U.S. NUCLEAR REGULATORY COMMISSION

DRAFT REGULATORY GUIDE DG-4028

Proposed new Regulatory Guide 4.26

Issue Date: March 2020
Technical Lead: Jenise Thompson

VOLCANIC HAZARDS ASSESSMENT FOR PROPOSED NUCLEAR POWER REACTOR SITES

A. INTRODUCTION

Purpose

This regulatory guide (RG) provides guidance for facilitating U.S. Nuclear Regulatory Commission (NRC) staff review of volcanic hazards assessments performed by applicants to support the siting of new nuclear power reactors. The RG also provides applicants with the methods and approaches the NRC staff considers acceptable for the assessment of volcanic hazards in license applications.

Applicability

This RG applies to applicants under Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, “Domestic Licensing of Production and Utilization Facilities,”10 CFR Part 52, “Licenses, Certifications, and Approvals for Nuclear Power Plants,” and 10 CFR Part 100, “Reactor Site Criteria.”

Applicable Regulations

- 10 CFR Part 50, Appendix A, “General Design Criteria for Nuclear Power Plants,” General Design Criterion 2, “Design Bases for Protection Against Natural Phenomena,” item (1), addresses the importance of “appropriate consideration of the most severe of the natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin for the limited accuracy, quantity and period of time in which the historical data have been accumulated.”

- 10 CFR 52.17(a)(1)(vi) for an early site permit and 10 CFR 52.79(a)(1)(iii) for a combined license state that technical information in the final safety analysis report shall include “…geologic characteristics of the proposed site with appropriate consideration of the most severe of the natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin for the limited accuracy, quantity and period of time in which the historical data have been accumulated.”

This RG is being issued in draft form to involve the public in the development of regulatory guidance in this area. It has not received final staff review or approval and does not represent an NRC final staff position. Public comments are being solicited on this DG and its associated regulatory analysis. Comments should be accompanied by appropriate supporting data. Comments may be submitted through the Federal rulemaking Web site, http://www.regulations.gov, by searching for draft regulatory guide DG-4028. Alternatively, comments may be submitted to the Office of Administration, Mailstop: TWFN 7A-06M, U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001, ATTN: Program Management, Announcements and Editing Staff. Comments must be submitted by the date indicated in the *Federal Register* notice.

Electronic copies of this DG, previous versions of DGs, and other recently issued guides are available through the NRC’s public Web site under the Regulatory Guides document collection of the NRC Library at https://nrcweb.nrc.gov/reading-rm/doc-collections/reg-guides/. The DG is also available through the NRC’s Agencywide Documents Access and Management System (ADAMS) at http://www.nrc.gov/reading-rm/adams.html, under Accession No. ML20007D621. The regulatory analysis may be found in ADAMS under Accession No. ML20007D618.

- 10 CFR Part 100, “Reactor Site Criteria,” establishes siting requirements for power and test reactors subject to 10 CFR Part 50 or 10 CFR Part 52.
    - 10 CFR 100.23(c) states that “…each applicant shall investigate all geologic and seismic factors (e.g., volcanic activity) that may affect the design and operation of the proposed nuclear power plant irrespective of whether such factors are explicitly included in this section.”

Related Guidance

- NUREG-0800, “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition,” Section 2.5.1, Revision 5, “Geologic Characterization Information,” issued July 2014 (NRC 2014a), briefly considers volcanic hazards but does not provide details on acceptable methods to assess volcanic hazards at a proposed site. Section 2.5.3, Revision 6, “Surface Deformation,” issued October 2019 (NRC 2019a), provides guidance to the staff on review of surface deformation of geologic features.

- RG 4.7, “General Site Suitability Criteria for Nuclear Power Stations,” and RG 1.206, “Applications for Nuclear Power Plants,” provide guidance on siting and contents of applications for new nuclear power plants (NPPs); however, they do not address acceptable methods to assess volcanic hazards at proposed sites.

Purpose of Regulatory Guides

The NRC issues RGs to describe to the public methods that the staff considers acceptable for use in implementing specific parts of the agency’s regulations, to explain techniques that the staff uses in evaluating specific problems or postulated events, and to provide guidance to applicants. Regulatory guides are not substitutes for regulations and compliance with them is not required. Methods and solutions that differ from those set forth in RGs will be deemed acceptable if they provide a basis for the findings required for the issuance or continuance of a permit or license by the Commission.

Paperwork Reduction Act

This RG provides voluntary guidance for implementing the mandatory information collections in 10 CFR Parts 50, 52, and 100 that are subject to the Paperwork Reduction Act of 1995 (44 U.S.C. 3501 et. seq.). These information collections were approved by the Office of Management and Budget (OMB), approval numbers 3150-0011, 3150-0151, and 3150-0093. Send comments regarding this information collection to the Information Services Branch (T6-A10M), U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001, or by e-mail to Infocollects.Resource@nrc.gov, and to the OMB reviewer at: OMB Office of Information and Regulatory Affairs (3150-0011, 3150-0151, and 3150-0093), Attn: Desk Officer for the Nuclear Regulatory Commission, 725 17th Street, NW Washington, DC20503; e-mail: oira_submission@omb.eop.gov.

Public Protection Notification

The NRC may not conduct or sponsor, and a person is not required to respond to, a collection of information unless the document requesting or requiring the collection displays a currently valid OMB control number.

B. DISCUSSION

Reason for Issuance

The NRC staff developed this guide to provide an acceptable, risk-informed framework for consideration of volcanic hazards in licensing new reactors. Although volcanic hazards occur only at specific locations in the United States, new nuclear reactors may be considered for areas that are characterized by past volcanic activity and, consequently, by potential hazards related to volcanism.

Background

The NRC conducted previous licensing reviews for volcanic hazards at six facilities in the United States. These facilities range in relative size and radiological risk from NPPs to interim spent fuel storage installations (ISFSIs). The following paragraphs summarize these licensing insights for consideration during a volcanic hazards analysis.

As of 2019, the Columbia Generating Station (Columbia) in Washington is the only operating NPP in the United States with a design basis for structures, systems, and components (SSC) that considers demands from a volcanic hazard. The Columbia site is approximately 215 kilometers (km) (135 miles (mi)) east of Mount St. Helens, which had its last major eruption in 1980. Because of its proximity to Cascade volcanoes, the Columbia NPP includes volcanic ash fall as a design- and operational-basis event (e.g., NRC, 2014b). The Columbia safety case includes demonstration of the plant's ability to withstand the wet and dry loads of potential ash-fall deposits, operational considerations for mitigating the effects of ash falls on plant SSCs, and the installation of oil-bath air filters during an ash-fall event.

The Trojan Nuclear Power Plant in Oregon was located approximately 55 km (34 mi) southwest of Mount St. Helens, along the western bank of the Columbia River. Because of its proximity to Mount St. Helens and other Cascade volcanoes, plant licensing considered the potential effects of future volcanic eruptions (PGE, 1976). The potential effects of future volcanic hazards were considered to have an insignificant effect on the design and operation of the plant because of the low frequency of occurrence and the characteristics of potential volcanic phenomena expected at the site (e.g., Oregon Department of Geology and Mineral Industries, 1978). Subsequently, the May 1980 eruption of Mount St. Helens created debris flows that partially infilled the Columbia River channel below the Trojan water intake structures and deposited several millimeters of ash fall at the site (Schuster, 1981). Volcanic hazards at Trojan were reevaluated based on the 1980 eruption characteristics (PGE, 1980, as referenced in Schuster 1981), and no changes were made to the plant's operating basis. Trojan was decommissioned in 1992.

The NRC also licensed two ISFSIs on or adjacent to the Idaho National Laboratory: TMI-2 (NRC, 1999a) and the Idaho Spent Fuel Facility (NRC, 2004); and the Eagle Rock enrichment facility (NRC, 2010). Each of these installations had to consider the possibility of volcanic lava flows, in addition to ash-fall hazards, that could affect the site. These nuclear material installations represent lower radiological risks than an NPP, which is reflected in the regulatory requirements for siting and the scope of the NRC staff's safety reviews. The acceptability of volcanic hazards at these sites was demonstrated at the time of licensing by (1) appropriate design and operational bases for ash fall, (2) low likelihood of lava-flow inundation, and (3) confidence in the licensee's ability to divert potential lava flows.

