PVHA–YM VERSION 2.0 — PROBABILISTIC VOLCANIC HAZARDS ASSESSMENT METHODS FOR A PROPOSED HIGH-LEVEL RADIOACTIVE WASTE REPOSITORY AT YUCCA MOUNTAIN, NEVADA

Prepared for

U.S. Nuclear Regulatory Commission
Contract NRC–02–97–009

Prepared by

Laura Connor
Charles B. Connor
Brittain E. Hill

Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

September 2002

PVHA_YM VERSION 2.0—PROBABILISTIC VOLCANIC HAZARDS ASSESSMENT METHODS FOR A PROPOSED HIGH-LEVEL RADIOACTIVE WASTE REPOSITORY AT YUCCA MOUNTAIN, NEVADA

Prepared for

U.S. Nuclear Regulatory Commission
Contract NRC–02–97–009

Prepared by

Laura Connor
Charles B. Connor
Brittain E. Hill

Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

September 2002

ABSTRACT

The assessment of long-term performance of the proposed high-level radioactive waste repository at Yucca Mountain, Nevada, requires the use of mathematical models to consider the probability of disruptive scenarios. Volcanism is one important disruptive scenario to consider in site evaluation. The purpose of the PVHA_YM software is to provide and document mathematical models developed to assist staff in the probabilistic volcanic hazards assessment of the Yucca Mountain site.

PVHA_YM is intended to be launched from a web browser. PVHA_YM includes JAVA applets that can be used to estimate the probability of a volcanic event occurring within an effective area about the repository using kernel density estimators to smooth the point pattern map distribution of previous volcanic events in the region. Two types of kernel density estimators are included: Gaussian and Epanechnikov. These density estimators are used to calculate the probability of volcanic events at the site and to plot conditional probability maps of the location of volcanic events, given the occurrence of a volcanic event in the magmatic system.

PVHA_YM Version 1.0 contained JAVA applets that produced graphical estimates of volcanic disruption probability for the proposed Yucca Mountain repository site, using methods discussed in Connor and Hill (1995). Modifications to obtain PVHA_YM Version 2.0 include

- Data sets are now stored as simple text files, which enables alternative conceptual models of volcanism and repository designs to be tested by simply loading new files.
- Gravity data may be incorporated into the analysis following the methods outlined in Connor, et al. (2000).
- Event (e.g., dikes and vent alignments) length and orientation are now included in the analysis.

With these modifications, PVHA_YM now includes all major features used in the NRC-sponsored analysis of probability of volcanism at the Yucca Mountain site.

References:

Connor, C.B. and B.E. Hill. "Three Nonhomogeneous Poisson Models for the Probability of Basaltic Volcanism: Application to the Yucca Mountain Region, Nevada, U.S.A." *Journal of Geophysical Research*. Vol. 100, No. B6. pp. 10,107–10,125. 1995.

Connor, C.B., J.A. Stamatakos, D.A. Ferrill, B.E. Hill, G. Ofoegbu, F.M. Conway, B. Sagar, and J.S. Trapp. "Geologic Factors Controlling Patterns of Small-Volume Basaltic Volcanism: Application to a Volcanic Hazards Assessment at Yucca Mountain, Nevada." *Journal of Geophysical Research*. Vol. 105. pp. 417–432. 2000.

TABLE OF CONTENTS

FIGURE

ACKNOWLEDGMENTS

This report was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the U.S. Nuclear Regulatory Commission (NRC) under Contract No. NRC–02–97–009. The activities reported here were performed on behalf of the NRC Office of Nuclear Material Safety and Safeguards, Division of Waste Management. The report is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the NRC.

The authors thank the following individuals for their contributions to the CNWRA research on probabilistic volcanic hazards assessment at Yucca Mountain: Brittain Hill, John Stamatakos, David Ferrill, Peter La Femina, Michael Conway, Goodluck Ofoegbu, Ron Martin, Budhi Sagar, John Trapp, and Chris Condit. Brittain Hill compiled the data presented in the data table. The JAVA class *graph* used in PVHA_YM is modified from code developed and freely distributed by Leigh Brookshaw, according to the GNU licensing agreement. Technical reviews were performed by Nathan Franklin, Randy Folck, and H. Lawrence McKague. Programmatic review was performed by Budhi Sagar, with editorial reviews by Cathy Cudd and Barbara Long, and secretarial support from Rebecca Emmot. The efforts of these individuals are gratefully acknowledged.

QUALITY OF DATA, ANALYSES AND CODE DEVELOPMENT

DATA: No CNWRA-generated original data are contained in this report. Sources for other data should be consulted for determining the level of quality for those data.

CODES: The PVHA code Version 2.0, including the PVHA-Graph JAVA applet, and the PVHA-Map JAVA applet, has been developed following the procedures described in the CNWRA Technical Operating Procedure (TOP)-018, Development and Control of Scientific and Engineering Software, which implements the quality assurance (QA) guidance contained in the CNWRA QA Manual.

