U.S. NUCLEAR REGULATORY COMMISSION
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VOLCANIC HAZARDS ASSESSMENT FOR PROPOSED NUCLEAR POWER REACTOR SITES

A. INTRODUCTION

Purpose

This regulatory guide (RG) provides guidance for facilitating the U.S. Nuclear Regulatory Commission (NRC) staff's 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." Though intended for nuclear power reactors, this RG may also provide useful guidance relevant to applications for other nuclear installations.

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 and with sufficient margin for the limited accuracy, quantity, and time in which the historical data have been accumulated.

Written suggestions regarding this guide or development of new guides may be submitted through the NRC's public Web site in the NRC Library at https://nrcweb.nrc.gov/reading-rm/doc-collections/reg-guides/, under Document Collections, in Regulatory Guides, at https://nrcweb.nrc.gov/reading-rm/doc-collections/reg-guides/contactus.html.

Electronic copies of this RG, previous versions of RGs, and other recently issued guides are also available through the NRC's public Web site in the NRC Library at https://nrcweb.nrc.gov/reading-rm/doc-collections/reg-guides/, under Document Collections, in Regulatory Guides. This RG is also available through the NRC's Agencywide Documents Access and Management System (ADAMS) at http://www.nrc.gov/reading-rm/adams.html, under ADAMS Accession Number (No.) ML23167A078. The regulatory analysis may be found in ADAMS under Accession No. ML20007D618. The associated draft guide DG-4028 may be found in ADAMS under Accession No. ML20007D621, and the staff responses to the public comments on DG-4028 may be found under ADAMS Accession No. ML20272A169.

- 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 (for example, 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, "Geologic Characterization Information," Revision 5, 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. NUREG-0800, Section 2.5.3, "Surface Deformation," Revision 6, issued October 2019 (NRC 2019a), provides guidance to the staff on the review of surface deformation of geologic features.

- RG 1.208, "A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion," provides guidance on seismic site characterization and contents of applications for new nuclear power plants (NPPs). Although it does not specifically address acceptable methods to assess volcanic hazards at proposed sites, this RG establishes the concepts of site region (320-kilometer (km) [200-mile (mi)] radius from the site) and site vicinity (40-km [25-mi] radius from the site), which are applicable to the assessment of volcanic hazards.

- 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 NPPs; however, they do not address acceptable specific methods to assess volcanic hazards at proposed sites.

- RG 1.233, "Guidance for a Technology-Inclusive, Risk-Informed, and Performance-Based Methodology to Inform the Licensing Basis and Content of Applications for Licenses, Certifications, and Approvals for Non-Light-Water Reactors," provides guidance on the identification and analysis of licensing basis events; safety classification of structures, systems and components (SSCs); and evaluation of defense in depth for nonlight-water reactor designs.

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), under control number 3150-0011, 3150-0151, and 3150-0093 respectively. Send comments regarding this information collection to the FOIA, Library, and Information Collections 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, DC, 20503; e-mail: oira_submissions@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

RG 4.26 is being revised to correct an administrative error in the text and a subheading in Section C "Staff Regulatory Guidance." In the discussion of Step 4 "Evaluate Eruption Potential and/or Hazard Potential," two paragraphs and two bullet points discussing model support were unintentionally deleted, despite their inclusion in the draft guide released for public comment and a subsequent draft presented to NRC's Advisory Committee on Reactor Safeguards for review in spring 2021.The subheading for the following section, Step 5 "Develop Risk Insights," was also omitted. This revision restores the omitted text from Step 4 and the subheading for Step 5. In addition, there were several minor editorial changes to conform to the current template for RGs.

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. The following paragraphs summarize insights derived from the licensing reviews for consideration during a volcanic hazards analysis.

As of 2021, the Columbia Generating Station (Columbia) in Washington is the only operating NPP in the United States with a design basis for SSCs that considers demands from a volcanic hazard. The Columbia site is approximately 215 km (135 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 the demonstration of the plant's ability to withstand the wet and dry loads of potential ash fall deposits, discussion of operational considerations for mitigating the effects of ash fall deposits on plant SSCs, and the installation of oil-bath air filters on some diesel generators 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 three facilities on or adjacent to the Idaho National Laboratory, two interim spent fuel storage installations, the Three Mile Island Unit 2 facility (NRC, 1999a) and the Idaho Spent Fuel Facility (NRC, 2004), as well as the Eagle Rock uranium enrichment facility (NRC, 2010). Each of these installations considered the possibility of volcanic lava flows and ash fall hazards that could affect those facilities. 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 pre-closure and post-closure safety for the proposed geologic repository for high level radioactive waste at Yucca Mountain, NV, the NRC staff reviewed the risks associated with volcanic activity affecting the facility. For the pre-closure (i.e., operational) period, the applicant screened out volcanic hazards involving direct effects of an eruption within the site footprint, based on event probability. However, it included ash fall hazards from distant volcanoes as credible, and it evaluated their potential for initiating an event sequence. The applicant determined that effects of volcanic ash 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 post-closure 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 can produce a variety of potentially hazardous phenomena, many of which can affect a site simultaneously. Some of these phenomena, such as ash fall, might be mitigated through appropriate design and operational bases. Other phenomena, such as lava flows, might 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 nuclear reactor.

Overview of Volcanic Hazards

In addition to the prior licensing actions conducted by the NRC, volcanic hazards have been evaluated for nuclear facilities around the world. The International Atomic Energy Agency (IAEA) developed Specific Safety Guide (SSG)-21, "Volcanic Hazards in Site Evaluation for Nuclear Installations," issued 2012,[1] to establish a graded approach for volcanic hazards assessments. To support SSG-21, in 2016 the IAEA published IAEA-TECDOC-1795, "Volcanic Hazard Assessments for Nuclear Installations: Methods and Examples in Site Evaluation," which includes a detailed discussion of volcanic phenomena and associated hazards for nuclear installations. Although IAEA-TECDOC-1795 was developed for the siting of nuclear installations, much of the technical information in this report is relevant to the licensing of new reactors in the United States. However, the NRC is not endorsing IAEA SSG-21 for volcanic hazards analysis for new reactor applicants in the United States. The Consideration of International Standards section, presented later in this guide, discusses the rationale for this decision.