As part of the evaluation of preclosure and postclosure safety for the proposed geologic repository for high-level radioactive waste at Yucca Mountain, Nevada, the NRC staff reviewed the risks associated with volcanic activity affecting the facility. For the preclosure (operational) period, the applicant screened out the volcanic hazards involving direct effects of an eruption within the site footprint, based on event probability. Ash fall hazards from distant volcanos were included as credible and their potential for initiating an event sequence evaluated. The applicant determined that the effects of ash fall on the site could be sufficiently mitigated so as not to adversely impact safe and secure operations, and the NRC review found the applicant's analysis acceptable (NRC, 2015). For the postclosure period, the NRC staff reviewed detailed analyses on the likelihood of a new volcano forming at the proposed repository site, and the potential consequences of that event on the performance of the proposed waste isolation system. The NRC staff determined that the risk from future volcanic activity was acceptable because (1) the likelihood of future volcanic events was low, (2) the amount of high-level waste that could be entrained and ejected during a volcanic eruption was small, and (3) the combination of natural and engineered barriers was sufficient to limit radionuclide release from damaged waste packages remaining in repository drifts after a volcanic event (NRC 2014c).

These reviews demonstrate that a typical volcanic eruption produces a variety of potentially hazardous phenomena, many of which can affect a site simultaneously. Some of these phenomena, such as ash fall, can be mitigated through appropriate design and operational bases. Other phenomena, such as lava flows, present significant design and operational challenges to nuclear facilities. The rare occurrences of volcanic eruptions, and the diverse character of eruptive phenomena, can create significant uncertainties in a volcanic hazards analysis that must be evaluated in regulatory decision-making. The next sections of this guide develop the technical basis for an acceptable analysis of volcanic hazards for a proposed commercial nuclear reactor.

Overview of Volcanic Hazards

The International Atomic Energy Agency (IAEA) published IAEA-TECDOC-1795, "Volcanic Hazard Assessments for Nuclear Installations: Methods and Examples in Site Evaluation," issued 2016, which includes a detailed discussion of volcanic phenomena and associated hazards for nuclear installations.[1] This document was developed to support IAEA Specific Safety Guide (SSG)-21, "Volcanic Hazards in Site Evaluation for Nuclear Installations." Although IAEA TECDOC 1795 was developed for the siting of nuclear installations, the NRC staff is focusing on the information most relevant to the licensing of new reactors in the United States. The following provides an overview of siting and design considerations for potential volcanic hazards.

Volcanic hazards can present a range of physical demands on nuclear SSCs that are important to safety. The magnitude of these demands usually depends on the distance between the proposed site and the source characteristics of the volcanic phenomena. For example, for sites located relatively far from a volcano, volcanic ash fall has the potential to deposit layers of finely pulverized rock that might quickly clog filtration systems, introduce abrasive debris into mechanical systems, and add static loads to structures. Alternatively, sites located close to a new volcano could experience ground displacements on the order of meters and inundation by meters-thick, hot flows (greater than 1,000 degrees Celsius [C]; 1,800 degrees Fahrenheit [F]) of dense lava (2,600 kilograms per cubic meter [kg/m^3]; 162 pounds per cubic foot [ft^3]). In addition, an individual volcanic eruption potentially can produce multiple hazardous phenomena, each of which might need to be considered in a volcanic hazards assessment.

---

[1] This definition thus includes: nuclear power plants; research reactors (including subcritical and critical assemblies) and any adjoining radioisotope production facilities; storage facilities for spent fuel; facilities for the enrichment of uranium; nuclear fuel fabrication facilities; conversion facilities; facilities for the reprocessing of spent fuel; facilities for the predisposal management of radioactive waste arising from nuclear fuel cycle facilities; and nuclear fuel cycle related research and development facilities.

- *Ash Fall*: Many volcanic eruptions eject large volumes of pulverized rock into the atmosphere, which can travel tens to hundreds of kilometers from the source volcano. The pulverized rock fragments can be very small (0.001–2 millimeters [mm], 4×10^{-5}–0.08 inch [in]) and are relatively hard (e.g., comparable to hardened metal alloys). During an eruption and for some time afterwards, airborne concentrations of volcanic ash can range from less than 0.01 to approximately 1 gram per cubic meter (g/m^3) (less than 10^{-5}–0.001 ounce per ft^3). Deposits of volcanic ash can impart physical loads on the order of 100–1,000 kilograms per square meter (kg/m^2) (6.2–62 pounds per square foot [ft^2]) when dry, which can double when wet. When dampened (e.g., by fog or light rain), volcanic ash can be sufficiently conductive to create significant arcing across electrical insulators. Because volcanic ash is transported by atmospheric winds, initial arrival of ash at a site might occur hours after the onset of an eruption at a distant volcano. The design basis of the Columbia NPP, and NPPs elsewhere around the world, considered volcanic ash falls.

- *Opening of a New Vent*: The formation of a new volcanic vent directly disrupts an area of about 1 square kilometer (247 acres) and can include significant ground deformation (on the order of meters of displacement) and the expulsion of meter-sized blocks up to several kilometers away from the vent. In addition, lava flows often erupt from the newly formed vent and typically can travel 1 km (0.6 mi) or more a day. Precursory earthquake activity may occur for several weeks before a new vent forms, although some new vents have formed within a day of earthquakes being felt in the vent area. IAEA SSG-21 concluded that the opening of a new volcanic vent within approximately 1 km (0.6 mi) of a proposed site represented an exclusion condition at the site selection stage.

- *Lava Flows*: Lavas are dense (roughly 2,500 kg/m^3, 156 pounds per ft^3), hot flows (1,000–1,200 degrees C, 1,830–2,200 degrees F) of molten rock that tend to follow topographic gradients but often overcome topographic obstacles. Lava flows generally travel 1–10 meters per second (2–22 miles per hour), but greater or lesser speeds can occur based on site conditions. Flows generally extend up to tens of kilometers from a vent and often spread laterally from a central channel. In some terrains, lava flows can block drainages and create water impoundments and upstream flooding. IAEA SSG-21 concluded that lava flows at a proposed site represented an exclusion condition at the site selection stage.

- *Pyroclastic Density Currents*: Pyroclastic density currents are moving mixtures of pulverized rock and hot volcanic gases (greater than 300 degrees C [570 degrees F]) that can flow across the ground at speeds of hundreds of meters per second. Some volcanoes in the United States (e.g., Mount St. Helens) have the potential to produce small-volume pyroclastic density currents, which usually travel less than tens of kilometers from the vent. A few volcanoes in the United States (e.g., the Yellowstone Caldera) have produced large-volume pyroclastic density currents, which have traveled hundreds of kilometers from the vent and are capable of overtopping large topographic features. IAEA SSG-21 concluded that pyroclastic density currents at a proposed site represented an exclusion condition at the site selection stage.

- *Debris Flows*: Volcanic debris flows typically occur when a mass of pyroclastic material, either during or after an eruption, becomes mixed with water and flows down gradient. As the flow travels down gradient, it incorporates additional sediment and water and typically overtops existing stream or river channels. Volcanic debris flows typically contain greater than 50 percent suspended solids (which can include automobile-sized boulders) within tens of kilometers of the source, but they eventually dilute to more typical flood conditions as distance further increases from the source. Volcanic debris flow can occur with little warning time and can be triggered by either slope failure or intense rainfall events. IAEA SSG-21 concluded that debris flows at a proposed site represented an exclusion condition at the site selection stage.

- *Volcanic Earthquakes*: The rise of molten rock from deep in the earth's crust typically creates swarms of small-magnitude (i.e., generally less than M5 on the moment magnitude scale) earthquakes within tens of kilometers of the eventual surface eruption. Volcanic systems in the United States are located in active tectonic terranes, which typically have the potential to produce significantly larger magnitude earthquakes from local or regional tectonic sources. IAEA SSG-21 recommends consideration of a site-specific volcano-seismic hazard assessment for a site affected by other volcanic hazards.

- *Other Proximal Hazards:* Some additional volcanic hazards can occur within several tens of kilometers of a volcano or new volcanic vent. Depending on the characteristics of the volcanic systems in the site region, some consideration might be warranted for (1) potential debris avalanches arising from slope failures, (2) tsunami or seiche phenomena if a large debris avalanche enters a large body of water, and (3) the possibility of hydrothermal systems or emission of volcanic gases reaching a proposed site. These volcanic phenomena have a broad range of physical, thermal, and chemical characteristics, some of which could create unusual demands on the design and operation of a nuclear reactor.

Approach for Volcanic Hazards Assessment

In developing a rationale to support the technical positions outlined in Section C, the NRC staff relied heavily on the detailed technical information provided in IAEA-TECDOC-1795, as well as other cited sources of information. This guide focuses on the data and methods needed for an acceptable volcanic hazards assessment and does not present a detailed discussion of the conduct of a probabilistic volcanic hazards assessment. Many of the details on conducting a probabilistic volcanic hazards assessment are provided in existing documents, for example, IAEA SSG-21 and IAEA-TECDOC-1795. NUREG-2213, "Updated Implementation Guidelines for SSHAC Hazard Studies," and associated references discuss additional details on conducting a risk informed probabilistic assessment of volcanic hazards.