1 OVERVIEW OF PVHA_YM

This document presents computer codes and procedures used by the staffs of U.S. Nuclear Regulatory Commission (NRC) and the Center for Nuclear Waste Regulatory Analyses (CNWRA) to perform an independent probabilistic volcanic hazards assessment for the proposed high-level radioactive waste repository at Yucca Mountain, Nevada. NRC and CNWRA staffs will use PVHA_YM to review information provided by the U.S. Department of Energy (DOE) as part of any license application to NRC for construction authorization of the proposed repository. Specifically, PVHA_YM codes have been developed as part of the Igneous Activity Key Technical Issue with the goal of streamlining the License Application review. Staff anticipate using PVHA_YM to evaluate probabilities of igneous events and perform sensitivity analyses of associated model and data uncertainties.

Volcanic hazards at the proposed repository site arise from the proximity of Yucca Mountain to small-volume basaltic volcanoes (e.g., Figure 1-1; NRC, 1999; Connor, et al., 2000). The probability of igneous disruption is an important parameter in repository performance assessments, which use a probability-weighted expected annual dose to a reasonably maximally exposed individual as the quantitative performance standard. In this context, PVHA_YM has been developed as a tool to assist NRC in its mission to assure decisions affecting public health and safety are made with realistic models that consider appropriate uncertainties.

PVHA_YM relies on the distribution and ages of existing basaltic volcanoes (Figure 1-1) as indicators of the expected rate of volcanic activity and the expected distribution of future volcanic events in the Yucca Mountain region. PVHA_YM is intended to be viewed and used within a web browser. Two JAVA applets are used to run computer programs that estimate the probability of volcanic eruptions at the proposed repository site. The PVHA-Graph applet plots a graph of the probability of volcanic eruption at the site as a function of smoothing distance, using a Gaussian or an Epanechnikov kernel. The PVHA-Map applet creates a map of the probable distribution of future volcanic events using the same two kernel functions. These maps may include, at the user's option, gravity data that reflect structural controls on volcanic activity in the region (Connor, et al., 2000). Furthermore, the user may specify probability density functions for event length and orientation. The nature of these events (e.g., vent alignments or dike intersection) depends in large part on the user's choice of event definition. This information is used to estimate the probability of igneous disruption of the proposed site. Instructions in the use of these codes are provided within each applet.

1.1 Notes on Installing and Running PVHA_YM Version 2.0

PVHA_YM Version 2.0 requires JAVA™ 2 Runtime Environment Version 1.4.0, which is included on the CD-ROM provided with this report. To install, double-click CD:\PVHA_YM\Java\j2re-1_4_0_01_Windows-i586.exe and follow the installation instructions.