This RG uses the information in these IAEA documents, along with other technical literature, to provide 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

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[1] The definition of "nuclear installations" includes NPPs, 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 reprocessing spent fuel, facilities for the predisposal management of radioactive waste arising from nuclear fuel cycle facilities, and research and development facilities related to the nuclear fuel cycle

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 can potentially produce multiple hazardous phenomena, each of which might require consideration in a volcanic hazards assessment. These hazardous phenomena might include one or more of the following:

- *Ash Fall*: Many volcanic eruptions eject large volumes of pulverized rock and volcanic glass into the atmosphere that can travel tens to hundreds of kilometers (miles) 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, and those loads can double when the ash is wet. When dampened (e.g., by fog or light rain), volcanic ash can also 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 (e.g., on the order of meters [feet] of displacement) and the expulsion of meter-sized blocks up to several kilometers (miles) 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 in 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- and volcano-specific conditions. Flows generally extend up to tens of kilometers (miles) 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 flow hazards 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 (feet) 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 (miles) 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 (miles) from the vent and are capable of overtopping large topographic features. IAEA SSG-21 concluded that pyroclastic density-current hazards 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 the topographic gradient.

  As the flow travels down-gradient, it incorporates additional sediment and water and typically overtops existing stream and river channels. Volcanic debris flows typically contain greater than 50-percent suspended solids, which can include automobile-sized boulders, within tens of kilometers (miles) of the source, but eventually dilute to more typical flood conditions as distance increases from the source. A volcanic debris flow can occur with little warning time and can be triggered by slope failure or intense rainfall events. IAEA SSG-21 concluded that debris flow hazards 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 (miles) of the eventual surface eruption. Volcanic systems in the United States are located in active tectonic terranes that 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:* Additional volcanic hazards can occur within several tens of kilometers (miles) of a volcano or new volcanic vent. Depending on the characteristics of the volcanic systems in the site region, 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 of this RG, the NRC staff used detailed technical information provided in IAEA-TECDOC-1795, as well as other cited sources of information. This RG focuses on the data and methods needed for an acceptable volcanic hazards assessment but does not present a detailed discussion on the conduct of a probabilistic volcanic hazards assessment. Many of the details on conducting a probabilistic volcanic hazards assessment are found in existing documents (e.g., IAEA SSG-21 and IAEA-TECDOC-1795). NUREG-2213, "Updated Implementation Guidelines for SSHAC Hazard Studies," issued October 2018 (NRC, 2018), 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 for 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

As part of the site characterization process performed to satisfy 10 CFR 100.23(c), an applicant typically compiles geologic information in the region extending 320 km (200 mi) from the proposed site (RG 1.208, [2007]). In addition, the applicant typically conducts a more detailed evaluation of geologic characteristics within 40 km (25 mi) of the proposed site (RG 1.208, [2007]). The emphasis of these investigations is to develop an understanding of geologic processes that might affect the design and operation of a proposed facility.

For Quaternary volcanoes in the United States, most potentially hazardous volcanic phenomena are restricted to within 320 km of the source volcano (e.g., IAEA-TECDOC-1795). The exceptions are pyroclastic hazards from huge, “super-volcano” eruptions, such as the Yellowstone caldera. As an initial screening criterion, the NRC staff determined that evidence of Quaternary volcanic activity within the site’s region of interest (i.e., less than 320 km [200 mi] from the proposed site) demonstrates a potential for future volcanic activity and indicates the need to conduct further evaluations of volcanic hazards at the proposed site.

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).” The NRC staff recognizes that huge, super-volcano eruptions, although extremely rare, have the potential to create hazards more than 320 km (200 mi) from a site. Information in IAEA-TECDOC-1795, for example, indicates that some volcanic ash fall hazards might extend 500–1,000 km (310–620 mi) for very large but infrequent eruptions. The NRC staff determined that a reasonable screening criterion for these types of large eruptions is the occurrence of Quaternary pyroclastic deposits within 40 km (25 mi) of the proposed site. The presence of such deposits within the site vicinity (i.e., less than 40 km [25 mi]) indicates the need to conduct further evaluations of potential hazards from a source volcano more than 320 km (200 mi) from the proposed site.

If there is no evidence of Quaternary volcanism in the site region and no evidence of Quaternary volcanic deposits in the site vicinity, the NRC staff determined that an applicant should not perform a volcanic hazards assessment. 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.

Thus, the need to consider potential volcanic hazards is determined by information developed during the site characterization process required under 10 CFR 100.23(c). An additional assessment of potential volcanic hazards is indicated by either (1) a Quaternary volcano within the 320-km (200-mi) region around the proposed site, or (2) a volcanic deposit within the 40-km (25-mi) vicinity of the proposed site from a Quaternary volcano located more than 320 km (200 mi) away. If neither of these conditions occur, an applicant would not be expected to conduct an assessment of volcanic hazards.

Consideration of Proximal Hazards

Using the information in, for example, IAEA-TECDOC-1795, the NRC staff determined that some volcanic hazards are expected to be restricted to within 40 km (25 mi) of a volcanic vent. These proximal volcanic hazards are (1) debris avalanches, landslides, and slope failures, (2) volcanic missiles, (3) volcanic gases and aerosols, (4) atmospheric phenomena such as lightning, (5) ground deformation, and (6) hydrothermal systems and groundwater effects. Consequently, if a proposed site is located more than 40 km (25 mi) from a Quaternary volcano, the volcanic hazard analysis would not need to evaluate these potentially hazardous phenomena.