Rationale for the Period of Interest

General Design Criterion 2 of 10 CFR Part 50, Appendix A, requires consideration of natural phenomena that have been reported historically for the site. The NRC staff has long considered the approximately 200-year historical period for many parts of the United States as inadequate to evaluate the timing and character of infrequent-to-rare but potentially hazardous natural events, such as earthquakes and ground deformation. For geologic phenomena, the NRC staff considers the Quaternary Period (i.e., the last 2.6 million years) as providing sufficient margin to the historical period to accurately evaluate the timing and character of past geological events (e.g., NUREG-0800, Section 2.5.1). The duration of the Quaternary Period provides sufficient confidence that low-likelihood events have been captured in the geologic record, such that projections of future events can be reasonably based on this record.

Rationale for the Regions of Interest

For the purpose of the initial evaluation of potential hazards from volcanic phenomena other than ash falls, the region of interest extends 320 km (200 mi) from the proposed site. In the staff's view, evidence of past volcanic activity within the region of interest during the Quaternary Period indicates a potential for future volcanic activity, which represents the need to conduct further investigations of the potential for volcanic hazards at the proposed site. This distance encompasses typical screening distances for many potential volcanic hazards (e.g., IAEA-TECDOC-1795). This region of interest is consistent with previous NRC guidance related to site investigations, particularly the region investigated for other geological features and potential geologic hazards (i.e., NUREG-0800, Section 2.5.1).

NUREG-0800, Section 2.5.1, states that "[i]n some locations, for example, the potential for very large earthquakes or for volcanic activity might require investigations to be performed at greater distances from the site than 320 km (200 mi)." For the purposes of the initial evaluation of potential hazards from volcanic ash falls, the NRC staff has determined that the region of interest should extend a sufficient distance to encompass those Quaternary volcanic systems with the potential to exceed the design basis of the proposed reactor's SSCs. In practice, the NRC staff notes that, in accordance with IAEA-TECDOC-1795, volcanic ash-fall hazards may necessitate extending the region of consideration 500–1,000 km (310–620 mi) from a proposed site.

If there is no evidence of Quaternary volcanic activity in the appropriate regions, the NRC staff determined that no further analysis of volcanic hazards is warranted. Within the framework of volcanic activity in the United States, the NRC staff determined that an absence of volcanic activity in the last 2.6 million years provides sufficient basis to conclude that hazards from potential volcanic events are not significant in the context of the safe design and operation of a proposed nuclear facility.

Risk Informed Regulation

The NRC has a longstanding policy on implementing risk-informed regulation through the use of probabilistic risk assessment (PRA) methods in regulatory activities (60 FR 42622). In the current risk-informed, performance-based regulatory framework for NPP licensing, the staff uses insights from PRA analyses to support a range of regulatory decisions. SECY-98-144, "White Paper on Risk-Informed and Performance-based Regulation," dated March 1, 1999 (NRC 1999b), states the following:

> A "risk-informed" approach to regulatory decision-making represents a philosophy whereby risk insights are considered together with other factors to establish requirements that better focus licensee and regulatory attention on design and operational issues commensurate with their importance to public health and safety. A "risk-informed" approach enhances the deterministic approach by:
>
> (a) Allowing explicit consideration of a broader set of potential challenges to safety,
>
> (b) Providing a logical means for prioritizing these challenges based on risk significance, operating experience, and/or engineering judgment,
>
> (c) Facilitating consideration of a broader set of resources to defend against these challenges,
>
> (d) Explicitly identifying and quantifying sources of uncertainty in the analysis (although such analyses do not necessarily reflect all important sources of uncertainty), and
>
> (e) Leading to better decision-making by providing a means to test the sensitivity of the results to key assumptions."

Importantly, NRC (SECY-98-144) emphasizes the distinction between the suite of information used to support risk-informed decision making and a risk-based decision framework that relies solely on the results of a numerical PRA. For example, as discussed in NRC Office of Nuclear Reactor Regulation Office Instruction LIC-106, "Integrated Risk-Informed Decision-Making for Licensing Reviews," dated June 10, 2019 (NRC 2019b), risk-informed regulatory decisions typically begin with an understanding of the sensitivity of new information to the results of a facility's PRA. Once these numerical results are understood, additional qualitative or quantitative information typically is considered to gain additional insights on risk significance. This information can include consideration of available alternatives to a proposed action, degree of uncertainty in new information such as the likelihood of initiating events, or additional qualitative or quantitative investigations. Simply stated, risk-based decision-making would consider only the results of a PRA, whereas a risk-informed decision allows consideration of the PRA results within the broader context of the NRC's regulatory framework (e.g., NRC, 2018).

In the context of a volcanic hazards assessment, the NRC staff notes that risk insights provide a valuable mechanism to assess whether potential volcanic hazards are significant to safety. The approach to developing these insights relies on having an appropriate PRA for the proposed facility and using the intermediate results from the volcanic hazards assessment to test the sensitivity of key PRA assumptions. In practice, sensitivity analyses would assume that the performance of SSCs are degraded because of the conditional likelihoods of volcanic hazards occurring and then would assess the significance of that assumption to the PRA results. The significance of the volcanic hazards assessment could then be determined using the suite of information available to support risk-informed decision-making (i.e., items a–e in SECY-98-144).

Senior Seismic Hazards Analysis Committee Study Guidelines

The scientific community has not achieved consensus on specific modeling approaches that are both generally acceptable and suitable for evaluating low-likelihood volcanic phenomena at facilities that have stringent safety requirements. Selection of an appropriate approach is important because alternative modeling approaches can result in significantly different volcanic hazards assessment results. A volcanic hazards assessment must rely on interpreting the characteristics of poorly preserved past events and projecting these events into a range of potential future events. These projections must consider the possibility that new phenomena or patterns that are inconsistent with the patterns of past activity might occur in the future. Potentially significant uncertainties in data and models usually are evaluated and propagated through a probabilistic assessment. A well-documented probabilistic assessment provides an acceptable basis for NRC regulatory review and safety decisions (e.g., Volume 60 of the *Federal Register*, page 42622 [60 FR 42622]).

The NRC established the use of the Senior Seismic Hazards Analysis Committee (SSHAC) process as an acceptable method to account for a wide range of uncertainties in the analysis of natural hazards and other technical subjects. The NRC published the most recent guidelines in NUREG-2213, "Updated Implementation Guidelines for SSHAC Hazard Studies," issued October 2018 (NRC, 2018). The SSHAC process (or its equivalent) has been used successfully to evaluate seismic and volcanic hazards at a variety of sites worldwide, as described more fully in NUREG-2117, "Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies," issued April 2012 (NRC, 2012).

A SSHAC study can be accomplished at four levels that increase in complexity and cost and that result in corresponding increases in regulatory assurance. Selection of the appropriate study level is subjective and considers many qualitative factors, such as the level of public concern about the proposed facility and the scope of regulatory requirements. Nevertheless, the NRC staff provides the following guidance on selecting the SSHAC study level to support a volcanic hazards assessment:

- Level 1: facility with low-level source terms or design fragilities, modest number of alternative hazard models available, high confidence in the completeness and accuracy of the geologic record, and several straightforward hazard scenarios considered

- Level 2: facility with intermediate source terms or design fragilities, modest number of alternative hazard models available; moderate confidence in the completeness and accuracy of the geologic record, and multiple hazard scenarios considered

- Level 3: facility with potentially large source terms or design fragilities; potentially significant number of alternative hazard models available; moderate-to-low confidence in the completeness and accuracy of the geologic record; and complex, multi-hazard scenarios considered

- Level 4: facility with potentially large source terms or design fragilities; significant number of alternative or potentially contradictory hazard models available; low confidence in the completeness and accuracy of the geologic record; and numerous complex, multi-hazard scenarios considered

Harmonization with International Standards

IAEA recognizes volcanic hazards as presenting potential challenges for the siting and operation of nuclear installations. As discussed in IAEA Safety Guide NS-G-1.5, "External Events Excluding Earthquakes in the Design of Nuclear Power Plants," issued 2003, some nuclear installations located in volcanic terranes likely would need to consider volcanic hazards as potential design-basis events if such hazards at the site did not preclude development of the installation (IAEA, 2003). Consideration of volcanic hazards also is a specific site requirement in IAEA Specific Safety Requirement (SSR)-1, "Site Evaluation for Nuclear Installations," issued 2019, which indicates that a potential site would be unsuitable if volcanic hazards could not be accommodated within a proposed installation's design basis (IAEA, 2019b). IAEA Specific Safety Guide (SSG)-18, "Meteorological and Hydrological Hazards in site Evaluation for Nuclear Installations," issued 2011, also recognizes that volcanic activity can initiate land movements that trigger floods, tsunamis, and seiches (IAEA, 2011). Although these IAEA guidance documents recognize the need for the evaluation of potential volcanic hazards, they do not provide specific guidance on the conduct of a volcanic hazards assessment or criteria to evaluate the significance of potential volcanic hazards. IAEA SSG-21, "Volcanic Hazards in Site Evaluation for Nuclear Installations," issued 2012, does present these important details (IAEA, 2012).