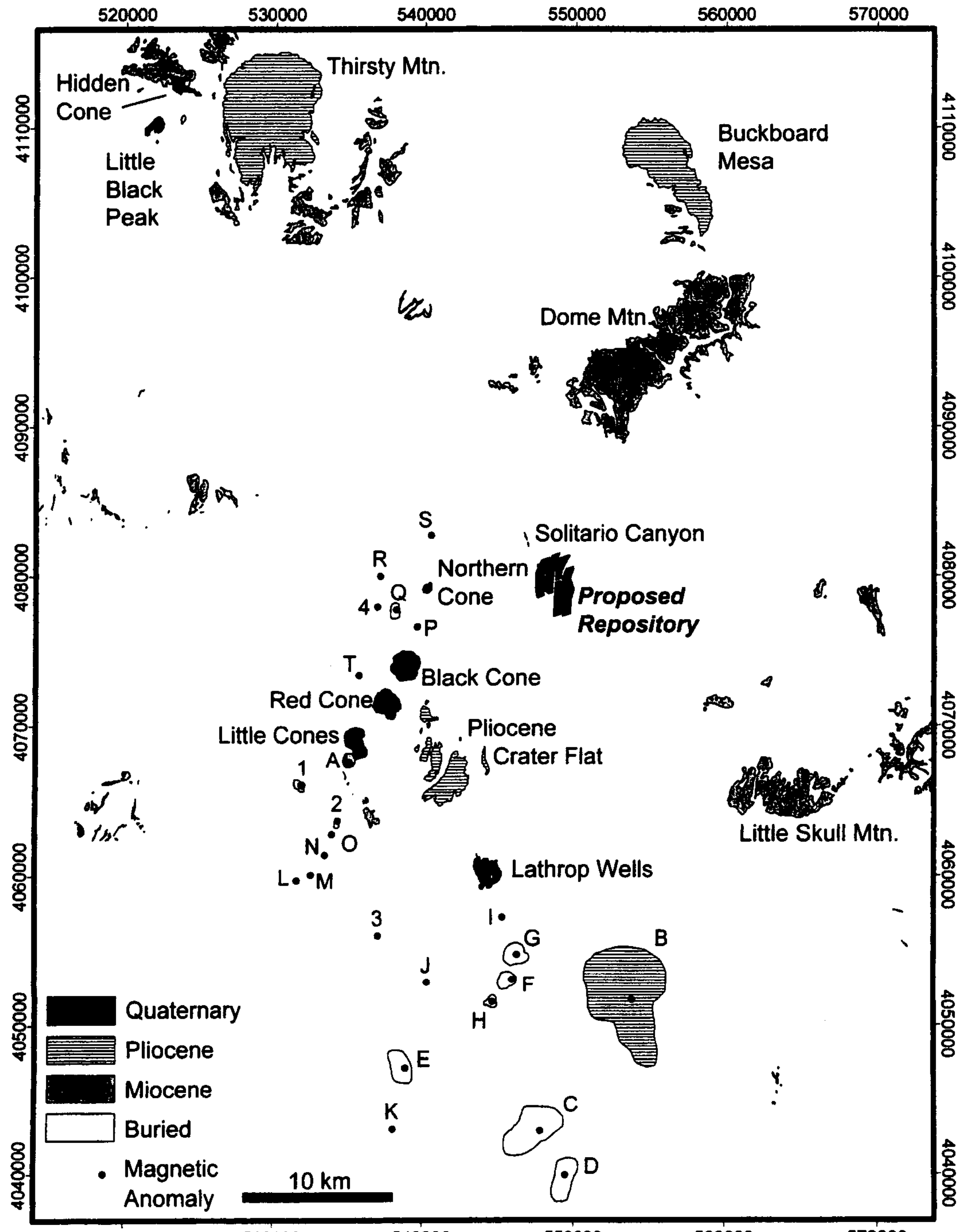

Figure 1-1. Locations of Basaltic Volcanoes in the Yucca Mountain Region. Lettered Magnetic Anomalies Represent Locations of Possible Buried Basaltic Volcanoes, Using Designations from Hill and Stamatakos (2002). Map Coordinates in Universal Transverse Mercator Zone 11 Meters, North American Datum 1927.

To run PVHA_YM Version 2.0 from the CDROM provided, launch the *PHVA.HTML* file in a web browser. This code has been developed and tested using the Microsoft Explorer Web browser, Version 6. Alternatively, copy the \PVHA directory from the CDROM to the preferred hard drive of your choice. Once PVHA_YM Version 2.0 is resident on the hard drive, it is possible to add new data files to the *PVHA\applets\datafiles* directory, as described in more detail in the following sections.

1.2 Input/Output Files

Several text files are used as input to PVHA_YM Version 2.0. The input files include a volcanic events file, a repository location file, and a gravity data file. These input files can be found in the *\PVHA\applets\datafiles* directory. JAVA applets running within web browsers are only able to access data files within their own HTML hierarchy. This limitation is imposed for security purposes. Any new data files created by a user must be stored within this hierarchy or the inherent JAVA security system will not allow the files to be opened. If the user wants to define new data files, PVHA_YM should be installed to a drive in which the user has write privileges. New data files should reside in the *PVHA\applets\datafiles* directory.

For PVHA_YM Version 2.0 to read new data files, the files must also adhere to a specific format. These files must be simple text files created with a simple text editor such as Windows Notepad™. It is recommended these new input files contain comments to explain their contents. Comment lines must begin with the # symbol. The comment lines are ignored by the program, but they make the file more humanly readable. The data lines in a volcanic events file must contain three columns separated by one or more white spaces:

```
# Comments on volcano file volcano.event
        easting(1)   northing(1)   volcano_name(1)
        easting(2)   northing(2)   volcano_name(2)
        easting(n)   northing(n)   volcano_name(n)
```

where easting and northing are the Universal Transverse Mercator coordinates of the volcano. These are real numbers or integers in meters. All coordinates provided in the file must be within the same Universal Transverse Mercator zone. If some volcanoes are not located within the same Universal Transverse Mercator zone, reproject the coordinates into a single Universal Transverse Mercator zone. The volcano name has any number of characters, however, there can be no white space within the volcano name. There is no limit to the number of data lines within an event file. Volcano location files should be named consistently, and use *.event* as the file extension.

The probability of volcanic disruption of the proposed repository also depends on the repository area. In some proposed plans, the repository area is divided into discrete blocks. In PVHA_YM Version 2.0, each block is represented as a polygon that is specified in an input file. The data lines within a repository location file contain the northing, easting coordinates of the vertices of a closed polygon outlining some fraction of the total repository area. Total repository area may comprise any number of simple polygons (i.e., no internal polygons or intersecting boundaries). The vertices of each polygon must be listed in counterclockwise order on a single line, with the coordinate series returning to the coordinates of the initial vertex. This counterclockwise order is important, because it ensures that the area of each polygon is a positive number. A polygon is described in the input data file as follows:

 # Comment on repository file *repository.area*
polygon 1 northing,easting(1) northing,easting(2) northing,easting(n...)
polygon 2 northing,easting(1) northing,easting(2) northing,easting(n...)

Each vertex is separated by one or more white spaces. Additional polygons are appended as additional lines to this file. All polygons within a single file are considered part of the total repository area and used in the probability calculations. Repository location data files should use the extension *.area* to easily distinguish them from volcanic event files.

Gravity data are contained in a file named *usgs_grav_200.XYZ*. These isostatic gravity data are from Ponce, et al. (2001), which were gridded and contoured onto a 200-m [656-ft] grid. The data lines are arranged as follows:

northing,easting,gravity_value

Note that the data spacing in this file is 200 m [656 ft]. This spacing determines the minimum grid spacing for the PVHA-MAP JAVA applet. Larger grid spacings are chosen as multiples of this minimum spacing. The default spacing for the PVHA-Map applet is 1,000 m [3,281 ft]. In this way, a gravity value can always be read for any grid point on the map. Although other gridded data can be used with PVHA_YM Version 2.0, these data must have a constant grid spacing of 200 m [656 ft], and the data file must be named *usgs_grav_200.XYZ.*

The results of the PVHA-Map can be written in X,Y,Z format to a separate window. The variables X and Y are the Universal Transverse Mercator coordinates of the grid point, Z is the probability of a volcanic event centered somewhere within the 1-km^2 [0.39-mi^2] area about this grid point, given that a volcanic event occurs within the region. These data can then be copied and pasted into another program for further processing. JAVA applets cannot create files on a client's computer or write to files on a client's computer within the context of a browser. This limitation is imposed for security purposes.

