Pliocene and Quaternary volcanic events. There will be three subgroups of the calculations of the probability of magmatic disruption: disruption of the waste isolation system, disruption of the controlled area, and disruption of the repository. The calculations for the latter two subgroups will be separated also by intrusion versus eruptive events.

The spreadsheet matrix will be used to construct a histogram of each of the data sets. Individual histograms will be evaluated for distribution models, symmetry of data distribution, skewness, and evidence of modality (bimodal, trimodal). Univariate statistics will be calculated for the probability sets. Statistical parameters will include but not be limited to minimum, maximum, mean, geometric mean, mode, variance, and standard variation. Simulation modeling will be conducted of the data for the recurrence rate and the disruption ratio using the computer program @RISK to calculate the probability distribution of Pr(E1 given E2)Pr(E1). The simulations will use Monte Carlo and Latin Hyper cube sampling methods combined with a range of distribution models (poisson, modified poisson, triangle, Weibull).

Expert Opinion

An important issue for assembling the matrices of probability calculations and the simulation modeling of the probability distributions is to ensure that the resulting data adequately represent the complete range of possible probability outcomes. This can be addressed by two processes. First, we will attempt to systematically examine and evaluate all reasonable models of the recurrence rate and the disruption ratio, *p*. We will solicit suggestions of alternative models of the disruption probability from external review groups, from the Nuclear Regulatory Commission, and from the State of Nevada. Additionally, we will continue to develop models as new data are obtained from the site characterization program. Yearly updates will be issued on alternative probability models following completion of the first revised probability matrices and distributions. Further, we will use formal procedures of expert opinion to independently test for completeness of incorporation of alternative probability models.

Second, in the initial compilation of probability matrices and distributions, all models will be given equal weight. However, different models will have different geologic credibility. Moreover, uniform incorporation of all models may not guarantee calculation of representative probability distributions. 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. We will attempt to reduce this bias by employing a second emphasis of expert opinion. Recognized experts in the fields of tectonics and volcanology will be asked to rank the suitability of models of the recurrence rate and the disruption ratio with respect to two criteria. Those criteria are first, the credibility of the models relative to the Pliocene and Quaternary volcanic setting of the Yucca Mountain region, and second, the credibility of the models relative to scientific understanding of magmatic and volcanic processes. Finally, methods of expert opinion will be used to weight the process of incorporation of alternative models in probability calculations to limit the introduction of bias.

The exact procedures for application of expert opinion have not been established for volcanism studies. These procedures will be developed after completion of the first set of revised probability calculations

and added as an appendix to this Study Plan. However, the primary application of expert opinion is as an aid in attempting to reduce bias in development of final probability distributions. Expert opinion will not be used in generating the initial probability values.

3.4.2.3 Detailed Technical Procedures

Two technical procedures will be developed for this activity. They include:

- Methods for Magma Volume Determinations for Calculating the Probability of Magmatic Disruption of the Repository and Controlled Area. This is a standard procedure. It will be completed in September of 1990.

- Methods for Weighing Volcanic Probability Calculations through Use of Expert Opinion. This is a standard procedure. It will be completed in March of 1991.

- Procedure for Geomorphic Studies of Volcanic Landforms. This is a standard procedure. It will be completed in June of 1990. This procedure describes the operation and application of the laser theodolite for surveying volcanic landforms.

- Computer software for probability calculations will follow the requirements of TWS-QAS-QP-3.17, 3.18, 3.19, 3.20, 3.21, and 3.22.

3.4.2.4 Equipment and Software for Data Analysis

- AST/386 MS-DOS Compatible Computers with numeric coprocessors (80387).
- Series 151 Image Processor with Digital Camera, Imaging Technology Incorporated, Woburn, Massachusetts
- Software Development Package for the Imaging Technology Series 151 Image Processing System and ITEX Software Library, Infrascan Inc. Version 1.3
- Surface Display System Contour and 3D Surface Plotting Software, Design Professional Management Systems, Version 2.2
- SYSTAT Statistical Software, Version 4.0, Systat Inc.