The volcanic hazards approach in this guide is generally consistent with IAEA SSG-21. IAEA recognized the value of using a stepwise approach to conducting volcanic hazards assessments that uses available information to conduct a screening evaluation and then additional information to conduct a more detailed hazard analysis. IAEA also endorsed the use of a scaled approach, in which the level of effort in the hazard analysis is proportional to the risk of the nuclear facility being considered. The guidance in SSG-21, however, applies to all nuclear installations, so facility risk was scaled from nuclear reactors (high) to radioactive waste storage facilities (low).

Although SSG-21 discusses risk-informed concepts, these discussions are sufficiently generalized to accommodate regulatory frameworks around the world. In this guide, the NRC staff has developed a practicable approach for the application of risk insights in the volcanic hazards assessment, which is consistent with the NRC's risk-informed, performance-based regulatory framework. While the guide's approach is consistent with IAEA's risk-informed concepts, it provides appropriate information so that applicants and staff have clear guidelines on the information needed to support risk-informed decision-making.

This draft guide does not include three principal concepts developed in SSG-21:

(1) For the detailed volcanic hazards assessment, IAEA supported the use of both deterministic and probabilistic methods. Although the NRC staff considers deterministic methods appropriate for initial screening analysis, the NRC approach is to use probabilistic methods for a detailed volcanic hazards assessment. The rationale is that the NRC recognizes probabilistic methods as appropriately capturing an appropriate range of uncertainty in underlying models and data and for producing results that can be evaluated in a risk-informed regulatory framework.

(2) IAEA characterizes some hazardous volcanic phenomena as "site exclusion criteria." The NRC staff does not believe that such exclusionary criteria are consistent with the regulatory approach taken in 10 CFR 100.23, "Geologic and Seismic Siting Criteria," and are not consistent with a risk-informed regulatory framework. Although the NRC staff recognizes that some volcanic phenomena might create demands that exceed existing design bases, applicants should have the option to develop new design bases if warranted by the risks from volcanic hazards at a proposed site.

(3) IAEA has requirements for monitoring volcanoes if there are any volcanic hazards at the site. Although this requirement appears sensible, it does not appear applicable for nuclear reactors in the United States. The IAEA guidelines are applicable to member states around the world, some of which do not have well-funded national programs for volcano monitoring. That condition does not exist for the United States. The U.S. Geological Survey has statutory authority to monitor all potentially active volcanoes in the United States. If there is a perceived gap in monitoring activities at a proposed commercial nuclear reactor, the U.S. Geological Survey will fill that gap.

The NRC staff is not aware of any other internationally accepted standards for volcanic hazards assessments that would be relevant to applications for proposed new reactors. The NRC staff is aware of and has staff participants in an American Nuclear Society working group to develop a standard related to volcanic hazards. This standard is not yet available and therefore not considered further in this draft guide.

C. STAFF REGULATORY GUIDANCE

The Volcanic Hazards Assessment

For new reactors, the NRC staff determined the approach given below is acceptable for conducting a volcanic hazards assessment to meet applicable regulatory requirements. The information and associated uncertainties considered in the following steps can be evaluated acceptably through the SSHAC process (NRC, 2018).

Figure 1 of this guide illustrates the sequential steps of a risk-informed approach for conducting volcanic hazards assessments to support license applications for new reactors. As shown in Figure 1, the outcome of each step may result in the completion of the volcanic hazards assessment. Subsequent steps should be conducted as needed.

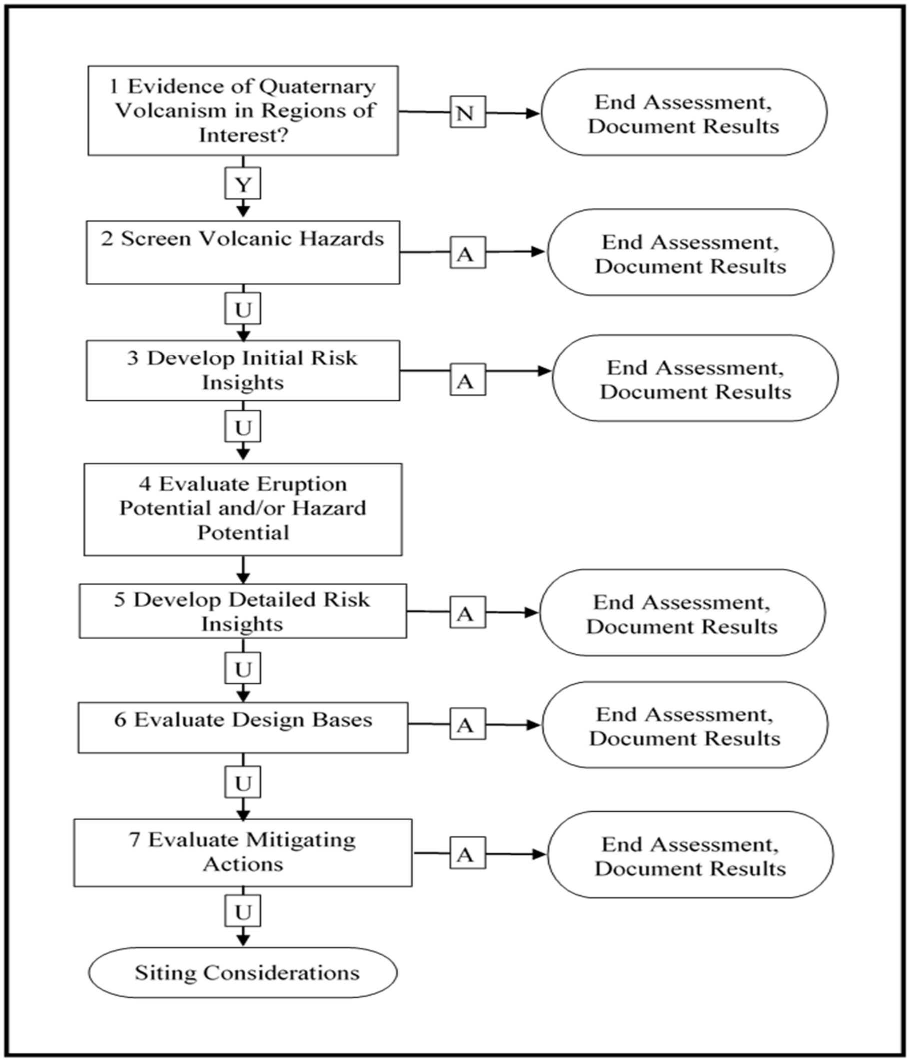

Figure 1 Flowchart for an acceptable volcanic hazards assessment.

(“Y” = Yes, “N” = No, “U” = Unacceptable performance, A = “Acceptable performance)

Step 1: Perform Initial Characterization

The volcanic hazards assessment should consider the Quaternary Period, defined as the geologic timeframe ranging from 2.6 million years ago to the present, to provide sufficient margin to the historical period to accurately evaluate the timing and character of infrequent geologic events such as volcanic eruptions.

The volcanic hazards assessment should consider a radius of at least 320 km (200 mi), extending in all directions from a proposed facility, as the appropriate region of interest for initial characterization of volcanic hazards other than ash fall, consistent with NUREG-0800, Section 2.5.1. Ash-fall hazards can occur from volcanoes located farther than 320 km (200 mi) from a site. For the purpose of the initial evaluation of potential hazards from volcanic ash falls, the region of interest for the volcanic hazards assessment should extend a sufficient distance beyond 320 km (200 mi) to encompass those Quaternary volcanic systems that have the potential to affect the design or operation of the proposed reactor.

If there is evidence of Quaternary volcanism in the regions of interest, a conceptual model of tectono-magmatic processes should be developed early in the characterization stage of the volcanic hazards assessment. The conceptual model, or series of alternative models, should develop an understanding of the geological sources and controls of Quaternary volcanism in the systems of interest. The goal of the tectono-magmatic model is to determine how the past patterns of Quaternary volcanism should be projected to estimates of future activity.

