Recommendations for Assessing Volcanic Hazards at Sites of Nuclear Installations

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5.1 INTRODUCTION

Volcanic events are, at best, a parenthesis in current regulations or guidance for determining site suitability and for licensing decisions for most nuclear installations. This condition is understandable, as volcanic eruptions are rare natural events that have not created a significantly adverse condition at an operating nuclear installation. Nevertheless, unlike most geologic hazards, generally acceptable methodologies have not been established to assess volcanic hazards at a site or to determine if future volcanic events could be withstood by an appropriately designed nuclear installation. To address some of these challenges, the International Atomic Energy Agency (IAEA) has commissioned a multinational panel of consultants to revise preliminary guidance for assessing volcanic hazards at sites for nuclear installations. This chapter represents a summary of the consultants' recommendations, which are being considered for adoption within an IAEA Safety Guide for volcanic hazards assessment.

The goal of this chapter is to formulate a systematic approach for evaluating volcanic hazards at any candidate site. The approach must be flexible enough to assess a broad range of complex, often interrelated volcanic phenomena, yet still provide a transparent methodology to support decision making. Two fundamental outcomes need to be supported by the volcanic hazards assessment. If the assessment determines volcanic hazards are credible external events at a site, the results of the assessment will need to provide sufficient technical detail to support development of design bases or operational criteria to mitigate the effects of potential future events on safety (*e.g.* IAEA, 2003a). However, if volcanic hazards appear beyond the design or operational limits of a potential installation, then the results of the hazards assessment will need to provide an appropriate technical basis for a site suitability decision.

Volcanic hazards arise from phenomena that have broad ranges, scales, and magnitudes of physical characteristics. These processes may occur in isolation, or in combination with other phenomena, even during a single volcanic eruption. Some of these phenomena can occur long before or long after an eruption. Thus, the term *volcanic event* is adopted in this chapter to indicate a set of potentially hazardous phenomena that may occur before, during, and after volcanic eruptions.

Both deterministic and probabilistic approaches currently are used to assess volcanic hazards, but with different degrees of formalism. Simply stated, deterministic methods use thresholds to screen specific phenomena from further consideration. Conversely, probabilistic methods use probability density functions to estimate the likelihood of specific volcanic phenomena. Although a deterministic approach may provide a transparent basis for decision making, screening criteria are often difficult to develop, and defend, because the geologic record often contains only poorly preserved examples of a limited number of past events. Accommodation of large uncertainties in the number and character of past events can drive a deterministic approach to use extreme events as the basis for decision making. Reliance on extreme events can result in the rejection of a potentially acceptable site, or require design bases that are not commensurate with safety. A probabilistic approach, however, can readily incorporate uncertainties that arise from an incomplete geologic record, account for an appropriate range of natural variability in volcanic phenomena, and consider uncertainties in scientific knowledge of processes that control volcanic phenomena. Probabilistic approaches also can result in quantitative assessments that allow for direct comparisons of hazard, or risk, between geologic events and other external events. Nevertheless, a probabilistic approach relies on numerical models that may be complex and sometime difficult to test, and can result in a more complex basis for decision making. Neither approach currently presents a clear advantage over the other in assessing volcanic hazards at sites for nuclear installations. Thus, either, or both, of these approaches appear suitable for consideration in a volcanic hazard assessment.

5.2 Principles of Volcanic Hazard Assessment

5.2.1 Nature of Volcanic Hazards

Volcanic events are infrequent, relative to most other natural events that can affect the performance of nuclear installations. Some volcanoes have erupted after lying dormant for thousands of years, or even longer. As a general guide, volcanoes that have erupted during the last 10,000 years (*i.e.* the Holocene) are usually considered active (*e.g.* Simkin and Siebert, 1994). Around the world, there are more than 1500 volcanoes that can be considered active on this basis. Holocene volcanoes may experience eruptions after long periods of inactivity. However, some volcanoes have reactivated after periods of inactivity longer than 10,000 years. Therefore, consideration of volcanic hazards should not be limited only to Holocene volcanoes.

Within a geographic region, volcanic activity can persist for longer time scales than associated with individual volcanoes. For example, many volcanic arcs exhibit recurring volcanic activity for longer than 10 Myr, although individual volcanoes within the arc itself may remain active only for around 1 Myr. Because such distributed activity can persist for many millions of years, volcanic regions that have had activity during the past 10 Myr should be considered to have at least the potential for future activity.