1.3 Code Limitations

PVHA_YM contains codes used to estimate probabilities of volcanic events within the area of the proposed Yucca Mountain repository to assist in reviewing any DOE License Application. Nevertheless, a complete probabilistic volcanic hazards assessment for the proposed repository cannot be accomplished using PVHA_YM alone. PVHA_YM is simply one tool used to help perform a complete probabilistic volcanic hazards assessment.

2 DEFINITION OF VOLCANIC EVENTS

Volcanic events must be defined explicitly in a probabilistic volcanic hazards assessment. PVHA_YM Version 2.0 provides several volcanic event data sets that are used in NRC and CNWRA analyses. In addition, a user may define completely new data sets. In NRC-sponsored investigations for the Yucca Mountain site (e.g., Connor and Hill, 1995; Connor, et al., 2000), the definition of a volcanic event is limited to extrusive eruptions that result in the formation of basaltic vents as indicated by cinder cones, spatter mounds, and lava flows. A complete compilation of basaltic vents in the Yucca Mountain region is provided in the *datatable.html* file, which is complied from Appendix A in NRC (1999). Estimates of the probability of dike intersection, without volcanic activity, are not considered explicitly in PVHA_YM.

Even using this event definition, volcanic events can be defined in various ways in PVHA_YM. Individual vents can be considered volcanic events, or closely spaced and similarly aged vents can be grouped together as single events. Furthermore, only cones younger than a specific age might be included in the analysis as volcanic events. Because vents may be grouped together into volcanic events in varying ways depending on their timing and distribution, several data sets are predefined for PVHA_YM Version 2.0. Formally, each volcanic event in these data sets is considered independent of the other volcanic events in the data set.

The regional recurrence rate used to estimate probability also depends on the definition of volcanic events. For example, grouping volcanic vents by alignments in the Yucca Mountain region results in fewer Quaternary volcanic events, and consequently a lower regional recurrence rate than results from treating individual vents as independent volcanic events. In practice, a range of recurrence rates must be considered in the hazards assessment because of uncertainties about the appropriate values to use. Volcanism in the Yucca Mountain region may be episodic or respond to external factors, such as geologic strain rate, in ways not well understood at the present (e.g., Connor and Conway, 2000). Furthermore, the area likely affected by volcanic events varies with the definition of volcanic events. Therefore, a range of parameters is used in the volcanic hazards assessment (Connor and Hill, 1995; Connor, et al., 2000).

Data file *CFB_mio-quat-mag.event* includes Miocene through Quaternary vents within the Crater Flat structural basin (Stamatakos, et al., 2000), and 10 high-to-moderate confidence aeromagnetic and ground magnetic anomalies (Hill and Stamatakos, 2002). This data set includes Miocene basalt in Solitario Canyon, drill core VH–2, and southwestern Crater Flat. This data set assumes magnetic anomalies are Miocene in age and includes 33 volcanic events. An average recurrence rate for this data set is approximately three events per million years. Collectively, these data represent all basalt <12 Ma within approximately 35 km [21.7 mi] of the proposed Yucca Mountain repository site, which have a similar petrogenesis related to eruption within the Crater Flat structural basin.

Data file *CFB_plio-quat-mag.event* is a subset of *CFB_mio-quat-mag.event* that includes only Pliocene through Quaternary vents within the Crater Flat structural basin (Stamatakos, et al., 2000). Ten high-to-moderate confidence aeromagnetic and ground magnetic anomalies (Hill and Stamatakos, 2002) are assumed Pliocene in age, yielding 29 volcanic events. Different recurrence rates can be assigned to these events, based on the user's interpretation of alternative hypotheses regarding potential temporal clustering of past events (i.e., Hill and Stamatakos, 2002). This is the default volcano data set for PVHA_YM Version 2.0 and provides a direct comparison for data used for the DOE probability models in CRWMS M&O (1996).

Data file *miocene-quaternary_47events.event* includes Miocene through Quaternary vents mapped throughout the Yucca Mountain region. This data set corresponds to data set 1 used in Connor and Hill (1995) and treats individual volcanic vents as independent volcanic events. This data set includes the some magnetic anomalies in the Amargosa Desert (Langenheim, et al., 1993) assumed to be Miocene or younger in age. Forty-seven volcanic events are included in this file. An average regional recurrence rate for this data set is approximately five events per million years.

Data file *miocene-quaternary_57events.event* adds 10 high-to-moderate confidence aeromagnetic and ground magnetic anomalies (Hill and Stamatakos, 2002) to the data file *miocene-quaternary_47events.event*. This file allows evaluation of how new aeromagnetic interpretations may affect existing probability models using data set 1 in Connor and Hill (1995), assuming the anomalies represent buried volcanoes of Miocene or younger age.