The hazard analysis can screen out volcanic systems that are not consistent with the tectono-magmatic model. This screening, however, is dependent on establishing sufficient confidence in the underlying technical basis showing that future volcanism is not a credible event. For example, if the locus of volcanic activity in the region has shifted through time because of tectonic processes, a rationale might be developed to exclude older Quaternary volcanic centers from the analysis (e.g., Yogodzinski et al., 1996).

The hazards analysis should characterize volcanic systems that are consistent with the tectono-magmatic model. Insights from the tectono-magmatic model should be used to guide subsequent data collection and model development. For example, volcanic systems that show potential relationships between regional tectonic stresses and vent locations would likely characterize a larger tectonic province than a system that shows strong influences of only local tectonic stresses (e.g., Sherrod et al., 1997).

Quaternary volcanoes that are consistent with the tectono-magmatic models should be characterized sufficiently to support each stage of the hazard analysis, as needed. Determination of sufficiency of available information is a key part of the SSHAC process through which the center, body, and range of technically defensible interpretations of data, models, and methods are evaluated (NUREG-2213). For some volcanic hazards assessment studies, characterization might proceed in stages, commensurate with the level of information required to support the next stage of the analysis. For example, large uncertainties about the timing of past events might be acceptable during the initial screening analyses but might produce unacceptable results if propagated into a probabilistic assessment of eruption likelihood. Thus, the need to reduce that magnitude of uncertainty through radiometric dating might be deferred until after a probabilistic hazard assessment is conducted and the risk significance of that hazard is assessed.

Volcanic systems tend to be long lived, with some loci of activity persisting throughout the Quaternary Period. In addition, volcanic systems generally are complex topographic features with both constructive and destructive processes operating at relatively high rates through time. Consequently, the record of past events will be incompletely preserved at the present-day surface. An acceptable characterization program will need to consider the potential for buried or eroded deposits in the region of interest and evaluate the uncertainties that such buried or eroded deposits represent in the appropriate hazard analyses (e.g., Wang and Bebbington, 2012). Evaluating the completeness of the geologic record often requires complex investigation and should be undertaken early in the volcanic hazards assessment (e.g., through the SSHAC process) to allow for development of an appropriate technical basis to support ensuing analyses.

Insights from the tectono-magmatic model should be used to consider whether the timing and characteristics of past events appropriately represent potential future events in the region of interest. In many volcanic systems, the record of past events (and associated uncertainties) provides an appropriate basis to consider the range of potential future events. Trends in this record also likely provide information on increases or decreases in the timing or magnitude of future events, which would need to be considered in the volcanic hazards assessment. Nevertheless, some volcanic systems have the potential to evolve though time in ways that are not consistent with the past patterns of activity. For example, spatial patterns might make an abrupt shift due to recent changes in local accommodation of tectonic stresses, or the potential for large-volume explosive eruptions might be significantly lower due to significant changes in magma system processes (e.g., Christiansen et al., 2007). The tectono-magmatic model provides an important framework to develop a technical rationale for how past patterns of activity should or should not be projected to future patterns.

Step 2: Screen Volcanic Hazards

After determining which Quaternary volcanoes in the region of interest are consistent with the tectono-magmatic model, the characterization studies should focus on developing sufficient information to determine the maximum credible distance that potentially hazardous volcanic phenomena can travel from the volcanic source. For each potential volcanic source, only those phenomena that are credible for the volcanic source need to be considered (e.g., lava flows would be considered for basaltic scoria cones, but large pyroclastic density currents would not be considered).

For each credible volcanic phenomenon, spatial screening criteria generally can be developed from the distance that the most extensive past event traveled from its source. This approach assumes that the character of past events is reasonably constrained and represents an appropriate basis to consider the character of future events. Most importantly, any spatio-temporal trends in the volcanic system need to be sufficiently characterized to provide confidence that the range of past events provides an appropriate maximum bound on the character of future events.

Burial and erosion of older deposits is a common problem that should be evaluated in the characterization of any volcanic system. The screening analysis should directly address whether burial or erosion of older deposits creates uncertainties in evaluating the maximum bound on the extent of past events and, if warranted, develop appropriate estimates of uncertainty on the maximum bound to account for burial or erosion processes. In some terranes, a long history of burial and erosion of volcanic deposits might make it impracticable to develop confidence in the maximum extent of past events. Other factors, such as spatio-temporal trends in the volcanic system or insufficient site-characterization information, might also affect the confidence in the maximum extent of past events. In these situations, maximum-extent estimates might be developed from information in appropriate analogue volcanic systems or from general information in, for example, IAEA-TECDOC-1795. The rationale for using alternative sources of information should be thoroughly documented.

After establishing the maximum distance that potential hazards can extend from the source(s), the screening analysis should evaluate whether the proposed site is located within or beyond the reach of each hazard. This analysis must consider whether the locations of future eruption sources have been appropriately evaluated. For many distributed volcanic fields (e.g., eastern Snake River Plain), future vent locations are not known and can only be estimated based on interpretations of past patterns of activity. In addition, many central vent volcanoes can erupt from vents on the flanks, or beyond the base, of the volcano (e.g., Sherrod et al., 1997). Consequently, the screening analysis needs to consider uncertainties in the location of future vents.

In addition to uncertainties in vent locations, the screening analysis also should consider whether past characteristics in topography or atmospheric wind conditions appropriately represent future characteristics. Changes in surface topography through time can strongly affect the direction and extent of surface flows, and the screening analysis should consider whether uncertainties in the maximum distance should be adjusted to account for the potential effects of an evolving topography between the source vent and the site. Similarly, analyses of ash-fall hazards should consider if atmospheric conditions that controlled the distribution of the largest past events are appropriate representations of potential future conditions.

After consideration of the appropriate uncertainties, a volcanic hazard can be screened from further consideration in the volcanic hazards assessment if the site is located more than the maximum distance the hazardous phenomena can extend from the source vent. Only those volcanic hazards that could potentially extend to the proposed site (i.e., screens in) need to be evaluated in the next steps of the volcanic hazards assessment. If a proposed site is located beyond the maximum distance for all credible volcanic hazards from all potential source volcanoes in the region of interest (i.e., screens out), then no further volcanic hazards assessment is warranted.

Step 3: Develop Initial Risk Insights

For potential hazards that are included in the volcanic hazards assessment after Step 2 screening, initial risk insights can be developed with a simplified analysis that assumes the occurrence of these volcanic hazards would represent a beyond-design-basis event. Thus, the PRA could assume the probability of SSC failure (i.e., unacceptable performance) is 100 percent. Using these assumptions, the PRA results could be evaluated to determine whether the total system performance would be acceptable for volcanically induced failure of the SSCs. This evaluation would necessarily include the suite of considerations used to make risk-informed regulatory decisions (e.g., SECY-98-144). If these initial risk insights determined that volcanically induced failure of SSCs resulted in acceptable performance, then no further volcanic hazards assessment would be warranted. However, if performance is viewed as unacceptable, or there are other risk insights that warrant consideration, then the volcanic hazards assessment would proceed to Step 4.

Step 4: Evaluate Eruption Potential and/or Hazard Potential

A traditional volcanic hazards assessment would first calculate the probability of a future volcanic eruption occurring (PE), then calculate the conditional likelihoods of potentially hazardous phenomena reaching the site (PH). The product of these two probability distributions would then be convolved to produce a probability of occurrence (or exceedance) for volcanic hazards at a site. The NRC staff believes that this traditional approach represents one acceptable method for conducting a volcanic hazards assessment.

Nevertheless, the NRC staff notes that efficiencies can be gained in some volcanic hazards assessments by initially evaluating either PE or PH independently, then developing risk insights to determine if additional volcanic hazards analyses are warranted. If either PE or PH indicates a potential for significant effects on facility safety (i.e., Step 5 in Figure 1), then analysis of the complementary probability (i.e., either PE or PH) would be needed. However, if either PE or PH shows that potential volcanic hazards did not significantly affect safety, then additional analyses would not be warranted.

This stepwise approach to conducting volcanic hazards assessments allows applicants to avoid unnecessary investigations unless initial probability estimates indicate potential safety significance for volcanic hazards. Many volcanic systems can have relatively large uncertainties in the timing of past events, which can be challenging to evaluate. Nevertheless, PE calculations will depend on interpretations of these timing uncertainties. In contrast, the range of past hazard characteristics might represent more straightforward interpretations of the geologic record, which could be used to evaluate PH with greater confidence and efficiency than PE. In such situations, initially evaluating the risk significance of either PE or PH provides a risk-informed basis to decide whether additional analyses are warranted.