Episodes of eruptive activity at individual volcanoes can last from hours to decades, and in rare cases for even longer periods of time. The intensity of volcanic eruptions can vary from low energy events, which may produce small lava flows and limited-range ballistic projectiles, to high energy events that bury the countryside in tens of meters of hot ash. Even volcanoes located hundreds of kilometers from a site can produce hazardous phenomena such as tephra fallout or tsunamis, which may adversely affect the performance of a nuclear installation. A summary of volcanic phenomena and primary hazards associated with these phenomena is presented in Table 5.2. Additional information on the physical characteristics of these potentially hazardous phenomena is presented in, for example, Connor *et al.* (Chapter 2, this volume).

Volcanic events rarely produce just a single hazardous phenomenon. Eruptions usually initiate a complex sequence of events that produce a wide range of volcanic phenomena. The occurrence of some volcanic phenomena may change the likelihood of occurrence for other phenomena. A volcanic hazard assessment should use a systematic methodology to evaluate credible, interrelated phenomena and ensure that all relevant hazards are integrated into the analysis.

Non-eruptive phenomena at volcanoes also can produce hazards for nuclear installations. Volcanoes are often unstable landforms. Even after long periods of repose, portions of volcanoes may suddenly collapse to form landslides and debris flows. Such events can impact areas of thousands of square kilometers around the volcano. Some volcanoes are closely linked to tectonic faults or geothermal activity. In such instances, seismic activity related to fault movement also may cause collapse of the volcano edifice. Volcanic hazard assessments for a nuclear installation should consider the influence of hydrologic and tectonic processes on the likelihood and characteristics of future volcanic events.

5.2.2. Database Requirements

The cogency and robustness of any volcanic hazards assessment are dependent on a sound understanding of the (i) character of each individual volcanic source within the appropriate geographic region; (ii) wider volcanological, geological and tectonic context of such volcanic sources; and (iii) types and magnitudes of volcanic phenomena potentially produced by each of these sources. To achieve an appropriate level of transparency in the assessment, detailed information for each of the volcanic sources and their context in the region should be established or acquired, and compiled in a database.

The database should incorporate all the information that is needed to support decisions at each stage of the volcanic hazard assessment. The database structure should be flexible enough to accommodate increasing levels of information, completeness and integration as the assessment progresses through advancing stages of complexity. Initially, the database may be based upon, or include, information from existing international and national compilations of volcanological data. As site characterization progresses, additional data collected specifically for the assessment should be incorporated into the database.

Partitioning the data collection requirements by distance from the site (*e.g.* IAEA, 2002a) is not necessarily the most effective way to approach a volcanic hazards assessment. This is because volcanic hazards, although they are associated often with a single, easily identified point source, can (i) occur as a range of phenomena with widely varying magnitudes and intensities that are less attenuated with distance than, for example, earthquake effects; and (ii) affect widely varying areas, depending on their individual characteristics as well as local variations in topography and the meteorological conditions in the region.

In addition to serving as an information resource, the database should also provide a structure that documents the treatment of data during the volcanic hazard assessment. This structure will serve to record the evidence and interpretations on which scientific decisions are made, as well as providing a basis for data quality assurance. For instance, all data used to formulate screening criteria and their consequent decisions should be contained in the database. Data considered in the assessment but rejected or otherwise not used should also be retained in the database and identified as such. Additional guidance on database goals and considerations are given in Section 5.3.

5.2.3 Geologic Record and Data Uncertainty

The representative characteristics and frequencies of past events are critical data for any volcanic hazards assessment. The geologic record, however, usually is an incomplete source of these data. Large magnitude volcanic events are much more likely to be preserved in the geologic record than small events. Yet such unrecorded small events may represent credible hazards to nuclear installations. Events missing from the geologic record, and interpretation of this record, create uncertainties that should be included in the hazard assessment.

The geologic record of an individual volcano does not necessarily encompass the potential characteristics and extent of future activity. Hazard assessments should consider that volcanic systems evolve, and that the characteristics of their hazards may change over time, sometimes quite rapidly. Information from analogous volcanoes can help constrain or reduce uncertainties arising from interpretations of an incomplete geologic record, and to further characterize potential changes in volcanic hazards through time.