3.4.2.5 Representativeness

Several major questions must be assessed concerning the suitability of probability calculations for evaluating the risk of future volcanism for disposal of high-level radioactive waste. First, is the approach valid for volcanic hazard assessment? Second, are the data for probability calculations (7 Quaternary centers, 6 Pliocene centers) sufficient to undertake the calculations with an acceptable degree of uncertainty?

The first question can be answered at least partly by examining the success of application of probabilistic assessments for other scientific disciplines and evaluating the role of probabilistic assessment in studies of disposal of high-level radioactive waste. The requirements of a probabilistic approach include a random or exponential distribution of the phenomena interest. The time-space distribution of volcanic activity appears not to satisfy either of the constraints. The occurrence of volcanic activity in the geologic record is not random. Volcanic events occur episodically and they are commonly associated with periods of increased tectonic activity. The location of basalt centers is controlled generally by structural features. Basalt magma undoubtedly ascends along paths of structural weakness. Thus, at first examination, a probabilistic approach to volcanic hazards seems

difficult to justify. However, a probabilistic approach is commonly used for many phenomena that do not exhibit a Poisson distribution. For example, there is an ongoing debate in the seismology literature concerning the suitability of probabilistic assessment for seismic risk assessment. The time-space-magnitude distribution of seismic events is not independent in time or space (although seismicity may tend more towards a Poisson distribution than does volcanic activity). Nonetheless, considerable success has been obtained in forecasting seismic hazards using a probabilistic approach. The trend in seismic risk studies has been to use a stochastic approach when data are limited (chronology or magnitude data) but to attempt to apply more deterministic models as an increased understanding of seismic mechanisms is obtained. The approaches used for seismic and volcanic analyses are similar, particularly for paleoseismic studies. In general, seismic models for risk assessment are much more developed than are volcanic models, and earthquake events are more common than volcanic events. However, volcanic studies offer the advantage of providing a greater range of techniques for obtaining chronology data (isotopic, and radiometric age determinations of the volcanic events), and the magnitude of events is recorded directly in the geologic record (volume of the eruptive deposits).

We suggest that there are three major reasons why a probabilistic approach is feasible for volcanic risk assessment for the Yucca Mountain site. First, the regulatory requirements (Nuclear Regulatory Commission, Environmental Protection Agency) are slanted strongly toward a probabilistic approach. A probabilistic perspective to volcanic risk assessment is therefore much more readily applied to licensing requirements than other approaches. Second, there is a clearly demonstrated close association between seismic and volcanic activity (Shaw, 1980). We regard the success and increasingly rigorous models of seismic risk assessment to be indicative of the potential for application of similar techniques to volcanic risk assessment. Finally, a stochastic approach to volcanic risk assessment can be justified if it can be demonstrated that the assessment is conservative. A major concern of a stochastic approach is the requirement of uniform rates of activity. If rates of volcanic activity have increased, a stochastic approach could underestimate the probability of future volcanic events. However, evaluations of magma effusion rates can be used to test for indications of changing rates of volcanic activity. Thus, a stochastic approach cross-checked and supplemented by deterministic methods is an acceptable method for assessing risk.

The second question, the quantity of data available for assessment of volcanic risk, is difficult to answer. The Yucca Mountain site is caught in a logic trap. If more Quaternary volcanic events were present in the site vicinity, there would be increased data for calculating 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 calculations will be answered by two parts of this study plan. First, permissible data ranges will be defined for probability calculations by the incorporation of multiple data approaches to parameters of the probability equation. These data ranges will be evaluated continually as the activities of this study plan progress. Second, an important constraint on data uncertainty is the current status of volcanic processes in the Yucca Mountain region. All studies are not yet completed, but the decreasing volume of erupted basalt in the Pliocene and Quaternary in the region suggests that volcanism is waning (Vaniman and Crowe, 1981; Crowe, 1986). If this proves to be the case, then

probability calculations based on an assumed steady-state model of volcanic activity can be demonstrated to be conservative.

4.0 APPLICATION OF RESULTS

The primary use of the results from this study will be to support the evaluation of postclosure scenarios for evaluating the total system performance. Section 8.2.5.13 of the SCP outlines the performance allocation for the total system, including a list of potential release scenario classes. The current list of initiating events associated with volcanism will require information on the probability of the initiating events. This study plan will provide the data for assigning event probabilities.