In addition, this approach allows sites with only a potential hazard from volcanic ash fall to directly analyze the conditional hazard of ash fall exceeding certain design bases or limits without having to first evaluate the probability of an ash-fall eruption occurring. This approach allows the volcanic hazards assessment to evaluate a range of future eruption conditions (e.g., eruption volume, duration, grain-size characteristics) without having to determine the likelihood of an ash-fall eruption occurring in the future. The conditional ash-fall hazard, typically expressed as an exceedance probability, could provide an appropriate technical basis to develop a proposed NPP's design basis or determine if an existing design basis was resilient to the conditional ash-fall hazard.

Typically, PE is based on past patterns of eruption in the history of the volcanic system. This eruptive history generally will be incomplete, due to erosion and burial of older units. The PE evaluation will need to develop a suitable technical basis to determine how much of the volcanic system's record is appropriate to use in the PE calculations. A common concern arises when the most recent eruptions are the best documented, whereas older eruptions have increasingly larger uncertainties in their timing and character. The selection of a subset of a volcanic system's history should be supported by a technical basis that provides confidence that the PE calculation was based on an appropriate record of the system's past activity. Insights from the tectono-magmatic model often provide a technical rationale for determining what part of a volcano's history is representative of expected future conditions.

The evaluation of the uncertainties in the timing and character of past events represents a significant investigation for calculating PE (e.g., Wang and Bebbington, 2012). In many volcanic systems, only a subset of representative deposits has sufficient age information to support the PE calculation. Older deposits might be wholly or partially buried, yet they are still representative of the volcanic system's past activity and needed for calculation of PE. Because a large range of uncertainties in data and models likely will need to be evaluated for both PE and PH, the NRC staff considers the SSHAC process an acceptable approach to evaluating these uncertainties.

The past patterns of eruptions in many volcanic systems vary through time and commonly show patterns of waxing or waning activity (e.g., Yogodzinski et al., 1996). In addition, there might be prolonged periods of inactivity or very low eruption rates, followed by marked changes in activity patterns (e.g., Bebbington, 2007). The tectono-magmatic model should provide a framework to develop an understanding of potential geological controls on eruption patterns and to determine whether such geological processes are expected to occur in the future. Statistical approaches used to evaluate such nonstationary processes require a level of confidence that the model parameters were selected based on traceable interpretations of geological processes and data rather than by mathematical convenience.

Typically, PH is evaluated through numerical modeling of individual volcanic phenomena, using a range of characteristics that are interpreted from past volcanic events. A modeling approach is used to account for the incompleteness in the geologic record, which might not accurately represent the range of future events. As discussed in IAEA-TECDOC-1795, many different types of numerical models are available to simulate the characteristics of potentially hazardous phenomena. However, there is no technical consensus on which numerical models are most appropriate for evaluating a range of potential future phenomena. As a result, a significant part of the PH evaluation should focus on the development of a technical basis to support model selection. The NRC staff considers the SSHAC process an acceptable approach to develop support for model selection and to determine appropriate model parameters.

A particular challenge in volcanology is that individual volcanic phenomena can exhibit a wide range of physical, thermal, and chemical characteristics, presenting significant challenges in developing numerical models that accurately represent complex thermo-fluid-dynamical interrelationships. This large range of characteristics is not shared with other natural hazards, such as earthquakes or floods. For many volcanic phenomena, different models can calculate significantly different hazards at sites away from the source volcano. As a result, the volcanic hazards assessment should develop an appropriate technical basis to support the selection of numerical models used in the analysis. Based on guidance presented in NUREG-1804, "Yucca Mountain Review Plan," issued July 2003 (NRC, 2003), the NRC staff concludes that an acceptable level of volcanic hazards assessment model support consists of the following:

- Model parameters are based, to the extent possible, on the characteristics of the volcanic system being evaluated.

- Uncertainties and variabilities in these characteristics have a transparent technical basis and are accounted for in the model parameters.

- Alternative conceptual models have been considered, and the selection of a preferred model (or models) is supported by an appropriate technical basis.

- The precision and accuracy of the preferred models have a transparent technical basis, which typically is supported by comparison to empirical observations (e.g., field investigations, natural analogs, laboratory testing).

In calculating PH, the tectono-magmatic model should be used to determine whether past patterns of activity provide a sufficient basis to extrapolate to future patterns of activity, or if changes or trends to these past patterns need to be accounted for in extrapolations to future patterns of activity. For example, the volumes of lava flows might show a waning trend with younger eruptions (e.g., Valentine and Perry, 2006). Although a broad range in lava-flow volumes has occurred throughout the eruptive history, the tectono-magmatic model might provide confidence that the system characteristics have shifted to the production of smaller volume eruptions, which better represent the character of potential future eruptions. In this example, the calculation of PH might consider extrapolations based on the smaller volume period of activity rather than the entire history of eruptive activity in the volcanic system.

Once either PE or PH has been calculated, the NRC staff considers it acceptable to proceed to Step 5 of the volcanic hazards assessment and determine whether additional analyses are warranted. If the detailed risk insights in Step 5 show that either PE or PH might be significant to facility risk, then the remaining evaluation in Step 4 (i.e., calculation of either PE or PH) should be completed. The NRC staff also notes that an acceptable volcanic hazards assessment can skip an intermediate evaluation of risk insights (i.e., using only PE or PH), proceed to calculate both PE and PH, and then evaluate the detailed risk insights.

Step 5: Develop Detailed Risk Insights

Using the same approach as in Step 3, risk insights can be developed using a simplified analysis that assumes the occurrence of either a volcanic eruption (i.e., PE) or a volcanic hazard (i.e., PH) would represent a beyond-design-basis event. In this simplified approach, the analysis could assume that the probability of SSC failure (i.e., unacceptable performance) is represented in the PRA by either the PE or PH.

Using these assumptions, the PRA results could be evaluated to determine whether the total system performance would be acceptable for a volcanically induced failure of the SSCs. This evaluation would necessarily include the suite of considerations used to make risk-informed regulatory decisions (e.g., SECY-98-144). If these risk insights determine that volcanically induced failure of SSCs result in acceptable performance of either PE or PH, then no further volcanic hazards assessment is warranted.

If performance is unacceptable, or other risk insights warrant consideration, then the analyst returns to Step 4 and evaluates the unanalyzed component of the volcanic hazard (i.e., either PE or PH). Once both PE and PH are evaluated, a simplified PRA can be conducted using the assumption that the probability of SSC failure (i.e., unacceptable performance) is represented in the PRA by (PE x PH). Using this assumption, the PRA results could be evaluated to determine whether the total system performance would be acceptable for a volcanically induced failure of the SSCs. This evaluation would necessarily include the suite of considerations used to make risk-informed regulatory decisions (e.g., SECY-98-144, NRC 2019b, and RG 1.174). If these risk insights determine that volcanically induced failure of SSCs results in acceptable performance at (PE x PH), then no further volcanic hazards assessment is warranted. If this conclusion cannot be reached, then Step 6 of the volcanic hazards assessment should be conducted.

Step 6: Evaluate Design Bases

This step is optional if all previous steps have been completed and the volcanic hazards assessment analysis could proceed directly to Step 7 to evaluate potential mitigating strategies. Nevertheless, the NRC staff concludes that this step could provide additional performance insights from a focused analysis of SSC design bases that considers the unusual demands produced by hazardous volcanic phenomena.

The risk-insights steps above make the conservative assumption that SSCs would have unacceptable performance, or fail, from the effects of a volcanic hazard. NPP SSCs have existing design bases that can accommodate large physical demands from other natural hazards, such as seismic ground motions. In addition to the SSC design basis, most SSCs also include additional safety factors in their design margins that provide additional capacity to resist failure during beyond-design-basis events (e.g., Kennedy et al. 1988). Consequently, a direct evaluation of SSC capacity to withstand demands from a volcanic hazard might determine that the likelihood of unacceptable performance could be lower than 100 percent, which was assumed in the preceding risk-insight steps of the volcanic hazards assessment. This evaluation also might determine that modest modifications to existing design bases could provide the additional capacity needed for acceptable performance from potential volcanic hazards.

For example, SSCs for air filtration systems typically consider the demands from windblown sands. Volcanic ash falls, however, typically have large amounts of rock particulates, which are significantly smaller than windblown sands and can create larger concentrations of airborne particles. To accommodate the demands from volcanic ash falls, filtration systems would need to consider removal of larger amounts of finer particulates than would occur with windblown sands, which might be present for weeks or longer after an eruption (e.g., Horwell and Baxter, 2006). The Columbia NPP (Energy

Northwest, and other plants around the world (IAEA-TECCOC-1795) have accommodated such demands by straightforward design and operational changes.