Many volcanic eruptions occur from easily recognized Quaternary volcanoes. However, the source of eruptions in some distributed volcanic fields is a new vent, which forms at a location that has not experienced eruptions in the past. In such distributed volcanic fields, the screening of proximal hazards would need to consider the potential for the formation of a new volcanic vent within 40 km (25 mi) of a proposed site. If a proposed site is located less than 40 km (25 mi) from the location of a potential volcanic vent, then pre-licensing interactions would be needed to determine the appropriate scope of the volcanic hazards assessment for proximal hazards. These interactions would likely need to consider the geologic characteristics of the site vicinity to determine which proximal volcanic hazards would be relevant to the hazards assessment.

Development of a Tectono-Magmatic Conceptual Model

In areas where potential volcanic hazards may exist, a volcanic hazards assessment fundamentally relies on projecting past patterns of volcanic activity to forecast future events that might result in hazards. To perform this projection, the analysis must consider if the tectonic and magmatic processes that controlled volcanism in the past are likely to occur with similar characteristics in the future.

Volcanic systems represent a complex interplay between regional and local tectonic forces and deeper magmatic processes, which have the potential to vary significantly within the Quaternary Period. A conceptual understanding of these geological processes can be used to help evaluate uncertainties associated with projections of past volcanic activity to future events. In addition, this conceptual understanding could be used to determine what Quaternary volcanoes warrant further consideration in a volcanic hazards assessment. Thus, the tectono-magmatic conceptual model develops an understanding of the key processes that resulted in the occurrence of past volcanic events and a rational framework for considering if past patterns of activity can be extrapolated to future events.

For example, a tectono-magmatic conceptual model might show that the locus of volcanic activity in the region has shifted through time because of changing tectonic processes, which might provide a rationale for excluding older Quaternary volcanic centers from the hazards analysis (i.e., Yogodzinski et al., 1996). Other conceptual models might show that the potential for large-volume explosive eruptions could be lower than extrapolated from past patterns of activity due to significant changes in the magma system (e.g., Christiansen et al., 2007). IAEA-TECDOC-1795, for example, includes additional examples of how tectono-magmatic conceptual models can be used in a volcanic hazards assessment.

In the early stages of the volcanic hazards assessment, the tectono-magmatic conceptual model can provide a rationale for the inclusion or exclusion of Quaternary volcanic systems for further consideration. For example, shifts in the locus of magmatic activity through time might indicate that some older Quaternary volcanoes in the region have a negligible potential for future eruptions, whereas younger Quaternary volcanoes are consistent with current tectonic and magmatic conditions. In this example, the older Quaternary volcanoes would not need to be considered in the volcanic hazards assessment, because they are inconsistent with the prevailing tectonic and magmatic conditions that control the potential for future eruptions in the system.

In the later stages of the volcanic hazards assessment, the tectono-magmatic conceptual model could provide the rationale for determining if the rate and character of past Quaternary events can be reasonably extrapolated to likelihoods of future events. For example, the rate of explosive eruptions might have decreased significantly due to the evolution of the magmatic system. The tectono-magmatic conceptual model could provide an explanation for what controlled the rate changes, so that appropriate models of past events could be used to calculate the likelihood of future events.

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 (Volume 60 FR of the *Federal Register,* page 42622 [60 FR 42622] [NRC, 1995]). 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-206, "Integrated Risk-Informed Decision-Making for Licensing Reviews," dated June 6, 2019 (NRC, 2019b), risk-informed regulatory decisions typically begin with an understanding of the sensitivity of new information to the results of the PRA for a facility. 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., NUREG-2213, [NRC, 2018]).

In the context of a volcanic hazards assessment, the NRC staff notes that risk insights could provide a valuable mechanism to assess whether potential volcanic hazards are significant to safety for those sites with Quaternary volcanoes within the site region or with Quaternary volcanic deposits within the site vicinity. The approach to developing these insights often relies on having an appropriate PRA for the proposed facility, which can use the intermediate results from a volcanic hazards assessment to test the sensitivity of key PRA assumptions. The significance of the volcanic hazards could then be determined using the suite of information available to support risk-informed decision-making (i.e., items (a) through (e) from Concept #5, "Risk-Informed Approach," in SECY-98-144).

However, a key challenge in the application of quantitative risk insights for volcanic hazards can arise from the need to consider potentially large levels of uncertainty associated with model results. These uncertainties occur from, for example, large variabilities in model parameter values, unresolvable inaccuracies in models of volcanic phenomena, and the likely need to consider alternative conceptual models to represent the range of characteristics for volcanic hazards.

In Rev. 0 of RG 1.233 (2020), the NRC adopted the use of numerical guidelines in Nuclear Energy Institute (NEI) 18-04, "Risk-Informed Performance-Based Technology Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development," Revision 1, issued August 2019 (NEI, 2019), to support risk-informed decision-making. These guidelines include identification of design-basis event (DBE) sequences as having mean occurrences of $1x10^{-2}$ to $1x10^{-4}$/reactor year and beyond-design-basis event (BDBE) sequences with mean occurrences of less than $1x10^{-4}$ but greater than $5x10^{-7}$/reactor year (NEI, 2019). The 5th and 95th percentile confidence intervals (i.e., uncertainties) about the mean also need to be considered in identifying DBE and BDBE sequences (NEI 18-04).

In the context of a PRA, a potential volcanic hazard could represent an initiating event for either DBE or BDBE sequences. The uncertainties in the likelihood of such initiating events, however, might span several orders of magnitude about a mean probability (e.g., Sandia National Laboratories, 2008). In addition, the responses of many SSCs to potential volcanic demands have not been fully examined, which could create additional uncertainties in the PRA evaluation of ensuing event sequences. As a result of these potentially significant uncertainties, risk insights on volcanic hazards might need to rely on a broader suite of non-PRA information than commonly used to support risk-informed decision-making (e.g., NRC, 1999b).

