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RESEARCH ARTICLE

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Hazard area and probability of volcanic disruption of the proposed high-level radioactive waste repository at Yucca Mountain, Nevada, USA

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Abstract Models that calculate the probability that a new volcano or a dike from a nearby eruption will intersect the footprint of the proposed high-level nuclear waste repository are generalized based on a conceptual model developed for the space transportation industry. The proposed hazard area, defined such that every new eruption that occurs there will disrupt the repository, plays a fundamental role in developing probability models. This hazard area is used not only to hedge the uncertainties in predicting patterns of future volcanic activity, but also to account for the characteristics of a new eruption during the post-closure performance period of an underground geologic repository. The paper discusses the advantages of probability comparisons, capabilities of conservativeness measurements and expert-elicitation on model parameters, and the implications to the proposed repository.

Keywords Casualty area · Dike intrusion · Expected casualty · Poisson process · Recurrence rate · Volcanic hazard and risk

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Introduction

In the Nuclear Waste Policy Act of 1982, the US Congress directed the Department of Energy (DOE) to investigate potential sites for the location of an underground geologic repository to contain the growing volume of high-level radioactive waste. In 1987, Congress amended the Act, directing DOE to study only Yucca Mountain (YM), Nevada, located about 160 km northwest of Las Vegas. As the first US DOE nuclear program subject to external regulation, the YM Site Characterization Project is one of the most closely reviewed programs ever undertaken by the federal government.

Studies of volcanic risk to the proposed high-level radioactive waste repository at YM have been ongoing for the past 25 years because basaltic volcanism has occurred since 11 Ma in the YM area, and several Quaternary alkali basalt volcanoes ranging from 1.0 Ma to 80 ka have erupted within 50 km of the proposed repository. Patterns of volcanism at YM have been the focus of numerous studies, primarily with the aim of better estimating the probability of volcanic disruption of the proposed geologic repository (Crowe et al. 1982; Crowe et al. 1993; Crowe et al. 1998; Smith et al. 1990; Ho et al. 1991; Ho 1991, 1992, 1995; Sheridan 1992; Connor and Hill 1995; Geomatrix Consultants 1996; Ho and Smith 1997, 1998; Connor et al. 2000; US Department of Energy 2001; Smith et al. 2002; Smith and Keenan 2005; and references therein). For example, Sheridan (1992) suggested that one parametric method of accounting for spatial heterogeneity in vent distribution is to assume that post-4 Ma volcanoes located close to the proposed repository are formed as a result of steady-state activity and that the dispersion of these volcanic vents represents two standard deviations of an elliptical Gaussian distribution. Using this assumption, Sheridan (1992) modeled the probability of repository disruption by Monte Carlo simulations for both volcanic events and dike intrusions. In addition, a comprehensive review of data and interpretation made by DOE contractors and the probabilistic volcanic hazard assessment (PVHA) panel of experts, convened by DOE in 1995–1996, is presented in DOE's analysis and model reports (AMRs; CRWMS M&O 2000a,b). The ten PVHA experts agreed on a general definition of a volcanic event as "a point in space representing a volcano, and an associated dike having length, azimuth and location relative to the point event." In addition, the AMRs state that "analyses...are based on the assumption that a plausible future eruption during the post-closure performance period would be of the same character as Quaternary basaltic eruptions in the Yucca Mountain region...a new volcano will contain some combination of scoria cone, spatter cone and lava flows on the surface, and one or more dikes in the subsurface."

This work presents a strategy for the evaluation and use of "hazards area" based on a model developed for licensing commercial space launch and reentry operations in the space transportation industry.

Hazard area

The licensing for the execution of a commercial space launch and reentry is directed by the US Federal Aviation Administration (FAA) Office of the Associate Administrator for Commercial Space Transportation. This licensing process is established to limit risks to public health, public safety, and the safety of property, as well as to ensure national security and foreign policy interests of the United States. Therefore, the procedures that a mission must follow before being licensed are extensive and stringent.