The evaluation of volcanic surface-flow phenomena on SSC performance appears more challenging than for ash-fall hazards because of the complex and dynamic processes that occur in surface flows. The demands from a lava flow, for example, might peak several days or possibly weeks after the initial occurrence of a flow at the site. This lag in peak demand might occur because many lava flows tend to stagnate at their flow fronts, while erupted lava continues to infill and thicken the flow (e.g., Hon et al., 1994). Thermal, mechanical, and chemical demands on structures encountered by the lava flow could continue to increase as the flow thickens for many flow scenarios. Consequently, an evaluation of SSC performance during a lava-flow event likely would need to consider the possibility that demands might plateau, and then rapidly increase, for the duration of an eruptive event.

If SSC design bases are reevaluated, the NRC staff observes that the volcanic hazards assessment should reevaluate the risk insights obtained in Step 5, using the appropriate values for SSC performance with the anticipated demands of a volcanic event. The likelihood of the volcanic event should reflect (PE x PH) at an appropriate likelihood of the specific demand being exceeded during the volcanic event. If the reevaluated risk insights are acceptable for SSC performance during a volcanic event, then no further volcanic hazards assessment is warranted. If additional capacity or margin in the system is required, the volcanic hazards assessment should consider the evaluation of mitigating strategies in Step 7.

Step 7: Evaluate Mitigating Actions

If the preceding steps of the volcanic hazards assessment indicate that volcanic hazards have the potential to affect the design and operation of the proposed new reactor, the analysis can evaluate the potential for human actions to mitigate the effects of the volcanic hazards. These actions typically involve the development of operational procedures for timely responses to a future volcanic event. Responses could range from enhanced maintenance procedures (e.g., removal of volcanic ash-fall deposits from electrical insulators; Wilson et al., 2012) to construction of diversionary structures against surface flows.

A key challenge in using mitigation actions for volcanic hazards is developing a robust technical basis for the amount of time that might be available between the onset of volcanic eruptive activity and the arrival of hazardous phenomena at the site. Although some historical volcanic eruptions have occurred in well-monitored locations, there are considerable uncertainties in applying these eruptive patterns to different volcanic systems. These uncertainties arise from the potentially significant differences in local-scale (and regional-scale) tectono-magmatic processes that control the ascent and eruption of molten rock from deep in the earth's crust.

In addition, volcanic systems rarely provide clear indicators of an impending eruption in the months or weeks before an actual eruption. Patterns of precursory earthquake activity might be very similar to movement of other fluids at depth, or of some tectonic earthquakes (e.g., McNutt, 1996). Volcanic systems also can produce monitoring signals, such as elevated earthquake activity or degassing events, which suggest a high likelihood of a near-term eruption, only to have those signals abruptly cease and the volcanic system return to ambient conditions (e.g., Hill et al., 1991).

To accommodate these uncertainties, an acceptable operational plan for mitigation of potential volcanic hazards needs to provide confidence of the following:

- Appropriate monitoring resources are established to provide early indication of a potential eruption.

- Changes in monitored activity relate to clear criteria for proposed mitigative actions.

- Sufficient time is available between the start of volcanic unrest, implementation of proposed mitigative approaches, and arrival of potential volcanic hazards at the site.

The proposed mitigative actions must be practicable in the timeframe between the initial indications of a potential eruption and the likely arrival time of volcanic hazards at the site. Although this timeframe will be highly dependent on specific conditions at individual volcanoes, this timeframe typically can be on the order of days to weeks.

The Columbia plant has developed practicable mitigative actions for volcanic ash falls. These actions include removal of ash-fall deposits from vulnerable structures; installation of oil-bath or enhanced air filters on diesel generators; and adjusting heating, ventilation, and air conditioning equipment. The actions would allow the Columbia plant to safely shut down in the event of a volcanic ash fall at the site from an eruption of a Cascade volcano.

Mitigation of surface phenomena, such as lava flows or debris flows, appears more challenging than for volcanic ash falls. Some volcanic lava flows have been diverted successfully in past eruptions of Mount Etna in Italy, but not all attempts have been successful (Barberi et al., 1993, and 2003). In addition, successful diversion occurred in channelized terrain with moderate topographic gradients, which allowed for some control on the direction of flows. Successful mitigation of lava flows on relatively shallow topographic gradients has sometimes been proposed (e.g., Lockwood and Torgerson, 1980) but has not been implemented. A paucity of lava-flow diversion attempts reflects, in part, the legal complexities of diverting a flow into areas that likely would not have experienced a flow without diversion efforts.

Mitigation actions that propose construction of diversionary structures against surface flows should provide the following:

- a robust technical basis to determine the efficacy of proposed structures to divert surface flows, which often relies on numerical models that account for site-specific conditions (e.g., Crisci et al., 2010)

- an examination of how similar diversionary structures have performed in past attempts to mitigate similar volcanic hazards

- sufficient information to demonstrate the proposed construction is practicable in the time between initial alert levels and arrival of a surface flow at the site

After the technical basis is established for determining the likelihood of successful mitigation of potential volcanic hazards, the volcanic hazards assessment should develop additional risk insights that consider the likelihood of successful mitigation. If the reevaluated risk insights are acceptable for SSC performance during a volcanic event, then no further volcanic hazards assessment is warranted. If the risk insights are unacceptable, the volcanic hazards assessment should consider developing alternative siting criteria that reduce volcanic hazard to acceptable levels.

Consideration of Alternative Sites

After completing all the steps of the volcanic hazards assessment, and the outcome of the volcanic hazards assessment indicates that volcanic hazards are beyond the facility’s design basis and cannot be mitigated effectively, then alternative sites should be investigated. Unlike most other natural hazards, most volcanic hazards are spatially restricted. For some site locations, the NRC staff notes that alternative sites with significantly lower levels of volcanic hazard might be located within several miles, or less, of the unacceptable site.

D. IMPLEMENTATION

The methods described in this regulatory guide will be used in evaluating applications for construction permits, early site permits, combined licenses, and limited work authorizations, which includes information under 10 CFR 51.49(b) or (f), with respect to compliance with applicable regulations governing the siting of new nuclear power plants and testing facilities, unless the applicant proposes an acceptable alternative method for complying with those regulations. Methods that differ from those described in this regulatory guide may be deemed acceptable if the applicant provides sufficient basis and information for the NRC staff to verify that the proposed alternative complies with the applicable NRC regulations.

REFERENCES[2]

U.S. Nuclear Regulatory Commission Documents

NUREG-Series Reports

NRC 2003, NUREG-1804, "Yucca Mountain Review Plan, Final Report," Revision 2, Washington, DC, July 2003. (ADAMS Accession No. ML032030389)

NRC 2010, NUREG-1951, "Safety Evaluation Report for the Eagle Rock Enrichment Facility in Bonneville County, Idaho, Docket No. 70-7015," Washington, DC, September 2010. (ADAMS Accession No. ML102710296)

NRC 2012, NUREG-2117, "Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies," Revision 1, Washington, DC, April 2012. (ADAMS Accession No. ML12118A445)

NRC 2014a, NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants," Section 2.5.1, Revision 5, "Geologic Characterization Information," Washington, DC, July 2014. (ADAMS Accession No. ML13316C067)

NRC 2014c, NUREG-1949, "Safety Evaluation Report Related to Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada," Volume 3, "Repository Safety After Permanent Closure," Washington, DC, October 2014. (ADAMS Accession No. ML14288A121)

NRC 2015, NUREG-1949, "Safety Evaluation Report Related to Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada," Volume 2, "Repository Safety Before Permanent Closure," Washington, DC, October 2014. (ADAMS Accession No. ML15022A146)

NRC 2018, NUREG-2213, "Updated Implementation Guidelines for SSHAC Hazard Studies," Washington, DC, October 2018. (ADAMS Accession No. ML18282A082)

NRC 2019a, NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants," Section 2.5.3, Revision 6, "Surface Deformation," Washington, DC, October 2019. (ADAMS Accession No. ML19009A314)

Regulatory Guides

NRC Regulatory Guide (RG) 1.174, "An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis," Washington, DC.

NRC RG 1.206, "Applications for Nuclear Power Plants," Washington, DC.

NRC RG 4.7, "General Site Suitability Criteria for Nuclear Power Stations," Washington, DC.

---

[2] Publicly available NRC published documents are available electronically through the NRC Library on the NRC's public web site at http://www.nrc.gov/reading-rm/doc-collections/ and through the NRC's Agencywide Documents Access and Management System (ADAMS) at http://www.nrc.gov/reading-rm/adams.html The documents can also be viewed online or printed for a fee in the NRC's Public Document Room (PDR) at 11555 Rockville Pike, Rockville, MD. For problems with ADAMS, contact the PDR staff at 301-415-4737 or (800) 397-4209; fax (301) 415-3548; or e-mail pdr.resource@nrc.gov.