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 onto a range of potential future events. These projections must consider the possibility that new phenomena or patterns, which 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., 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. 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," Revision 1, issued April 2012 (NRC, 2012). The purpose of a SSHAC study is to have a transparently documented and structured process for addressing uncertainties using expert judgment. The outcome of a SSHAC study is typically a hazard result that accounts for uncertainty, which can take on many forms depending on the need for the analysis. For example, a SSHAC study for addressing volcanic hazards could result in a hazard likelihood, an event likelihood, or a projected hazard characteristic such as thickness of ash fall, effectiveness of a mitigation strategy, or some combination of these.

A SSHAC study can be accomplished at four levels that increase in complexity and cost and result in corresponding increases in regulatory assurance, with the highest degree of regulatory assurance gained from Level 3 and Level 4 studies (Section 2.5 of NUREG-2213). 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. Section 3.2.1 of NUREG-2213 includes guidance on the relevant factors for selecting an appropriate SSHAC study level. However, the NRC staff provides the following guidance on selecting the SSHAC study level to support a volcanic hazards assessment:

- Level 1: Applicable to a facility with low-level source terms or design fragilities related to volcanic hazards, a modest number of available alternative hazard models, high confidence in the completeness and accuracy of the geologic record, and several straightforward hazard scenarios that can be considered.

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

- Level 3 or 4: Applicable to a facility with potentially large source terms or design fragilities; a significant number of available alternative or potentially contradictory hazard models; low confidence in the completeness and accuracy of the geologic record; and/or numerous complex, multi-hazard scenarios that can be considered. A Level 3 or Level 4 study may be chosen depending on the organization of the study (i.e., whether a single or multiple logic trees will need to be developed, the complexity of the study, the methods for characterizing uncertainty, and other factors). The NRC staff should be consulted in determining which study level is appropriate (NUREG-2213, Section 2.6.16).

The NRC developed guidelines in NUREG-2213 for selecting a SSHAC study level with certain qualitative aspects (e.g., "low confidence or potentially significant") to maximize flexibility in applying the SSHAC process to a variety of hazard assessments and types of facilities and to be applied both domestically and internationally. The guidelines can be beneficially applied for various site and technology types with varying completeness of available information and tailored to a specific facility design and location. In the description above about selecting a study level for a volcanic hazards study, qualifiers are used to allow flexibility. However, the staff notes that SSHAC Level 1 or 2 studies are often used if there is high confidence that the driving factors for hazard are well understood and uncertainty is low (i.e., there are not significantly conflicting models or interpretations, or sites may be "data rich"). In other words, the "center" of the center, body, and range of technically defensible interpretations are easily defined and well understood (NUREG-2213, Section 2.2 and Figure 2-1).

Higher levels of SSHAC studies are recommended when uncertainties are larger, to fully capture the body and range and to characterize uncertainty. In addition, NUREG-2213 specifies that higher levels of SSHAC should be used when additional stability of the hazard is necessary (e.g., the numerical results of the hazard analysis should be expected to remain stable for a reasonable period of time after completion of the study; for example, to support a licensing basis. Sections 2.5, 3.1, and 3.2 of NUREG-2213 provide full discussions of appropriate SSHAC study level selection. Subsequent sections of this RG define specifics of volcanic hazards to be considered in more detail. Finally, the NRC staff notes that SSHAC guidelines are a practical, approved method for developing hazard analyses that can assist in the efficiency of an NRC licensing action. However, use of the SSHAC process is not legally binding or a regulatory requirement. Applicants are encouraged to use preapplication interactions with the NRC on the use of the SSHAC process and for choosing the level of study if a SSHAC process is used (NUREG-2213, Section 2.6.16).

Consideration of International Standards

The International Atomic Energy Agency (IAEA) works with member states and other partners to promote the safe, secure, and peaceful use of nuclear technologies. The IAEA develops Safety Requirements and Safety Guides for protecting people and the environment from harmful effects of ionizing radiation. This system of safety fundamentals, safety requirements, safety guides, and other relevant reports, reflects an international perspective on what constitutes a high level of safety. To inform its development of this RG, the NRC considered IAEA Safety Requirements and Safety Guides pursuant to the Commission's International Policy Statement and Management Directive (2014), and Handbook 6.6, "Regulatory Guides (2016)."

The 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 (IAEA, 2003), some nuclear installations located in volcanic terranes would likely need to consider volcanic hazards as potential DBEs, if such hazards at the site did not preclude development of the installation. Consideration of volcanic hazards also is a specific site requirement in IAEA Specific Safety Requirement (SSR)-1, "Site Evaluation for Nuclear Installations," issued 2019 (IAEA, 2019), which indicates that a potential site would be unsuitable if volcanic hazards could not be accommodated within the design basis for the proposed installation. IAEA SSG-18, "Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations," issued 2011 (IAEA, 2011), also recognizes that volcanic activity can initiate land movements that trigger floods, tsunamis, and seiches. Although these IAEA guidance documents recognize the need to evaluate 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 (IAEA, 2012), does present these important details.

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

Although IAEA SSG-21 discusses risk-informed concepts, these discussions are sufficiently generalized to accommodate different regulatory frameworks. In this RG, the NRC staff has developed a practicable approach for the application of risk insights in volcanic hazards assessments that are consistent with the NRC's risk-informed and performance-based regulatory framework. The approach in this RG is also consistent with the IAEA's risk-informed concepts and provides clear guidelines to applicants and staff on the information needed to support risk-informed decision-making. However, this RG does not adopt three principal concepts developed in IAEA SSG-21:

(1) For the detailed volcanic hazards assessment (i.e., the likelihood of a volcanic hazard reaching the proposed site), the IAEA supported the use of both deterministic and probabilistic methods. Although the NRC staff considers deterministic methods appropriate for the initial screening analysis and some engineering analyses, the NRC approach uses only 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) As noted in the "Overview of Volcanic Hazards" section presented earlier in this guide, the IAEA characterizes some hazardous volcanic phenomena as "site exclusion criteria." The NRC staff does not agree that such exclusionary criteria are consistent with the regulatory approach taken in 10 CFR 100.23, "Geologic and Seismic Siting Criteria," or 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 alternative design bases or take mitigating actions if warranted by the risks from volcanic hazards at a proposed site.