Data file *pliocene-quaternary_20events.event* is a subset of *miocene-quaternary_47events.event* that includes only the Pliocene through Quaternary vents in the Yucca Mountain region. Magnetic anomalies of Langenheim, et al. (1993) are included. This data set corresponds to data set 2 in Connor and Hill (1995). Several closely spaced vents have been grouped and are treated as single volcanic events. For example, the two Little Cones are treated as a single volcanic event in this data set. Twenty volcanic events are listed in this file. Use of this data set implies that the distribution of Miocene vents has little influence on potential patterns of basaltic volcanism during the performance period of the repository. An average regional recurrence rate for this data set is approximately six volcanic events per million years.

Data file *pliocene-quaternary_30events.event* adds 10 high-to-moderate confidence aeromagnetic and ground magnetic anomalies (Hill and Stamatakos, 2002) to the data file *pliocene-quaternary_20events.event*. This file allows evaluation of how new aeromagnetic interpretations may affect existing probability models, assuming the anomalies represent buried volcanoes of Pliocene or younger age.

Data file *quaternary_8events.event* includes all known Quaternary vents mapped in the Yucca Mountain region. Magnetic anomalies are not included in this data set. Use of this data set implies that the expected distribution of future volcanic activity is best defined by the distribution of volcanism during the last 1 million years, and that older volcanic vents are not relevant to the analysis. Eight volcanic events are included in this data file. An average regional recurrence rate for this data set is eight volcanic events per million years.

Data file *crater_flat_alignment_3events.event* includes three events defined as volcanic alignments. These are the Quaternary Crater Flat volcano alignment, taken as centered on Red Cone, the Sleeping Butte alignment, taken as centered on Hidden Cone, and Lathrop Wells. Use of this definition implies that volcanoes within an alignment constitute a single volcanic event, and that Quaternary volcanism is the best guide to future volcanic activity. The distribution of older volcanoes or volcanic alignments is not considered as part of calculations using this data set. An average recurrence rate for this data set is three volcanic events per million years.

Data file *CFB_16aligmnent.event* contains 16 events defined as alignments, derived from Miocene through Quaternary aged basalts and aligned aeromagnetic anomalies. Isolated volcanoes are treated as single event anomalies, having a minimum event length of 1,000 m [3,281 ft] (e.g., NRC, 1999).

The data file *all_64events.event* includes all vent locations reported in *datatable.html* (NRC, 1999). Sixty-four volcanic events are listed in this file. An average recurrence rate for this data set is six volcanic events per million years.

3 BASIS FOR THE PROBABILISTIC VOLCANIC HAZARDS ASSESSMENT

The technical basis for a probabilistic volcanic hazards assessment of the Yucca Mountain site is provided in Connor and Hill (1995), NRC (1999), and Connor, et al. (2000). In summary, kernel density estimators are used to calculate a probability surface directly from the location and timing of past, discrete volcanic events. As a result, kernel estimators are sensitive to patterns commonly observed in basaltic volcano distributions, such as vent clustering (e.g., Connor and Conway, 2000). Furthermore, the resulting probability surfaces do not have the abrupt changes in probability that must be introduced in spatially homogeneous Poisson models (e.g., Crowe, et al., 1982; Ho and Smith, 1998). Thus, the kernel methods eliminate the need to predefine zones of volcanic activity.

Two types of kernel density functions are provided in PVHA_YM Version 2.0: Gaussian and Epanechnikov. The Gaussian kernel is defined as

$$k_i = 2\pi \exp\left[\frac{-1}{2}\left(\frac{d_i}{h}\right)^2\right] \tag{3-1}$$

where d_i is the distance from location *s* (the point at which probability is to be estimated) to the i^{th} volcano, and *h* is the smoothing parameter.

The Epanechnikov kernel is defined as

$$\begin{aligned} k_i &= \frac{2}{\pi}\left[1-\left(\frac{d_i}{h}\right)^2\right], \quad if \left(\frac{d_i}{h}\right)^2 < 1 \\ k_i &= 0, \quad \text{otherwise} \end{aligned} \tag{3-2}$$

In each case, the spatial recurrence rate of volcanic events in the 1 × 1-km [0.62 × 0.62-mi] area about the point *s*, given the occurrence of a volcanic event in the system, is

$$\lambda_s = \frac{1}{nh^2}\sum_{i=1}^{n} k_i \tag{3-3}$$

where *n* is the number of volcanoes.

The probability of one or more volcanic events within the area of the repository site is then

$$P\left[N \geq 1\right] = 1 - \exp\left[-t\ \lambda_t \sum_{a} \lambda_s\right] \tag{3-4}$$

where t is the time interval of interest, λ_t is the temporal recurrence rate of volcanic events in the magmatic system, and a is the effective area, an area within which a volcanic event might occur and disrupt the repository.

Assuming that λ_s does not vary on the scale of the repository:

$$P\left[N \geq 1\right] = 1 - \exp\left[-t\ \lambda_t\ a\ \lambda_s\right] \tag{3-5}$$

These probability techniques have been tested using the recurrence rates of volcanism and patterns of volcanic activity in other volcanic fields. In particular, these models have been tested in the Springerville volcanic field, Arizona (Condit and Connor, 1996). An introduction to patterns in basaltic volcanic fields also is given in Connor and Conway (2000).