Miscellaneous NRC Documents

NRC 1999a, "Safety Evaluation Report of Three Mile Island Unit 2 Independent Spent Fuel Storage Installation Safety Analysis Report," Washington, DC, March 19, 1999. (ADAMS Accession No. ML060970085)

NRC 1999b, SECY-98-144, "White Paper on Risk-Informed and Performance-Based Regulation," Washington, DC, March 1, 1999. (ADAMS Accession No. ML003753601)

NRC 2004, "Safety Evaluation Report, Chapter 2, 'Site Characteristics,'" Enclosure 2 to letter to Ronald D. Izatt, Tetra Tech FW Inc., "Issuance of Materials License No. SNM-2512 for the Idaho Spent Fuel Facility (72-25) (L23389.)," Washington, DC, November 30, 2004. (ADAMS Accession Nos. ML043420450, ML043360281)

NRC 2014b, "Columbia Generating Station - Interim Staff Evaluation Relating to Overall Integrated Plan in Response to Order EA-12-049 (Mitigation Strategies) (TAC No. MF0796)," Letter to Mark E. Reddemann (Energy Northwest), Washington, DC, January 29, 2014. (ADAMS Accession No. ML13337A266)

NRC 2019b, "Integrated Risk-Informed Decision-Making for Licensing Reviews," Office of Nuclear Reactor Research Office Instruction LIC-106, Washington, DC, June 10, 2019. (ADAMS Accession No. ML19031C861)

Federal Laws and Regulations

U.S. Code of Federal Regulations (CFR), "Domestic Licensing of Production and Utilization Facilities," Part 50, Chapter 1, Title 10, "Energy."

CFR, "Licenses, Certifications, and Approvals for Nuclear Power Plants," Part 52, Chapter 1, Title 10, "Energy."

CFR, "Domestic Licensing of Special Nuclear Material," Part 70, Chapter 1, Title 10, "Energy."

CFR, "Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater than Class C Waste," Part 72, Chapter 1, Title 10, "Energy."

CFR, "Reactor Site Criteria," Part 100, Chapter 1, Title 10, "Energy."

Federal Register Notices

NRC, "Use of Probabilistic Risk Assessment in Nuclear Regulatory Activities: Final Policy Statement," *Federal Register*, Vol. 60, No. 158, p. 42622, (60 FR 42622), Washington, DC, August 16, 1995.

Other Documents

Barberi, F., M.L. Carapezza, M. Valenza, and L. Villari, "The Control of Lava Flow during the 1991–1992 Eruption of Mt. Etna," *Journal of Volcanology and Geothermal Research*, 56: 1–34, 1993.

Barberi, F., F. Brondi, M.L. Carapezza, L. Cavarra, and C. Murgia, "Earthen Barriers to Control Lava Flows in the 2001 Eruption of Mt. Etna," *Journal of Volcanology and Geothermal Research*, 123: 231–243, 2003.

Bebbington, M., "Identifying Volcanic Regimes using Hidden Markov Models," *Geophysical Journal International,* 171: 921–942, 2007.

Christiansen, R.L., J.B. Lowenstern, R.B. Smith, H. Heasler, L.A. Morgan, M. Nathenson, L.G. Mastin, L.J.P. Muffler, and J.E. Robinson, "Preliminary Assessment of Volcanic and Hydrothermal Hazards in Yellowstone National Park and Vicinity," U.S. Geological Survey Open-File Report 2007-1071, Reston, VA, 2007.

Crisci, G.M, M.V. Avolio, B. Behncke, D. D'Ambrosio, S. DiGregorio, V. Lupiano, M. Neri, R. Rongo, and W. Spataro, "Predicting the Impact of Lava Flows at Mount Etna, Italy," *Journal of Geophysical Research*, 115: B04203, 2010.

Hill, D.P., M.J.S. Johnston, J.O. Langbein, S.R. McNutt, C.D. Miller, C.E. Mortensen, A.M. Pitt, and S. Rojstaczer, "Response Plans for Volcanic Hazards in the Long Valley Caldera and Mono Craters Area, California," U.S. Geological Survey Open-File Report 91-270, 1991.

Hon, K., J. Kauahikaua, R. Denlinger, and K. Mackay, "Emplacement and Inflation of Pahoehoe Sheet Flows: Observations and Measurements of Active Lava Flows on Kilauea Volcano, Hawaii," Geological Society of America Bulletin 106(3): 351–370, 1994.

Horwell, C.J. and P.J. Baxter 2006 "The Respiratory Health Hazards of Volcanic Ash: A Review for Volcanic Risk Mitigation," *Bulletin of Volcanology,* 69: 1–24, 2006.

International Atomic Energy Agency (IAEA), "External Events Excluding Earthquakes in the Design of Nuclear Power Plants," Safety Guide NS-G-1.5, 2003, Vienna, Austria: IAEA.[3]

IAEA 2011, "Meteorological and Hydrological Hazards in site Evaluation for Nuclear Installations," Specific Safety Guide SSG-18, 2011, Vienna, Austria: IAEA.

IAEA 2012, "Volcanic Hazards in Site Evaluation for Nuclear Installations," Specific Safety Guide SSG-21, 2012, Vienna, Austria: IAEA.

IAEA 2016, "Volcanic Hazard Assessments for Nuclear Installations: Methods and Examples in Site Evaluation, IAEA-TECDOC-1795, 2016, Vienna, Austria: IAEA.

IAEA, 2019b, "Site Evaluation for Nuclear Installations," Specific Safety Requirements SSR-1, 2019, Vienna, Austria: IAEA.

Kennedy, R.P., R.D. Campbell, and R.P. Kassawara, "A Seismic Margin Assessment Procedure," *Nuclear Engineering and Design*, 107: 61–75, 1988.

Lockwood, J.P. and F.A. Torgerson, "Diversion of Lava Flows by Aerial Bombing—Lessons from Mauna Loa Volcano, Hawaii." *Bulletin of Volcanology,* 43:727–741, 1980.

---

[3] Copies of International Atomic Energy Agency (IAEA) documents may be obtained through their web site: WWW.IAEA.Org/ or by writing the International Atomic Energy Agency, P.O. Box 100 Wagramer Strasse 5, A-1400 Vienna, Austria.

McNutt, S.R., “Seismic Monitoring and Eruption Forecasting of Volcanoes: A Review of the State-of-the-Art and Case Histories,” in Scarpa, R. and Tilling, R.I., *Monitoring and Mitigation of Volcano Hazards*, Springer, Berlin, pp. 99–146, 1996.

Oregon Department of Geology and Mineral Industries 1978, “Geologic Hazards Review, Trojan Nuclear Power Plant Site, Columbia County, Oregon,” Open File Report O-78-1, 1978, Portland, OR.

Portland General Electric Company (PGE), Final Safety Analysis Report, Trojan Nuclear Plant: Portland General Electric Company Docket No. 50-344, v. 1, 2, 1976.

Schuster, R.L., “Effects of the Eruptions on Civil Works and Operations in the Pacific Northwest,” in Lipman, P.W. and D.R. Mullineaux, *The 1980 Eruptions of Mount St. Helens, Washington*, US Geological Survey Professional Paper 1250, pp. 701–718, 1981.

Sherrod, D.R., L.G. Mastin, W.E. Scott, and S.P. Schilling, “Volcano Hazards at Newberry Volcano, Oregon,” U.S. Geological Survey Open-File Report 97-513, 1997. (Available at http://pubs.er.usgs.gov/publication/ofr97513.)

Valentine, G.A. and F.V. Perry, “Decreasing Magmatic Footprints of Individual Volcanoes in a Waning Basaltic Field,” *Geophysical Research Letters,* 33:L14305, 2006.

Wang, T. and M. Bebbington, “Estimating the Likelihood of an Eruption from a Volcano with Missing Onsets in Its Record,” *Journal of Volcanology and Geothermal Research,* 243–244: 14–23, 2012.

Wilson, T.M., C. Stewart, V. Sword-Daniels, G.S. Leonard, D.M. Johnston, J.W. Cole, J. Wardman, G. Wilson, and S.T. Barnard, “Volcanic Ash Impacts on Critical Infrastructure,” *Physics and Chemistry of the Earth*, 45: 5–23, 2012.

Yogodzinski, G.M, T.R. Naumann, E.I. Smith, T.K. Bradshaw, and J.D. Walker, “Evolution of a Mafic Volcanic Field in the Central Great Basin, South Central Nevada,” *Journal of Geophysical Research*, 101(B8): 17,425–17,445, 1996.