(3) The IAEA has requirements for monitoring volcanoes if there are any volcanic hazards at the site. Although this requirement appears logical, it does not apply to 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 in the United States because the U.S. Geological Survey (USGS) 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 nuclear reactor, potential licensees will need to work with the USGS to fill that gap.

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 (NUREG-2213 [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.

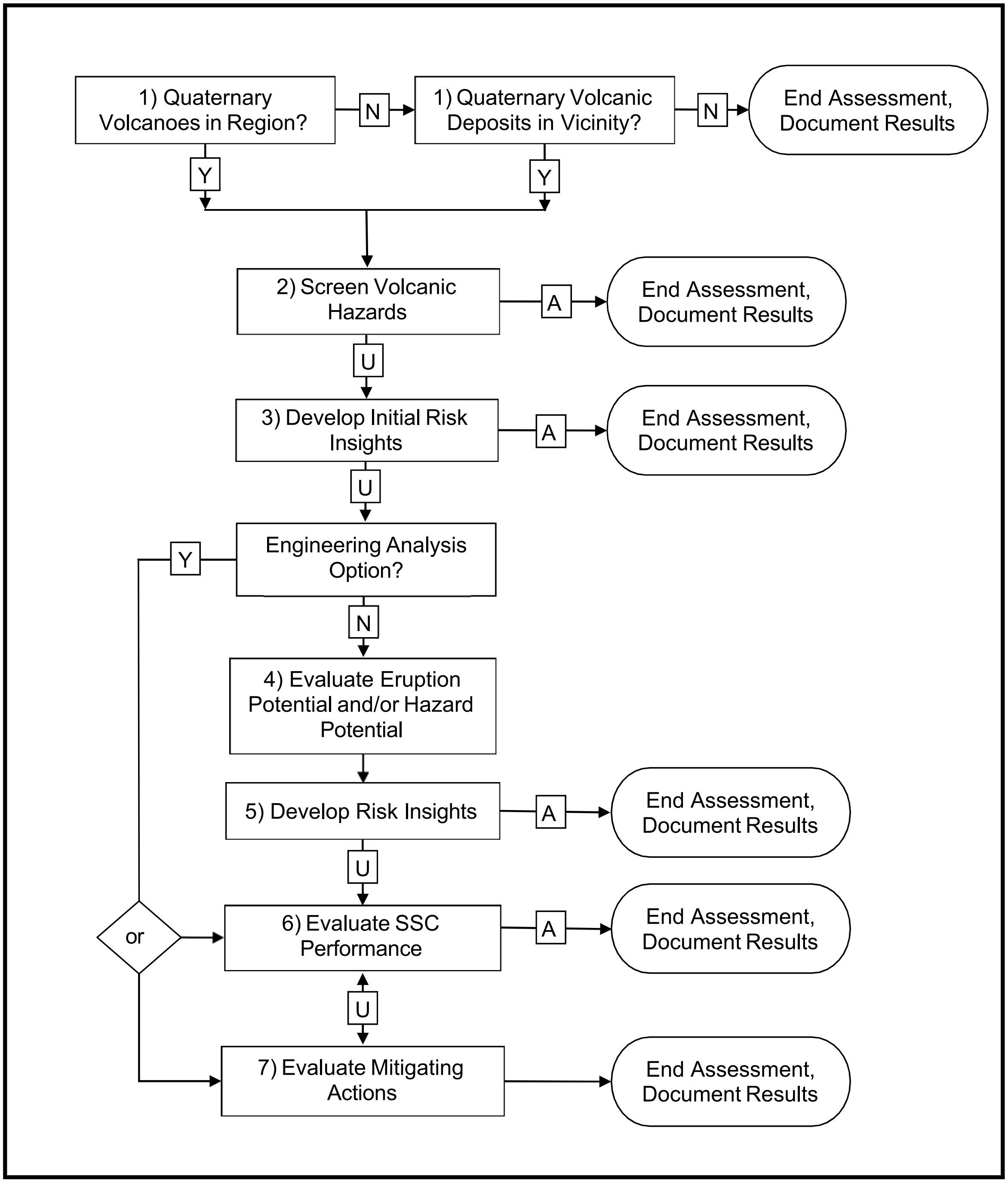

Figure 1 Flowchart for an acceptable volcanic hazards assessment

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

Step 1: Evaluate Site Characterization Information

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 for the historical period to accurately evaluate the timing and character of infrequent geologic events such as volcanic eruptions. Information developed during the geologic site characterization process should be sufficient to determine if volcanic features and deposits occur within the site region (320 km [200 mi]) or site vicinity (40 km [25 mi]), consistent with NUREG-0800, Section 2.5.1.

Sites with a Quaternary volcano within the site region should perform the next steps of a volcanic hazards assessment. The assessment can screen out proximal hazards if a Quaternary volcano, or the site of a potential new volcano, is not located within the site vicinity. However, hazards from large eruptions can occur from volcanoes located beyond the site region. For the purpose of the initial evaluation of potential hazards from large volcanic eruptions Quaternary pyroclastic deposits occurring within the site vicinity indicate that hazards from volcanoes located beyond the site region should be considered in the next stages of the hazards assessment.

If the site characterization demonstrates that there are no Quaternary volcanoes within the site region, and no Quaternary pyroclastic deposits within the site vicinity, then a volcanic hazard analysis is not warranted. The absence of relevant Quaternary volcanic features should be noted in the applicant's discussion of the geologic characteristics of a proposed site, consistent with NUREG--0800, Section 2.5.1.