Identified initiating events that require probability estimates from this study plan include

1. Direct penetration of the repository, controlled area, or the waste isolation system by magma followed by eruption of the magma causing radiological releases to the accessible environment.

2. Surface volcanic eruptions causing changes in topography or surface cover of the potential repository area, the controlled area, or the Yucca Mountain region. These changes could result in impoundment or diversion of drainage of surface water or changes in infiltration of moisture.

3. The formation of basaltic intrusions (sill, dikes) in the repository area, controlled area, or the waste isolation system that could result in changes in moisture flux.

4. The formation of basaltic intrusions (sill, dikes) in the repository area, controlled area, or the Yucca Mountain region, that result in the development of a barrier to water flow or in thermal effects of the intrusions that disrupt the water table, flux of moisture, or hydraulic gradient.

5. The formation of basaltic intrusions, resulting in changes in mechanical or geochemical properties of surrounding rocks.

Items two through four require information that will be supplied through Study Plan 8.3.1.8.1.2, Physical Processes of Magmatism and Effects on the Potential Repository.

A set of potentially significant release scenarios will be developed that address all events and processes that may affect the repository. For those volcanic events that are judged to be credible, probability estimates will be provided from this study plan to evaluate the significance of individual scenarios.

5.0 SCHEDULE AND MILESTONES

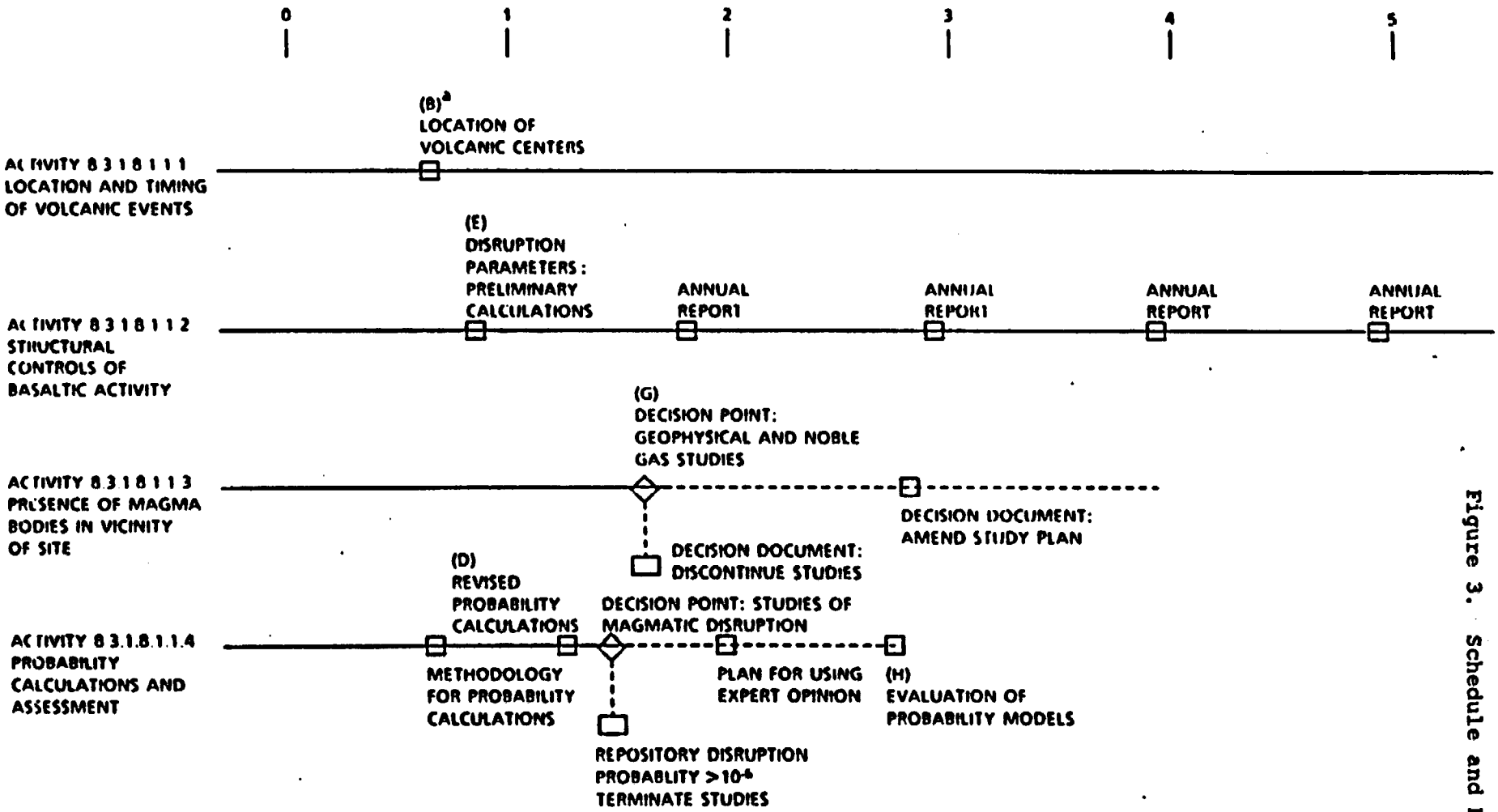
The milestones for Study Plan 8.3.1.8.1.1, Probability of Magmatic Disruption of the Repository, are listed in this section by activity. Figure 3 corresponds to the lists. lry objectives of this study plan are to provide calculations of the probability of magmatic disruption of the repository and the controlled area surrounding the repository, and to assess evidence with respect to the presence of magma in the crust beneath the Yucca Mountain region.