The frequency and timing of past events is incompletely understood and relatively uncertain at most volcanoes. For example, ages of the most recent volcanic eruptions can be difficult to determine at volcanoes lacking a record of historical activity. Criteria to decide whether a volcano is dormant or extinct often are subjective, and difficult to defend.

At most volcanoes, there is less uncertainty about the physical characteristic of past events than there is about the ages of these events. Thus, a volcanic hazard assessment that focuses on determining the geological characteristics of volcanic phenomena and their spatial extent will usually be less uncertain than one focusing on estimating the likelihood of occurrence for hazardous phenomena. Consequently, we develop an approach that emphasizes the initial screening of volcanic hazards based on their physical characteristics, rather than on their exact likelihood of occurrence. The concept of a *capable volcano* is introduced to define the potential for a volcano or volcanic field to produce hazardous phenomena that may affect a site. A *capable volcano* or volcanic field is one for which both (i) a future eruption or related volcanic event is credible; and (ii) such an event has the potential to produce phenomena that may affect a site. This definition is modified from McBirney and Godoy (2003) to more fully reflect the site-specific character of hazard investigations for nuclear installations. Identification of one or more *capable volcanoes* should result in development of a detailed, site-specific volcanic hazard assessment. The detailed hazard assessment, if warranted should then consider the likelihood of occurrence and associated uncertainties for volcanic phenomena that may reach a site.

5.3 Volcanic Hazards Assessment Methodology

A successful outcome of a volcanic hazards assessment is a transparent and traceable basis for making decisions about site suitability or facility design. A graded approach for information is warranted. Indeed, a graded approach for data analysis will allow the assessment to focus on volcanic phenomena that represent credible hazards to a site, rather than require an equivalent level of investigation and support for all possible types of hazards. The assessment approach advocated herein recognizes the need for increasing levels of information for increasing levels of potential hazard at the site. This approach also recognizes that sites located far from potentially active volcanoes may need to consider only a limited subset of potential hazards (*i.e.* distant tephra falls, volcanogenic tsunamis), whereas sites located closer to potentially active volcanoes may need to consider the full range of potential hazards.

During the initial stage of the site selection and evaluation process, relevant data should be collected from available sources (*e.g.* publications, technical reports, and related material) in order to identify volcanic phenomena with the potential for hazardous effects at the site. At each stage of the assessment, a determination should be made whether sufficient information is available to adequately evaluate the issue of volcanic hazards at the site. In some cases, available information could be sufficient to screen specific volcanic phenomena from further consideration. In other cases, additional information should be acquired in order to estimate volcanic hazards and determine site suitability, including consideration of volcanic hazards as design basis events (*e.g.* design for tephra loading).

The general goal for the volcanic hazards assessment is to determine the capability of a volcano or volcanic field to produce potentially hazardous phenomena that may reach the site of the nuclear installation, culminating in a comprehensive volcanic hazard model for the site, if deemed necessary. This goal can be accomplished in four stages, which are outlined in Figure 5.1 and presented in the remainder of this section.

5.3.1 Stage 1: Initial Scoping of Past Volcanism in a Region

5.3.1.1 Approach

Stage 1 of the assessment focuses on two primary considerations: (1) definition of an appropriate geographic region for the initial scoping of volcanic hazards; and (2) collection of evidence of volcanic activity occurring within the last 10 Myr. Stage 1 includes a detailed review of available information sources for an appropriate geographic region around the site. This detailed review would typically include geologic maps, results from previous geologic investigations, and other information.

The geographic region for the assessment does not have predetermined, symmetrical dimensions, but should consider the types of potentially hazardous phenomena that may have occurred at volcanoes younger than 10 Myr. For tephra-fall and other atmospheric hazards related to volcanoes, this region can extend for hundreds of kilometers from the site, giving due consideration to regional wind-field patterns (*e.g.* Hoblitt *et al.*, 1987). Assessment of volcanogenic tsunamis may need to consider an entire ocean basin for some coastal sites. Other volcanic phenomena likely extend for shorter distances around a volcano. The region considered for such potential hazards might only extend for tens of kilometers away from the site.