Quaternary volcanoes that are within the different areas of interest and consistent with the tectono-magmatic conceptual model should be characterized sufficiently to support each stage of the hazard analysis, as needed. If a tectono-magmatic conceptual model is not developed in the early stages of the volcanic hazards assessment, then all Quaternary volcanoes within the different areas of interest should be characterized.

Determining the 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 (i.e., 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 could 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 volcanic 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 volcanic hazards 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 the development of an appropriate technical basis to support additional analyses.

Step 2: Screen Volcanic Hazards

After determining which Quaternary volcanoes in the region of interest are consistent with the tectono-magmatic model, the site characterization studies should focus on developing sufficient information to determine the maximum distance that potentially hazardous volcanic phenomena can travel from the volcanic source. For each potential volcanic source, only those phenomena that are characteristic of 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 characteristic volcanic phenomenon, spatial screening criteria generally can be developed based on 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 a future maximum-magnitude event. Most importantly, any evolutionary trends in the volcanic system need to be sufficiently considered 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. Other factors, such as spatio-temporal trends in the volcanic system or insufficient site characterization information, might also affect uncertainty in the maximum extent of past events. In those situations, estimates of maximum extent might be developed from information in appropriate analog volcanic systems or from general information in, for example, IAEA-TECDOC-1795. The rationale for using alternative sources of information should be documented.

After establishing the maximum distance that potential hazards can extend from the volcanic source(s), the screening analysis should evaluate whether the proposed site is located within or beyond the reach of each hazard. This analysis should consider whether the locations of future volcanic sources have been appropriately evaluated. For many distributed volcanic fields (e.g., the 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 new vents on the flanks, or beyond the base, of the volcano (e.g., Sherrod et al., 1997). Consequently, the screening analysis should consider uncertainties in the location of future vents.

In addition to uncertainties in vent locations, the screening analysis should consider whether past characteristics in topographic or atmospheric 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., screen 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., screen out), then no further volcanic hazards assessment is warranted.

Step 3: Develop Initial Risk Insights

The screening analysis only provides confidence that the maximum-magnitude volcanic hazards have been identified for a proposed site. Estimates of mean hazard likelihood and associated confidence intervals typically would not be available at this early stage of the volcanic hazards assessment. Nevertheless, two approaches are available for developing initial risk insights for volcanic hazards identified from the screening analysis.

The first approach conducts a more traditional volcanic hazards analysis, which calculates the likelihoods of a future volcanic eruption and associated hazards. These likelihoods are then used to evaluate the potential significance of volcanic hazards to performance, using either PRA or other risk insight methodologies. For this approach, the analysis would proceed directly to Step 4 (Figure 2).

An alternative approach uses the maximum-magnitude volcanic hazard from Step 2 to evaluate the proposed plant's ability to operate safely, without considering the likelihood that volcanic hazards could affect the proposed site (Figure 3, Engineering Analysis). For this approach, , the volcanic hazards assessment could proceed directly to Step 6 and evaluate the performance of the SSCs of the proposed plant to the demands arising from the maximum-magnitude volcanic hazards identified in the screening analysis of Step 2. As discussed further in Step 6, the NRC staff recognizes that SSCs have been designed to withstand high levels of demand from other phenomena and might have the potential to perform intended safety functions successfully if demands from volcanic hazards occur. Ash fall is expected to be the primary hazard of concern for most sites. In addition, unsuccessful performance of the facility's DBE and BDBE sequences might have such a small likelihood of occurrence that a maximum-magnitude volcanic hazard would not represent a potentially significant contribution to initiating events. This information, along with the suite of information used to make risk-informed regulatory decisions (e.g., SECY-98-114), could be used to determine whether volcanic hazards warranted additional consideration. If volcanic hazards appeared potentially significant, the hazards assessment could proceed directly to Step 7 and evaluate possible mitigating actions or return to Step 4 and develop estimates of eruption potential or hazard potential, or both.

As an alternative to evaluating the plant's SSC performance (i.e., Step 6) after the screening analysis, the volcanic hazards assessment could proceed directly to Step 7 and evaluate potential mitigating actions for volcanic hazards (Figure 3). As discussed further in Step 7, the NRC staff recognizes that days-to-weeks of warning time occur between the initial indications of a volcanic hazard and arrival of potentially hazardous phenomena at the site. For some volcanic hazards, operator actions might be sufficient to acceptably mitigate the adverse effects of volcanic hazards. In addition, unsuccessful performance of the facility's DBE and BDBE sequences might have such small likelihoods of occurrence or potential offsite consequences that a mitigated volcanic hazard would not represent a potentially significant initiating event. This information, along with the suite of information used to make risk-informed regulatory decisions (e.g., SECY-98-114), could be used to determine whether volcanic hazards warranted additional consideration. If volcanic hazards appeared potentially significant, the hazards assessment could proceed directly to Step 6 and evaluate SSC performance for a mitigated volcanic hazard or return to Step 4 and develop estimates of eruption potential or hazard potential, or both.