Connor, et al. (2000) describe a method for modeling the kernel functions using additional geologic information. They found a correlation between regional gravity variation and volcanism. Basaltic volcanism in the region tends to occur in areas of low gravity. These areas have experienced increased basin development in response to crustal extension. This additional information is incorporated into the analysis by casting regional gravity data as a probability density function and weighting λ_s using this function (Connor, et al., 2000).

Some volcanic events have length and orientation. For example, volcanic events may be defined as volcanic vent alignments, within which all individual volcanic vents formed during a comparatively short period of time. Alternatively, events may include the dikes that feed individual volcanic events. The length and orientation of potential alignments is incorporated into the probabilistic hazards assessment because an event centered outside the proposed repository boundary may result in magma flow inside the repository. In PVHA_YM Version 2.0, event length and orientation are included as uniform random probability distributions, the bounds of which are set by the user.

3.1 Explanation of Parameters Used in PVHA_YM

Several parameters may be varied in the analysis. These parameters are related to the smoothing factor used in the kernel functions, the regional recurrence of volcanic activity, the effective area of the repository, the time interval for which probability calculations are made, the extent to which gravity is included in the analysis, and event alignment parameters.

The smoothing factor controls how probability is distributed about existing volcanic events, which are treated as a point process. Using a small smoothing factor tends to concentrate probability near existing volcanoes; a large smoothing factor results in a more even distribution of probability across the map area. The two kernel estimators, Gaussian and Epanechnikov, rely on different functions. As a result, the smoothing factor has a different effect in each case. In the Gaussian kernel, the smoothing factor is equivalent to the standard deviation of a symmetric, bivariate Gaussian distribution. For an Epanechnikov kernel, the smoothing factor determines the radius of the Epanechnikov distribution function about each point. The probability is zero at distances greater than the smoothing factor from the point and nonzero at distances less than the smoothing factor from the point (i.e., volcanic event).

Methods of estimating the smoothing factor are described in Connor, et al. (2000). The kernel function (Gaussian or Epanechnikov) may be recast in polar coordinates as a cumulative distribution function. In this form, the cumulative kernel function can then be compared to observed nearest-neighbor distances between volcanic events. Using this approach, Connor, et al. (2000) found that values of the smoothing factor greater than 7 km [4.4 mi] for the Gaussian kernel yield conservative estimates of probability. For Epanechnikov kernels, a smoothing factor greater than 18 km [11.2 mi] yields conservative results. The larger value for the Epanechnikov kernel compared to the Gaussian kernel results from the definition of the smoothing factor as the limit of the probability distribution in the former case and the standard deviation of the probability distribution in the latter case.

Probability models rely on estimates of the expected regional recurrence rate of volcanism to estimate the probability of future volcanic activity. In the Yucca Mountain region, estimates of the regional recurrence rate can vary between 2 to more than 15 volcanic events per million years (e.g., Smith, et al., 2002). Variations in the definitions of volcanic events account for at least part of this range. Furthermore, the rate of volcanic activity in the Yucca Mountain region could be stationary, nonstationary, or episodic. As a result, uncertainty in the regional recurrence rate of volcanism is significant and alternative hypotheses for temporal clustering must be evaluated.

The effective area of the repository includes the actual footprint of the repository, plus the area within which a volcanic event may occur and cause volcanic disruption of the repository. This additional area is included because volcanic events are treated as points in the analysis, but in reality affect an area about that point, due to dike injection and the formation of multiple vents. For example, Connor and Hill (1995) used an effective area of 8 km^2 [3.1 mi^2].

PVHA_YM Version 2.0 stores geographic information about the proposed repository boundary in a single text file. Multiple polygons may be defined to estimate probability of disruption of a repository with several blocks. This approach is considered important because some design proposals include up to seven separate repository blocks. In an analysis with multiple repository blocks, the probability of volcanic disruption of each block is estimated. These probabilities are then added to obtain a cumulative probability of disruption, assuming that the probability of more than one independent volcanic event occurring during the performance period is vanishingly small (Connor and Hill, 1995). If the repository footprint is sufficiently large, the spatial recurrence rate may vary significantly across the repository area. Therefore, the spatial recurrence rate is calculated on a grid across each repository polygon, using a grid spacing chosen by the user, and the probability of disruption is calculated using this set of spatial recurrence rate values. This means that calculated probabilities may vary slightly with grid spacing, depending on where exactly grid points fall within a repository boundary.

Regional gravity data reveal that Pliocene through Quaternary aged volcanoes in the Yucca Mountain region are largely restricted to the Amargosa Trough, a roughly north-trending region of low gravity values that includes part of the Amargosa Desert, Crater Flat, and Yucca Mountain. Lathrop Wells cinder cone, for example, lies outside Crater Flat topographic basin, but based on gravity data is located within the larger north-trending structural basin and at the margin of the prominent basement low in southernmost Crater Flat. Aeromagnetic anomalies in the Amargosa Desert produced by buried Neogene through Quaternary(?) basalts also lie within or at the margins of the southern extension of this basement trough. The most voluminous of these buried basalts lies close to north-trending gravity anomaly marking the presumed eastern edge of Amargosa Trough in this area. Probability models in PVHA_YM Version 2.0 can account for these geological relationships.