For surface-flow phenomena, consideration should be given to the topography between the site and potential volcanic sources. Areas with low elevation topography or broad, shallow drainages may be ineffective in diverting high-energy surface flows, even from volcanoes located more than 100 km from the site. Conversely, areas with steep topography and deep drainages may effectively capture and divert high-energy surface flows from volcanoes located much closer to the site. The definition of the appropriate region should be justified, to ensure that potentially hazardous volcanoes have been duly considered in the assessment.

Initial scoping studies should evaluate the evidence of volcanic activity occurring within the last 10 Myr. Because regions of volcanic activity can persist for millions of years or longer, a period of 10 Myr encompasses the geologic processes that could possibly affect an understanding of the potential for future volcanic activity within a region. Furthermore, a simplistic estimate of a regional volcanic recurrence rate of less than 1 event in 10 Myr would imply a probability of future activity less than 10^{-7} per year, which is a commonly used screening probability level for external events in hazard analyses for nuclear installations (*e.g.* IAEA, 2002b).

5.3.1.2 Data Requirements

A hierarchy of geological maps and volcanological data is needed for initial scoping in Stage 1. Available geological maps may be adequate if they provide appropriate data at various scales. For example, a 1:500,000 scale map may serve for the full area of study, moving down to 1:50,000 for nearby detailing. Geologic maps of volcanoes at a scale of 1:50,000 or larger will normally be required for initial scoping. Relevant information likely includes international and national compilations of volcanological data, especially for Holocene and Quaternary volcanoes.

Volcanism should be characterized in terms of the types of volcanoes concerned (*cf.* Connor *et al.*, this volume). In Stage 1, past volcanic activity should be considered in terms of age, overall spatio-temporal trends, morphology, eruptive products and associated range of eruptive behaviors, and tectonic setting. At some sites, offshore data, such as bathymetry or drill core logs or descriptions, may be important to consider in identification of potential volcanic sources during initial scoping. This characterization provides the groundwork for determination of the appropriate geographic region for the volcanic hazard assessment.

Age determinations are fundamental information for the initial scoping assessment. Such age determinations may include historical information, stratigraphic relationships, radiometric dating and morphological considerations. The level of information should be critically assessed for assurance that all relevant volcanic sources have been identified and have age determinations of suitable quality. If reliable age determinations are available they may provide an adequate basis for initial scoping.

For some cases, however, available information for initial scoping may not be sufficient for a robust appraisal at this stage of a site evaluation. In these circumstances, additional geological and volcanological data may need to be sought out, collected or commissioned. For instance, further age determination sampling may be needed in order to ascertain the age of volcanic products in the geographic region.

5.3.2 Stage 2: Characterize Sources of Volcanic Activity

5.3.2.1 Approach

If the outcome of the initial scoping in Stage 1 indicates that volcanoes or volcanic fields younger than 10 Myr are present in the selected geographic region, then these volcanic sources should be further characterized by additional investigations. If there is evidence of current or historical volcanic activity, then future eruptions should be assumed credible and the hazard assessment should proceed to Stage 3. Evidence of current or historical volcanic activity includes: records of volcanic eruptions, ongoing volcanic unrest, an active hydrothermal system (*e.g.* presence of fumaroles), and related phenomena.

Evidence of an eruption during the last 10,000 yr (*i.e.* the Holocene) is a widely accepted indicator (*e.g.* Simkin and Siebert, 1994) that future eruptions are credible. Information for determining if Holocene volcanic activity has occurred may come from multiple sources. Radiometric dating of volcanic products, however, provides the most direct evidence that volcanic eruptions occurred within the Holocene.

In some circumstances, especially in the early stages of site investigations, the exact age of the most recent products may be difficult to determine. In such circumstances additional criteria may be used to consider a volcano as Holocene, including: (i) volcanic products overlying latest Pleistocene glacial debris; (ii) youthful volcanic landforms in areas where erosion should have been pronounced after many thousands of years; and (iii) vegetation patterns that would have been far more developed if the volcanic substrates were more than a few thousand or hundred years old.

Nevertheless, reliable sources may disagree over the evidence of Holocene volcanism, or there may be significant uncertainty about the most reliable age estimate of the most recent eruption. In this case, such volcanoes could reasonably be classified as Holocene(?), which is consistent with established volcanological terminology (Simkin and Siebert, 1994). From a safety perspective, future eruptions could be considered credible for Holocene(?) volcanoes and the analysis should proceed to Stage 3.