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

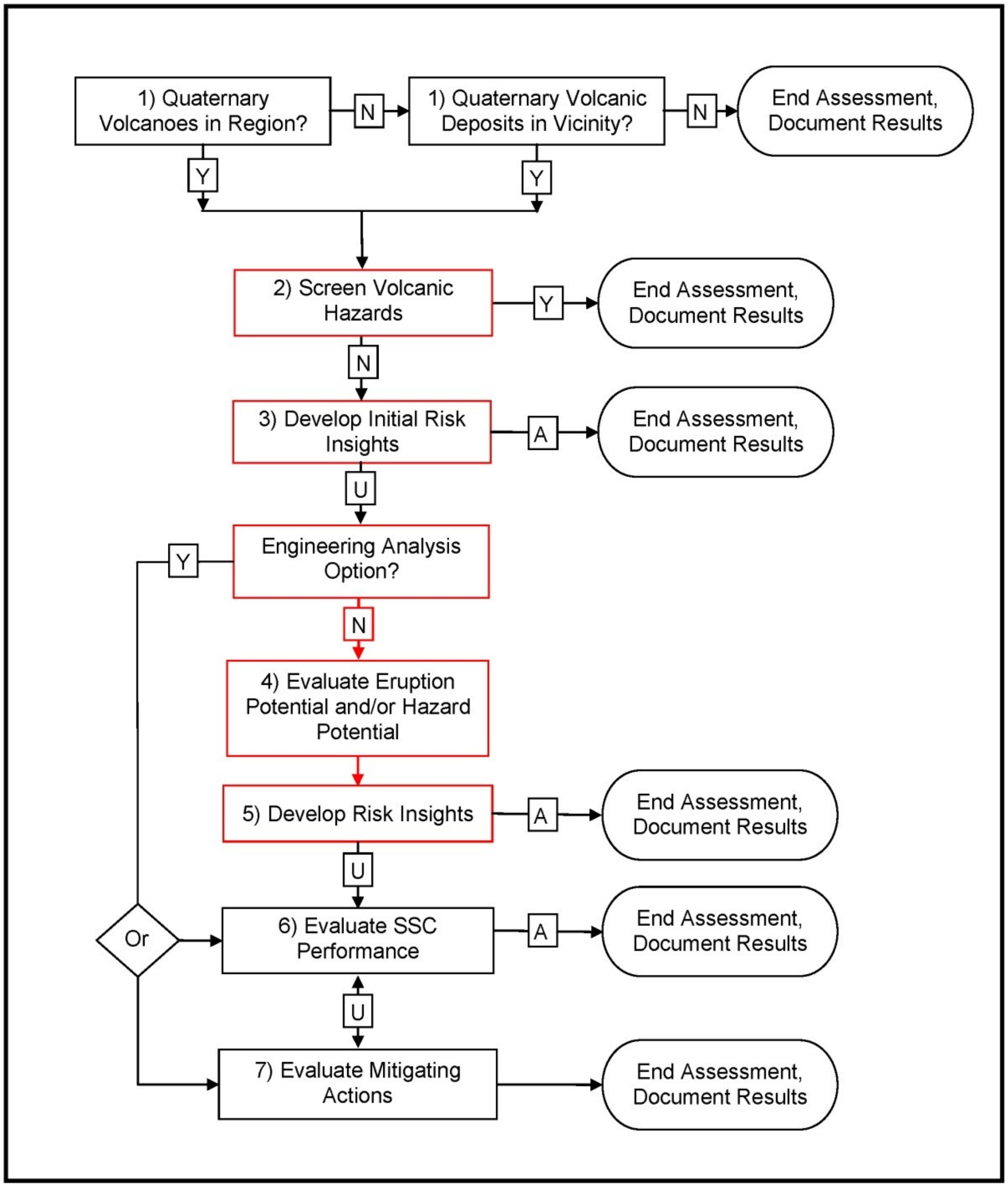

Figure 2. Flowchart for an acceptable volcanic hazards assessment using a traditional volcanic hazards analysis approach.