Based on these types of empirical observations, Connor, et al. (2000) included gravity data in models of the probability of volcanic eruptions at the Yucca Mountain site. As noted in Connor, et al. (2000), there is no technical basis for determining the weighing factor given to this information in the probability assessment. Thus, the weighing factor introduces an additional component of uncertainty in the probability model results. PVHA_YM Version 2.0 can incorporate gravity data in the volcanic hazard analysis and allows users to weight these gravity data in any way they choose. This enables users to explore the variation in probability of volcanic disruption of the site that results from different assumptions about the importance of crustal density variations and the structures they represent.

Including these gravity data in the probability models requires several steps. First, gravity data are read from a file. These data have been previously interpolated to a 200 × 200-m [656 × 656-ft] grid. The data are sampled at the current grid spacing chosen by the user {e.g., 600 m [1,969 ft] or 1,000 m [3,281 ft]} within the chosen map region. Data are then normalized using a binning function specified by the user. This binning function controls how the gravity values are mapped into a probability density function that integrates to unity across the entire map region. Default values for bin values are provided, based on the analysis of Connor, et al. (2000). The normalized gravity data are then incorporated into the analysis using a user-specified weighing function (0–100 percent). Choosing 100 percent assigns the same weight to the gravity data used in Connor, et al. (2000). Choosing lower values assigns less weight to the gravity data and more weight to the Gaussian or Epanechnikov kernel function. Note that including gravity data in the analysis does not change the probability that an event will occur in the map region; this approach simply redistributes the areas of highest or lowest probability within the map region, based on the addition of gravity information.

Bounding values of event length and orientation are specified parameters in PVHA_YM. Event length is the total length of a dike or vent alignment. The code treats event length as a uniform random probability density function. Maximum and minimum values for event length are specified by the user. Similarly, event orientation is treated as a uniform random distribution between bounding values provided by the user. Using these parameters, the code calculates the probability that an event centered at some location outside the repository boundary will result in a dike or vent alignment that will intersect the repository. This probability is calculated for each grid point. Using a small grid point spacing {e.g., 200 m [656 ft]} will yield a better estimate of the probability, but the calculation will also take considerably longer than a calculation using a large grid point spacing {e.g., 1,000 m [3,281 ft]}.

In summary, the probability that an event occurring at grid point *i, j*, within some small area about map point *x,y*, will disrupt the repository is

$$\begin{aligned} &P[\text{volcanic disruption resulting from event at } i,j] = P_{x,y} * P_{L,\Phi} \\ &P_{x,y} = 1 - \exp\left[-t\ \lambda_t\ a\ \lambda_s\right] \end{aligned} \tag{3-6}$$

where a is the area about the point x, y (i.e., square of the grid spacing), t is the time interval being considered, and recurrence rate is the temporal recurrence rate. The parameter, λ_s, is calculated as previously indicated, and may include gravity data depending on the user-defined weighting function. Parameter P_L,Φ is the probability that the event is sufficiently long and of appropriate orientation to intersect the repository, which depends on the maximum and minimum event lengths and event orientations, specified by the user. In the case where more than one repository block is intersected, only the largest value of P_L,Φ is used.

The resulting probabilities are summed for all grid points in the map area located outside the repository boundary. The total probability is then the probability that an event will occur centered inside the repository, plus the summed probabilities for event intersection for all grid points located outside the repository boundaries. As before, the code assumes that the probability of more than one independent event during the time period of interest is negligibly small, so the probabilities are summed only, without subtracting the probability of multiple events. Connor and Hill (1995) found the probability of more than one event in a 10,000-yr performance period is approximately 10^{-9}, so this assumption is justified. Nevertheless, if very large recurrence rates or very long time intervals were used, this assumption would need to be reevaluated.

The time interval for which probability is estimated may be varied to calculate annual probabilities or to calculate probabilities of volcanic disruption of the proposed site for different performance periods. The probability calculation assumes the time interval considered and the regional recurrence rate are independent.

4 APPLETS

PVHA_YM calculations are performed using the following JAVA applets.

4.1 PVHA-Graph

PVHA-Graph calculates the probability of a volcanic event centered within an effective area about the repository, given a temporal recurrence rate, time interval of interest, and selected data set. This estimate allows the user to select a Gaussian kernel or an Epanechnikov kernel and plots probability as a function of the smoothing parameter.

4.2 PVHA-Map

PVHA-Map calculates the recurrence rates for the Yucca Mountain region given a selected data set, a smoothing parameter, and variation in the gravity field, as described previously. This estimate uses a Gaussian kernel or an Epanechnikov kernel and plots the conditional probability of a volcanic event within a 1 × 1-km [0.62 × 0.62-mi] area, given an event in the magmatic system, as a contour plot of the region. Probability of volcanic disruption of the repository is also displayed, considering temporal recurrence rate and time interval of interest. Two options are provided for calculating probability values. The first option, *calculate contours* updates the probability map using the current information supplied by the user. This option, however, does not include the probability of dike intersection, only the probability that the event will be centered within the repository effective area. The probability will be updated to include event length if the *calculate event intersection* option is selected. Selecting this option will open a dialog box that prompts the user to enter parameters related to event length and orientation. Once these parameters are added, the probability is updated to include the probability that vents centered outside the repository effective area will result in disruption. Once other parameters are changed (e.g., smoothing parameter), the *calculate contours* button must be clicked to update the probability. Furthermore, the *calculate event intersection* button must be pressed again to update the probability of event intersection.