If evidence of current or Holocene activity does not exist, additional consideration should be given to assess the timing of older activity in the region. Evidence of an eruption during the last 2 Myr generally indicates future activity remains possible. Furthermore, for some volcanic systems such as distributed volcanic fields or infrequently active calderas, activity during the last 5 Myr or so also may indicate some potential for future activity. To ensure an adequate evaluation, the geologic data should be assessed to determine if any of the volcanoes or volcanic fields in the region as old as 10 Myr has the potential for a future eruption.

A probabilistic analysis of the potential for future volcanic events can provide useful information for this stage of the analysis. Probabilistic methods for this assessment can include frequentist approaches based on the recurrence of past volcanic eruptions, Bayesian methods that can incorporate additional volcanological information, or process-level models, such as those based on time-volume relationships. Expert elicitation might be used to help inform an assessment of the probability of future activity (*e.g.* U.S. Nuclear Regulatory Commission, 1996; Aspinall, 2006).

In some countries, a value for the probability of 10^{-7} per reactor-year is used in the design of new facilities as one acceptable limit on the probability value for interacting events having serious radiological consequences (IAEA, 2002b). As volcanism is an external hazard with potentially adverse consequences for safe facility operation, an annual probability of renewed volcanism at or below 10^{-7} per year could be considered a criterion for screening future events in the absence of additional information regarding potential volcanic hazards at a site.

Alternatively, a deterministic approach can be used. For example, analogous volcanoes might be investigated to determine the maximum duration of gaps in eruptive activity. For a volcano with an ongoing period of quiescence, the possibility of return to activity could be compared with the maximum duration of such gaps in activity at analogous volcanoes. An additional deterministic approach might invoke time-volume or petrologic trends in the volcanic system. For example, a time-volume relationship may show an obvious waning trend and demonstrable cessation of volcanic activity in the early Pleistocene or older periods. In this situation, renewed volcanism can be considered unlikely. In cases where a resolution based on these other criteria is not achieved, a deterministic approach could simply assume that future eruptions are possible for any volcano younger than 10 Myr.

The analyses in Stage 2 may determine that future volcanic activity in the geographic region is considered not possible. If sufficient information is available to support this conclusion, no further analysis is required and volcanic hazards do not need further investigation for this site. Conversely, in the absence of sufficient evidence, or if future volcanic events in the region of interest appear to be credible, additional analyses are warranted and the hazard assessment should proceed to Stage 3.

5.3.2.2 Data Requirements

An expanded scope and level of detail is required in the information needed for source characterization, hazards screening, and a site-specific assessment (*i.e.* Stages 2–4). Decisions resulting from Stages 2–4 of the hazard assessment rely on information about the timing and magnitude of activity at potential volcanic sources. Therefore, the database should document the (i) spatial distribution of volcanic sources and geologic controls on the distribution of these volcanic sources; (ii) number and timing of eruptions at each source; (iii) repose intervals between eruptions, and durations of eruptive episodes at each source, where it is possible to determine; (iv) range of eruption magnitudes, dynamic processes such as eruption intensity and style, eruptive products, and associated phenomena such as seismicity, ground deformation and hydrothermal activity; and (v) information about trends in eruptive activity, such as spatial migration of volcanic sources or temporal evolution of geochemical variations, and changes in the volume of eruption products.

For volcanic sources with any documented historical activity, the database should contain information relevant to an understanding of the scale and timing of this activity. Possible volcanological information taken from historical sources could include (i) dates and durations of eruptions; (ii) description of the types of eruptive products, including areal extent, mass and composition; (iii) areal extent and magnitude of associated seismic activity, ground deformation, and other geophysical and hydrological activity or anomalies; and (iv) description of current activity at the volcano including monitoring programs and review of monitored data, if any.

The database would likely include descriptions of any volcanic products younger than 10 Myr. For Holocene and younger volcanoes, including those that are currently active, the geologic history of the volcano should be investigated, not only the period of most recent volcanic activity. An evaluation of the uncertainty in age determinations should be included in this assessment. For example, the stratigraphy of pyroclastic units is often complex and incomplete. Assessment of the completeness of the geologic record should be attempted, even if all volcanic deposits cannot be mapped. The ages of volcanic deposits should be numerically expressed and correlated to provide a complete description of the history of volcanic activity.