The US Government considers many factors from the data collected before approving the licensing of a commercial launch. One of the components is the "expected casualty" of a mission. In this case, a casualty is classified as a fatality or serious injury and expected casualty is the predicted average number of human casualties for each commercial space mission. One of the most important ways to identify expected casualty is to find the "casualty area" during each step of the operation. The casualty area for each piece of debris is determined by finding the area where 100 % of the exposed population on the ground is a casualty, specifically defined as any human contact with vehicle debris that can cause injury or any exposure to explosive pressure 0.25 kg/cm^2 or greater. Note that at 0.25 kg/cm^2, 1% of the exposed population will experience eardrum damage. The area of each element from a vehicle failure such as an in-flight explosion and an aerodynamic overload, or from planned stage jettison operations is affected by the individual characteristics of the pieces such as size, angle of trajectory, impact explosion, and the resulting spray of scrap after ground collision. Other factors affecting the evaluations of the potential hazards involve the type of vehicle failure, the size of the fragments, their approximate landing zones, their energy and velocity vector, and the possibility of explosion.

A vehicle debris or breakup analysis is an essential first step to identifying the casualty area and provides debris lists for all the conceivable failure modes that may befall the vehicle through the course of the operation. The lists estimate the immediate post-breakup setting of the impaired vehicle, the characteristics of the debris, and the risk of casualty resulting from impacting fragments. A sample case for determining the casualty area for the simplest scenario is demonstrated in Fig. 1 (FAA 2000, Fig. 1). For this example, the desired casualty area for a vertically falling inert piece of debris is a circle whose radius is the sum of the radius of a circle enclosing the largest cross sectional area of the piece and the radius of a human being (1.0 ft). We find great similarities between the tasks described in this work and those of licensing commercial space missions. Thus, the comprehensiveness of FAA's approach may provide an acceptable alternative to world-wide modelers of volcanic hazard and risk studies. The following two-dimensional transformation from Fig. 1 to Fig. 2 is straightforward:

1. The circle representing a person is replaced with a minimal circle (A in Fig. 2) enclosing the repository. This circle may be generalized to an ellipse or another irregular shape depending on geologic structures of the target sites or other controlling factors.
2. The circle depicting a vertically falling inert piece of debris becomes a circle (B in Fig. 2) quantifying the effective size (including the associated dike and lava) of a disruptive eruption. This area is quite flexible in providing likely bounds for uncertainties associated with the magnitude of future eruptions.
3. The largest circle (C in Fig. 2), with radius the sum of those of circles A and B, is the desired area to be referred as "hazard area" in the following development.

Recall that the casualty area for each piece of debris is the area within which 100 % of the unprotected population on the ground is assumed to be a casualty. Analogously, the hazard area, in a defined volcanic field, is the area where every new eruption will disrupt the repository. Hence, the probability of a volcanic site disruption is equal to the chance that a new eruption occurs within the hazard area. Furthermore, repository failure modes, justified by geologically meaningful scenarios of a volcanic disruption (or consequence models), will facilitate the definition of the hazard area.

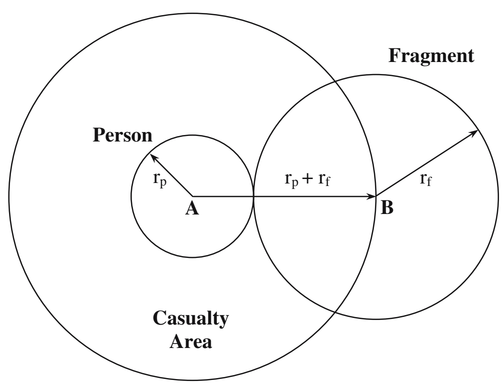

Fig. 1 Casualty area for fragment falling vertically (FAA 2000; Fig. 1). r_p=radius of person (1 ft); r_f = radius of the fragment