The schedule for this study is dependent on the overall site characterization program as described in the SCP (DOE, 1988). It 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 schedule for completion of milestones for this study plan is dependent on timely submission of data from these two sources.

The highest priority goals for this study plan are to establish the revised methodology for probability calculations and to begin calculations using the revised methodology. Because volcanism is judged to be a potential disqualifying issue, we intend to complete both goals within the next calendar year (initiated with the approval of the study plan). This requires revising the methodology, conducting a first set of calculations of the disruption parameter, and assembling the matrices of three sets of probability values (probability of a small-volume eruption, probability of formation of a new volcanic center, and probability of magmatic disruption of the repository and the controlled area). We anticipate that revisions and additions to these probability sets will continue throughout the site characterization process. However, it will be important to attempt to complete the next set of calculations of the probability of magmatic disruption within a calendar year. We will compare these values with the results of calculations completed in 1982 (Crowe, Johnson, and Beckman, 1982) and determine whether or not the revised calculations require changes in the judgments of the suitability or nonsuitability of the Yucca Mountain site with respect to the potential for future volcanism. When these revised calculations are completed, we will establish the procedures for using expert opinion to weight recurrence rate models and models of the structural controls of volcanic centers. 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 the second phase of geophysical and noble gas studies within a year and a half of approval of the study plan.

5.1 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.



a LETTERS IN PARENTHESES INDICATE CORRESPONDING MILESTONE IN SCP TABLE 8 3 1 8-9 (DOE, 1988)

Figure 3. Schedule and Milestones.

(B)* Location of Volcanic Centers

Report with compiled maps of the location of volcanic centers and referenced geochronology data. This report will be completed 6 months after completion of the data from Study Plan 8.3.1.8.5.1, Characterization of Volcanic Features.

5.2 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 report will compile the best available data from feeding studies and will be completed 9 months after approval of this study plan.

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.

5.3 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 Nobel Gas Isotopic Studies

A decision will be made one and a half years after approval of this study plan whether or not the second phase of detailed geophysical and noble gas isotopic studies will be required.

Decision Document: Discontinue Studies

If the second phase of studies are judged to be not required, a report will be issued describing the basis for the decision and documenting the data used to make the decision.

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

* Letters in parentheses designate corresponding milestones in Table 8.3.1.8-9 of the SCP (DOE, 1988).

format and will describe the required plans for the second phase of studies.

5.4 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. 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

A report on the methodology of calculation of the probability of magmatic disruption of the repository will be completed 6 months after approval of this study plan.

(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 one year after approval of this study plan. This report will use the best estimations of geochronology, eruptive stratigraphy, and volume determinations for the calculations. Data from the aeromagnetic anomalies will not be available at that time. The quality of the geochronology data may be dependent on the results of experimental methods (U-Th disequilibrium, $^3He/^4He$, and thermoluminescence). We also need approval to trench at the Quaternary centers to facilitate soils and to allow geomorphic studies, and to allow sampling for thermoluminescence age determinations.