5 REFERENCES

Condit, C.D. and C.B. Connor. "Recurrence Rates of Volcanism in Basaltic Volcanic Fields: An Example from the Springerville Volcanic Field, Arizona." *Geological Society of America Bulletin.* Vol. 108. pp. 1,225–1,241. 1996.

Connor, C.B. and F.M. Conway. "Basaltic Volcanic Fields." H. Sigurdsson, ed. *Encyclopedia of Volcanoes.* New York, New York: Academic Press. pp. 331–343. 2000.

Connor, C.B. and B.E. Hill. "Three Nonhomogeneous Poisson Models for the Probability of Basaltic Volcanism: Application to the Yucca Mountain Region, Nevada, U.S.A." *Journal of Geophysical Research.* Vol. 100, No. B6. pp. 10,107–10,125. 1995.

Connor, C.B., J.A. Stamatakos, D.A. Ferrill, B.E. Hill, G. Ofoegbu, F.M. Conway, B. Sagar, and J.S. Trapp. "Geologic Factors Controlling Patterns of Small-Volume Basaltic Volcanism: Application to a Volcanic Hazards Assessment at Yucca Mountain, Nevada." *Journal of Geophysical Research.* Vol. 105. pp. 417–432. 2000.

Crowe, B.M., M.E. Johnson, and R.J. Beckman. "Calculation of the Probability of Volcanic Disruption of a High-Level Nuclear Waste Repository within Southern Nevada, USA." *Radioactive Waste Management and the Nuclear Fuel Cycle.* Vol. 3. pp. 167–190. 1982.

CRWMS M&O. "Probabilistic Volcanic Hazards Analysis for Yucca Mountain, Nevada." BA0000000–1717–2200–00082. Rev. 00. North Las Vegas, Nevada: DOE, Yucca Mountain Site Characterization Office. 1996.

Hill, B.E. and J. Stamatakos. "Evaluation of Geophysical Information Used to Detect and Characterize Buried Volcanic Features in the Yucca Mountain Region." San Antonio, Texas: CNWRA. 2002.

Ho, C.-H. and E.I. Smith. "A Spatial-Temporal/3-D Model for Volcanic Hazard Assessment: Application to the Yucca Mountain Region, Nevada." *Mathematical Geology.* Vol. 30, No. 5. pp. 497–510. 1998.

Langenheim, V.E., K.S. Kirchoff-Stein, and H.W. Oliver. "Geophysical Investigations of Buried Volcanic Centers near Yucca Mountain, Southwestern Nevada." Proceedings of the Fourth Annual International Conference on High-Level Radioactive Waste Management. La Grange Park, Illinois: American Nuclear Society. pp. 1,840–1,846. 1993.

NRC. "Issue Resolution Status Report, Key Technical Issue: Igneous Activity." Rev. 2. Washington, DC: NRC. 1999.

Ponce, D.A., R.J. Blakely, R.L. Morin, and E.A. Mankinen. "Isostatic Gravity Map of the Death Valley Ground-Water Model Area, Nevada and California." U.S. Geological Survey Miscellaneous Field Studies, Map MF–2381–C. Scale 1:250,000. 2001.

Smith, E.I., D.L. Keenan, and T. Plank. "Episodic Volcanism and Hot Mantle: Implications for Volcanic Hazard Studies at the Proposed Nuclear Waste Repository at Yucca Mountain, Nevada." *GSA Today*. Vol. 4. pp. 4–10. 2002.

Stamatakos, J.A., B.E. Hill, D.A. Ferrill, P.C. La Femina, D. Sims, C.B. Connor, M.B. Gray, A.P. Morris, and C.M. Hall. "Composite 13-Ma Record of Extensional Faulting and Basin Growth of Crater Flat, Nevada." San Antonio, Texas: CNWRA. 2000.

ADDITIONAL INFORMATION FOR PVHA_YM VER. 2.0—PROBABILISTIC VOLCANIC HAZARDS ASSESSMENT METHODS FOR A PROPOSED HIGH-LEVEL RADIOACTIVE WASTE REPOSITORY AT YUCCA MOUNTAIN, NEVADA

Document Date:	095/03/2002
Availability:	Southwest Research Institute® Center for Nuclear Waste Regulatory Analyses 6220 Culebra Road San Antonio, Texas 78228
Contact:	Southwest Research Institute® Center for Nuclear Waste Regulatory Analyses 6220 Culebra Road San Antonio, TX 78228-5166 Attn.: Director of Administration 210.522.5054
Data Sensitivity:	■"Non-Sensitive" □ Sensitive □"Non-Sensitive - Copyright" □ Sensitive - Copyright
Date Generated:	06/02/1998
Operating System: (including version number)	Windows
Application Used: (including version number)	PVHA_YM, Version 2.0
Media Type: (CDs, 3 1/2, 5 1/4 disks, etc.)	1 - CD-ROM
File Types: (.exe, .bat, .zip, etc.)	Various
Remarks: (computer runs, etc.)	Media contains: PVHA_YM is intended to be launched from a web browser and includes JAVA applets; data sets are stored as simple text files; user's guide.