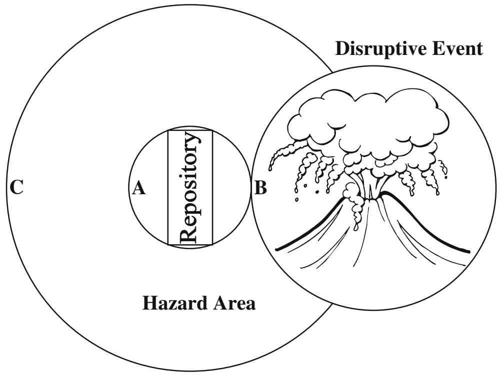

Fig. 2 Hazard area for a disruptive event. *Circle A* represents a minimal circle enclosing the repository; *circle B* quantifies the effective size (including the associated dike and lava) of a disruptive eruption; *circle C*, with radius the sum of those of *A* an *B*, is the desired area and is referred as "hazard area" in the text

Analogies and rationale

Patterns of volcanism

Volcanic activity usually shifts position within a volcanic field. Volcanic fields commonly migrate or expand and new volcanoes generally erupt at the periphery of an existing field. Patterns of volcanism are complex and shifts or migration in the location of volcanism over periods of million of years have been documented in many basaltic volcanic fields: Examples include the Coso Volcanic Field in California (Duffield et al. 1980; Condit et. al 1989); San Francisco Volcanic Field in Arizona (Tanaka et al. 1986); Lunar Crater Volcanic Field in Nevada (Foland and Bergman 1992); Michoacán-Guanajuato Volcanic Field in Mexico (Hasenaka and Carmichael 1985); and Cima Volcanic Field in California (Dohrenwend et al. 1984; Turrin et al. 1985). Recently, Smith et al. (2002) proposed a linkage between Quaternary volcanism near YM and in the Lunar Crater field nearly 100 km to the north. Volcanism was suggested to be episodic and sustained by a common area of hot mantle. Based on detailed studies of the temporal and spatial distribution of volcanoes in a belt stretching from Crater Flat to the Lunar Crater area in central Nevada, they argue that a migrating-expanding field model may be more meaningful than assuming that the locations of existing volcanoes are a key to the sites of future volcanism. Therefore, implementation of the proposed hazard area may resolve the debate and uncertainty in predicting the exact location of future eruptions in the YM volcanic field.

Disruptive scenarios

Future eruption is to the site disruption what vehicle debris is to the human casualty. As the debris analysis is essential in assessing the casualty area, so is the volcanic disruptive scenarios in quantifying the hazard area. The eruption styles characterized in DOE's AMRs and Valentine et al. (2005) provide a technical basis for the construction of a realistic hazard area. Although we agree that a new volcano will contain some combination of scoria cone, spatter cone and lava flows on the surface, and one or more dikes in the subsurface, we recommend that fissure and hydromagmatic eruptions be added to the list of volcanic disruptive scenarios. Major factors in assessing the hazard area include: volcanic disruptive scenarios, cone size, length of lava flow and dike, and the propagation modes for dikes.

Scale and impacts of site disruption

The upper limit of the risk for a commercial space launch has been determined by the FAA (2000) advisory circular to not surpass an expected average of 0.00003 casualties per mission. This limit is instilled to guarantee that threats to public safety induced by the launch and re-entry are within the range dictated by the Air Force. Likewise, according to Environmental Protection Agency (EPA) guidelines, volcanism should not be considered an issue for site selection, if there is less than one chance in 10,000 in 10,000 years of site disruption by volcanic eruption (Environmental Protection Agency 1985). This requirement is reiterated in the new EPA rule for Yucca Mountain (Environmental Protection Agency 2001). However, the compliance period does not reflect the peak dose (about 300,000 years) of the high-level radioactive waste, and the specific criteria of the consequence models for the site disruption have not been clearly defined. Potential impacts on the evaluation of the hazard area other than a scenario of "criticality" inside the repository due to a direct hit include:

1. The impacts of volcanic ash injection into the biosphere: there are several factors including the effects of ash on short term and long term climate, and radioactive ash accumulating in soil and dunes in the vicinity of the repository
2. The effects of a dike or eruption occurring near the repository: this near-miss scenario includes changes in ground water flow paths, rock alteration, and thermal effects related to dike emplacement
3. Ground motion caused by large magnitude earthquakes related to volcanic eruptions

Modeling

Assuming that the compliance period is $(0, t)$, a simple way to present the probability of site disruption is:

$$\begin{aligned} P_{sd} &= \mathrm{P}\ [\text{site disruption event occurs during } (0,\ t)] \\ &= \mathrm{P}\ [\text{at least one volcanic event occurs in } (0, t), \text{ which disrupts the repository}] \\ &= \mathrm{P}\ [\text{at least one event occurs in } (0, t)] \times \mathrm{P}[\text{events occur within the hazard area}] \\ &= P_e \times P_h \end{aligned} \qquad (1)$$

In general, evaluations of P_e and P_h in Eq. 1 depend on the probability models fitted to the targeted volcanism. For the following parameter estimates, a homogeneous Poisson process (HPP) is assumed to demonstrate the utility of the proposed hazard area for general applications and model comparisons.

Applications

For YM volcanism, the model assumption of an HPP leads Eq. 1 to (Ho et al. 1991; Ho and Smith 1998):

$$P_{sd} = \pi\lambda t(r_s + r_d)^2 \Big/ A \qquad (2)$$

Where,

λ recurrence rate of the volcanism
t observation period
r_s radius of a circle enclosing the repository;
r_d radius of a circle quantifying the size of the eruption;
A area of the defined volcanic field (to be addressed later).

Equation 2 is mathematically simple and straightforward for volcanoes with complete data, but the implementation would be a task of enormous challenge for YM modelers. The key is to resolve the main conceptual issues and uncertainties addressed below.

Recurrence rate

Smith et al. (2002) contend that there is more uncertainty in recurrence rate estimates than assumed by the DOE, the expert panel, and the NRC. Their petrologic data suggest that volcanic fields in the Crater Flat–Lunar Crater zone are linked to a common area of hot mantle. Also, they show that volcanism is episodic with the possibility of a new peak of activity occurring in the future. These observations imply that volcanism is not dead in the Yucca Mountain area and that a future pulse of activity could have recurrence rates equivalent to those recorded in the Lunar Crater–Reveille area of the Crater Flat–Lunar Crater zone. Specifically, the DOE and the NRC have used a recurrence rate of 3.7–12 events per m.y. to calculate the probability of volcanic disruption (Connor and Hill 1995; Crowe et al. 1998; Connor et al. 2000). Based on their arguments, Smith et al. (2002) conclude that a recurrence rate of 11–>15 events per m.y. is possible.

Defined volcanic field at YM

Area of the defined volcanic field at YM region is specified as some minimal area that encloses the repository and the area of the volcanic events that satisfies the requirement of a constant recurrence rate. Crowe et al. (1982) developed a computer program to find either a minimum area circle or minimum area ellipse that contains the volcanic centers of interest and the repository site. It is defined to accommodate tectonic controls for the localization of volcanic centers and to constrain λ to be uniform within the area of either the circle or ellipse. Their choices of this field range in size from 1,953 to 69,466 km^2.

Area of repository

The area of the actual repository is currently undetermined but is estimated to be 6–8 km^2, which prescribes a circle with a radius, $r_\mathrm{s} \approx 1.5$ km for the hazard area.

Size of eruption

Analysis of volcanic disruptive scenarios is essential in quantifying the hazard area. For example, emplacement of a cinder cone outside the repository may result in dike injection within the repository itself. The hazard area is quite flexible in providing likely bounds for uncertainties associated with scenarios like dike intrusion.