Decision Point: Studies on Magmatic Disruption

The directions of further work will be dependent on the results of the one-year report. If the probability of magmatic disruption of the site is greater than the parameter goal ($>10^{-6}$ for repository disruption, $>10^{-5}$ for intrusion of the controlled area), we will notify the Yucca Mountain Project staff who are conducting total systems performance. Further studies will be terminated until the impact of volcanism on the suitability of the Yucca Mountain site is determined. If the probability of repository disruption is less than the parameter goal ($<10^{-6}$ for repository disruption, $<10^{-5}$ for intrusion of the controlled area), studies will continue.

Report: Plan for Using Expert Opinion

Pending a positive decision from the report on revised probability calculations, we will start planning to apply expert opinion to the probability sets. Six months after the decision, a report will be completed developing a plan for using expert opinion. This plan will follow the format of the study plan and will be attached as an appendix to it.

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

Six months after developing the plan for using expert opinion, the panel of experts will be convened and the probability models evaluated. A report will be issued to present the results of the expert opinion analysis and the revised probability calculations.

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. This will include data on volume of volcanic events from studies at the Lunar Crater and Cima volcanic fields (constrain Vm of equation 4).

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QUALITY ASSURANCE MEASURES APPLICABLE TO STUDY PLAN 8.3.1.8.1.1

The work performed under this study plan is graded in Los Alamos Grading Report 32, Postclosure Tectonics, WBS 1.2.3.2.5.

Quality Assurance requirements are stated in Title 10 of the Code of Federal Regulations, Parts 50, 60, 71, and 72. The Office of Civilian Radioactive Waste Management issued the Quality Assurance Requirements and Descriptions (QARD) to provide a framework consistent for implementing quality assurance programs at every level within the Civilian Radioactive Waste Management Program. Los Alamos implements the requirements of the QARD through Quality Administrative Procedures (QPs). The following QPs apply to the work performed under this study plan:

TWS-QAS-QP-01.1,	Interface Control Procedure
LANL-YMP-QP-01.2,	Stop Work Control
LANL-YMP-QP-01.3,	Conflict Resolution
TWS-QAS-QP-02.3,	rocedure for Readiness Review
LANL-YMP-QP-02.4,	Management Assessment
LANL-YMP-QP-02.5,	Selection of Personnel
TWS-QAS-QP-02.7,	Personnel Training
LANL-YMP-QP-02.9,	Personnel Proficiency Evaluations
LANL-YMP-QP-02.11,	Personnel Orientation
LANL-YMP-QP-03.5,	Documenting Scientific Investigations
TWS-QAS-QP-03.7,	Procedure for Peer Review
LANL-YMP-QP-03.23,	Preparation and Review of Technical Information Products and Study Plans
LANL-YMP-QP-03.24,	Submittal of Design and Test-Related Information
LANL-YMP-QP-03.25,	Review of Design and Test-Related Information
LANL-YMP-QP-04.4,	Procurement of Commercial-Grade Items and Services
LANL-YMP-QP-04.5,	Procurement of Noncommercial-Grade Items and Services
LANL-YMP-QP-06.1,	Document Control
LANL-YMP-QP-06.2,	Preparation, Review, and Approval of Quality Administrative Procedures
LANL-YMP-QP-06.3,	Preparation, Review, and Approval of Detailed Technical Procedures
LANL-YMP-QP-08.1,	Identification and Control of Samples
LANL-YMP-QP-08.3,	Transfer of Data
LANL-YMP-QP-12.1,	Control of Measuring and Test Equipment
TWS-QAS-QP-13.1,	Procedure for Handling, Storage, and Shipping Equipment
TWS-QAS-QP-15.2,	Deficiency Reporting
LANL-YMP-QP-16.2,	Trending
LANL-YMP-QP-16.3,	Deficiency Reports
LANL-YMP-QP-17.4,	Records Preparation
LANL-YMP-QP-17.5,	Records Processing
LANL-YMP-QP-18.1,	Audits
TWS-QAS-QP-18.2,	Surveys
TWS-QAS-QP-18.3,	Auditor Qualification and Certification