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

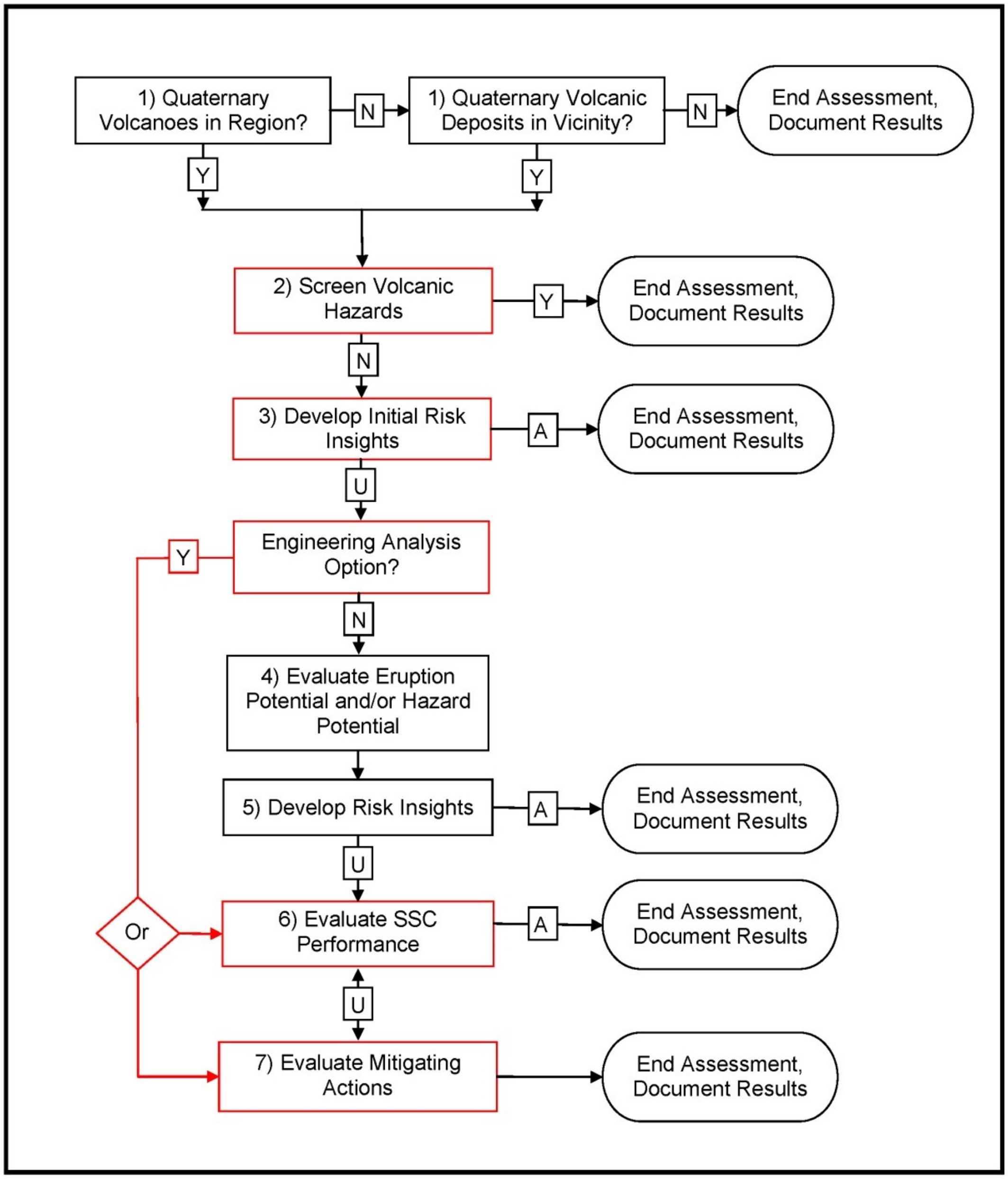

Figure 3. Flowchart for an acceptable volcanic hazards assessment using an alternative engineering analysis approach.

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

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 whether 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. If either PE or PH shows that potential volcanic hazards do not significantly affect safety, then additional analyses would not be warranted.

For example, this approach allows an applicant with a proposed site having only a potential hazard from volcanic ash fall to directly analyze the conditional hazard of ash fall exceeding certain design limits without first evaluating the probability of an ash fall eruption occurring. The applicant might decide that sufficient information on past ash fall eruptions exists (e.g., eruption volume, duration, grainsize characteristics) to calculate likelihoods of potential ash-deposit thicknesses at the site, without having to evaluate the likelihood of ash fall eruptions occurring in the future. The conditional ash fall hazard, typically expressed as an exceedance probability, could provide an appropriate technical basis for developing a proposed NPP's design-basis external hazard level or determining whether an existing design feature 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 should develop a suitable technical basis for determining 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 the history of a volcanic system should be supported by a technical basis providing confidence that the PE calculation considered an appropriate record of past activity in the volcanic system. Insights from the tectono-magmatic model often provide a technical rationale for determining what part of the history of the volcanic system is representative of expected future conditions.

Typically, PH is evaluated through numerical modeling of individual volcanic phenomena using a range of characteristics interpreted from past volcanic events. A modeling approach is used to account for 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 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, which present significant challenges for 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 numerical 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 in 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 risk insights in Step 5 show that either PE or PH might be significant, 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 risk insights in Step 5.

Step 5: Develop Risk Insights

In past practice, volcanic hazards have not warranted inclusion in nuclear PRAs due to the absence of these hazards at proposed sites. As discussed in NEI 18-04, many PRAs developed early in the licensing process include internal events but have not been expanded to include external hazards. The methodology identifies safety-related SSCs and design-basis accidents using the internal events PRA and design-basis external hazard levels (DBEHLs) that will determine the design-basis seismic events and other external events that the safety-related SSCs must withstand.

A similar approach can be applied to determine if a volcanic hazard has the potential to contribute to BDBE sequences (i.e., between 10^{-4} and $5x10^{-7}$/year likelihood). If volcanic hazards are not screened out in the assessments performed in accordance with ASME/ANS RA-S-1.4-2020 and thereby have the potential to contribute to BDBE sequences, applicants can consider additional SSC design evaluations in Step 6 or mitigation approaches in Step 7, if such measures are needed to address the potential risks posed by individual sequences or the cumulative risk metrics. As discussed in RG 1.233 (2020), "When supported by available methods, the PRA model is expected to address the full spectrum of internal events and external hazards that pose challenges to the capabilities of the plant, including external hazard levels exceeding the DBEHLs. The inclusion of external events within the BDBE category supports the overall risk-informed approach in NEI 18-04 and the Defense-In-Depth assessments described in subsequent sections."

Step 6: Evaluate SSC Performance

The NRC staff recognizes that NPP SSCs have existing designs that could 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 greater capacity to resist failure during BDBEs (e.g., Kennedy et al. 1988). Consequently, an evaluation of SSC capacity to withstand demands from a volcanic hazard might determine that SSCs could acceptably perform intended safety functions during volcanically initiated event sequences, even if these volcanic demands were not included in the original SSC design basis. This evaluation also might determine that modest modifications to existing SSC designs could provide the additional capacity needed for acceptable performance from potential volcanic hazards. ASME/ANS RA-S-1.4-2020 includes methods to assess plant and system fragilities to volcanic and other external hazards.

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 could 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 would likely need to consider the possibility that demands might plateau, and then rapidly increase, for the duration of an eruptive event.

If the preceding steps of the volcanic hazards assessment indicate that non-mitigated volcanic hazards have the potential to contribute to licensing basis events, the analysis could evaluate the potential for human actions to mitigate the adverse effects of the volcanic hazards. Additionally, the applicant can choose to conduct Step 7 directly after Step 3 and consider the ability to mitigate the maximum-magnitude volcanic hazard at the site. Mitigating 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.

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).

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

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

As an example, the Columbia plant developed practicable mitigation 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 actions that propose the construction of diversionary structures against surface flows should provide the following:

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

D. IMPLEMENTATION

The NRC staff will use the methods described in this regulatory guide 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 RG 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.

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[1] Publicly available NRC published documents are available electronically through the NRC Library on the NRC's public website 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. For problems with ADAMS, contact the Public Document Room staff at 301-415-4737 or (800) 397-4209, or email pdr.resource@nrc.gov. The NRC Public Document Room (PDR), where you may also examine and order copies of publicly available documents, is open by appointment. To make an appointment to visit the PDR, please send an email to PDR.Resource@nrc.gov or call 1-800-397-4209 or 301-415-4737, between 8 a.m. and 4 p.m. eastern time (ET), Monday through Friday, except Federal holidays.

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

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