Compliance period

It would be more appropriate to consider hazards up to the peak dose (300,000 years). However, for an extended compliance period, an HPP might not hold. The probability of site disruption should be interpreted with caution if volcanism is not stationary. In particular, the following statement is misleading: The estimated probability of site disruption is $8.65 \times 10^{-8} / yr$. We recommend that a statement regarding site disruption include the length of the compliance period. A better statement might be "the estimated probability of site disruption for an isolation time of 10^4 years is approximately *abc*, which increases to *xyz* if 10^5 years is the required isolation time."

Buried volcanoes

A high-resolution aeromagnetic survey of the YM area (O'Leary et al. 2002) revealed 19 dipolar magnetic anomalies that most probably represent buried basaltic volcanic centers. Their interpretation as buried centers is strongly supported by the alignment of many of the centers into northeast trending chains and proven by several drill holes that have encountered basalt. These volcanoes are buried beneath 160–640 km of basin fill (O'Leary et al. 2002). They have implications for the calculation of the recurrence rate and models for YM volcanism. An alternative approach that accounts for the uncertainty in the recurrence rate due to buried volcanoes is to make use of expert elicitation (e.g., Ho and Smith 1997) and Bayesian methods (e.g., Ho 1990, 1992; Marzocchi et al. 2004).

Results and analyses

For the purposes of model comparisons, we link Eq. 2 to the two components, P_e and P_h, defined in Eq. 1. They now are:

$$P_e = P\,[at\ least\ one\ event\ occurs\ in\ (0, t)] = 1 - \exp(-\lambda t) \approx \lambda t \quad (3)$$

$$P_h = P\,[events\ occur\ within\ the\ hazard\ area] = \pi (r_s + r_d)^2 / A \quad (4)$$

The effect of λ on P_e is linear (Eq. 3) when λt is small, which is applicable for YM volcanism (Ho et al. 1991). Apparently, P_e will be dominated by the estimates of the recurrence rate, and the size estimates of a disruptive event could significantly influence P_h. On the other hand, the conservativeness of each parameter assumption can be easily assessed, and necessary refinements may follow.

r_d equivalence

Multiple-expert hazard/risk assessments have considerable precedent, particularly in Yucca Mountain site characterization studies. Typically, in the elicitation of opinion, more than one source is tapped. For instance, a result of point estimates of P_h proposed by several experts range from 1.1×10^{-3} to 8×10^{-2} (Crowe et al. 1993, their Table 7.1). The underlying models represent three major groups: (1) a classical approach based on a simple Poisson process from Crowe et al. (1982), $P_h \approx 0.002$ (middle value); (2) Monte Carlo simulation results from Sheridan (1992), $P_h \approx 0.01$; and (3) a Bayesian prior applied to the area of most recent volcanism (AMRV) risk rectangles (Smith et al.1990; Ho 1992), $P_h \approx 0.05$. The degree of conservativeness can be compared using Eq. 4, if we normalize all the models to a set of parameters with all but one fixed. First, let r_s=1.5 km, r_d=0, P_h=0.002, and solve for A in Eq. 4, we get A=3,532 km^2. The values of "r_d equivalence" are then calculated as 1.85 and 6.0 km, respectively, for P_h=0.01 (Sheridan 1992) and 0.05 (Ho 1992), using the same set of known parameter values. Therefore, Sheridan's approach is relatively moderate, and Ho's method would be quite conservative, if A=3,532 km^2 is a reasonable estimate. Note that the area of the defined volcanic field, A=3,532 km^2, was obtained by setting the probability of Crowe et al. (1982) to match the base value, r_d=0. Adjustments can be implemented for additional model comparisons along the same path.

λ equivalence

In this case, the effect of λ on P_e is linear (Eq. 3). However, λ is the most debated parameter required in the YM volcanic site disruption probability studies. According to Environmental Protection Agency guidelines, volcanism should not be considered an issue for site selection if P_{sd} is less than 10^{-8}/year (Environmental Protection Agency 1985). This threshold value can be translated into a limit for λ by following the same logic described before. Although the soundness of A=3,532 km^2 remains to be challenged, for the sake of consistency, we shall use the same value for the following analyses. Thus, let r_s=1.5 km, r_d=0, A=3,532 km^2, t=1 year, and $P_{sd}=10^{-8}$/year, we get λ=5 events/m.y. from Eq. 2. In other words, P_{sd} will exceed the limit set by EPA, if the estimated recurrence rate for volcanic events is more than 5 events per m.y. This value of "λ equivalence" can be extended to any r_d>0. For example, its counterpart requires only 1.8 events/m.y. if r_d=1 km, an assumption which is less conservative than that of Sheridan's Monte Carlo simulation results. Moreover, the probability of site disruption is 10 times as likely as the EPA's limit, if the recurrence rate is 18 events/m.y., which is possible as claimed by Smith et al. (2002). Inclusion of the buried volcanoes (O'Leary et al. 2002) will introduce additional uncertainty in the probability estimate, which will be handled via a Bayesian approach shown in the next section.

Expert-elicitation and Bayesian analysis

In searching for a more flexible model, we consider, at least conceptually, a large volcanic center (belt) with cluster(s) of volcanoes in which, for any given volcano, the number of volcanic eruptions in (0, t) follows a Poisson process with recurrence rate $\mu=\lambda t$; however, the unit rate λ may be different from volcano to volcano. In particular, for this conceptually large population of volcanoes, we assume that λ is a continuous random variable that follows a probability density function, $g(\lambda)$. There is one more scenario that supports this generalization, which is also suitable for a single volcano. It arises from the fact that, although eruptions are caused by specific physical events or processes, there might be many casual factors with random influences on the sequence of eruptions. As a result, parameter λ is a random variable. Note that in the context of a Bayesian analysis, the density $g(\lambda)$ corresponds to a prior distribution for the parameter that involved in the analysis. The prior distribution reflects a degree of belief about the value of the parameter or some aggregated knowledge of experts of the parameter. For example, if we permit prior distribution for λ in Eq. 2, with all other parameters fixed as constants, we can incorporate uncertainties about the recurrence rate λ, which will eventually be averaged out as shown in Eq. 5.

$$P_{sd} = \int_{\lambda} \left\{ \pi\lambda t (r_s + r_d)^2 \Big/ A \right\} g(\lambda) d\lambda \qquad (5)$$

The prior distribution, $g(\lambda)$, of λ expresses experts' beliefs regarding the numerical values of λ accounted for the uncertainties of the buried volcanoes or some other risk factors. The determination of the prior is beyond the scope of this paper.

In case of general volcanic hazard assessment, the different kind of hazards (lava and pyroclastic flows, lahars, ash fall, earthquakes, ground deformation and so on...), different vulnerabilities, and different distribution of possible "target sites" make this work resemble more the vehicle-debris analysis described earlier. Future research will focus on the challenge posed by these tasks.

Conclusions

In response to several logical and carefully thought out issues related to volcanic hazard studies of the proposed high-level radioactive waste repository at Yucca Mountain, our modeling approach shares the same basic principle addressed in the FAA's Advisory Circular (FAA 2000):

> Using an acceptable methodology, such as that detailed in this Advisory Circular, an applicant would be required to demonstrate that the EC (expected casualty) for a proposed mission is equal to or less than the acceptable expected casualty threshold. Hence, an applicant may begin the risk management process using conservative assumptions and mitigate risks during the vehicle design, development, test and operational mission planning process to ensure that public safety considerations are satisfied.

In summary, we describe site disruption scenarios to validate the incorporation of the size of a volcanic event in the development of the hazard area in a defined volcanic field at Yucca Mountain. Every new eruption that occurs within the hazard area will disrupt the proposed repository. The probability of site disruption by volcanic activity is equal to the chance that a new eruption will occur in the same area. Simple equations are constructed for general application of volcanic hazards that meet specific requirements. The proposed methodology provides a platform for parameter-wise model comparisons related to the site characterization studies. Bayesian approaches incorporating expert-knowledge are also shown to be possible using the proposed framework.

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