Information in the database will form the substantive basis on which to assess the potential for specific phenomena to affect the site, and will be used to develop screening distance values for these phenomena (*i.e*. Stage 3). Therefore, data should be compiled on volcanic products that could reach the site from each potential source. Deposits younger than 10 Myr in the site vicinity should be identified and evaluated to provide information on the (i) type and distribution of the deposits, and identification of the likely source or sources; (ii) ages and volcanological characteristics of the associated eruptions; and (iii) chemical and lithological compositions and physical properties, including areal extents, thicknesses, densities, and particle size distribution.

The viability and usefulness of this type of information is highly dependent on the age of the deposits and completeness of the geologic record. Wherever possible, an appropriate range of volcanological information should be collected, in order to characterize individual phenomena and to evaluate long-term trends in the volcanic system. Care should be taken to appropriately characterize deposits that credibly might reach the site in the future. For example, a tephra fall from a nearby volcano that did not deposit at the site itself, perhaps only because of meteorological conditions during the eruption, also should be included in the database if future meteorological conditions could potentially direct tephra falls toward the site. Conversely, a pyroclastic flow deposit that was diverted from the site by a large topographic barrier should not be included, if that barrier is likely to exist during future eruptions and if larger or more energetic flows are not expected from future eruptions.

Geophysical and geochemical survey data collected at individual volcanoes within the region of interest can improve the overall hazard assessment. There are several reasons to survey such volcanoes: (i) to help reduce the level of uncertainty in the understanding of particular volcanic phenomena; (ii) to provide an objective basis for detecting changes in the level of activity of the volcano and prospects for future eruptive phenomena; (iii) to take advantage of new emerging or improved technologies or techniques to strengthen information about a specific volcano; and (iv) for *capable volcanoes*, to comply with safety requirements for dedicated monitoring (*e.g.* IAEA, 2003a). Conversely, there may be certain *capable volcanoes* within the geographic region around the site where surveys will not enhance a site-specific hazard assessment, depending on the nature of the volcanic phenomena concerned.

The type and extent of geophysical and geochemical surveys should be evaluated based on information needs for the volcanic hazards assessment. In the case of a new site evaluation, surveys should be considered at the earliest stages of the site characterization process. Survey data should be interpreted and integrated with other data that contributes to the site evaluation process, and included in the database. Close co-operation with existing monitoring systems, such as those implemented by national programs for prediction of volcanic eruptions and mitigation of disasters, should be sought. Exchange of observational data and consultation with experts in volcanology working in such programs is generally beneficial.

5.3.3 Stage 3: Screening Volcanic Hazards

In cases where future volcanic activity appears possible in the appropriate region around a site, the potential for hazardous phenomena to affect the site should be analyzed. This analysis should be performed for each of the phenomena associated with volcanic activity (*e.g.* tephra fallout, pyroclastic flows, lahars). In some cases, specific hazardous phenomena may be screened from further consideration, if there is negligible likelihood of these phenomena reaching the site. Screening decisions also should consider whether such phenomena might result from secondary processes or a complex scenario of volcanic events.

A deterministic approach to assessing hazards at Stage 3 can be based on establishing screening distance values for specific phenomena. Screening distance values can be defined in terms of the maximum known extent of a particular eruptive product, considering the characteristics of the source volcano and possibly the nature of topographic controls between the source volcano and the site. For example, most basaltic lava flows are known to travel no more than 10–100 km from source vents. A generic screening distance value of 100 km for basaltic lava flows appears justified for most basaltic volcanoes in most terrains. A shorter screening value distance may be justified, however, based on data gathered at analogous volcanoes or where topography prevents the phenomenon from reaching the site. In general, justification for the use of specific screening distance values for all types of volcanic phenomena should be consistent with representative examples from analogous volcanoes.

If the site falls outside the screening distance for a specific volcanic phenomenon, then no further analysis is needed for that phenomenon. Alternatively, if future volcanic activity appears possible and the site falls within the screening distance for a specific volcanic phenomenon, then the volcano or volcanic field should be considered *capable* and a comprehensive hazard assessment should be undertaken (*i.e.* Stage 4). An analysis for capability should be completed for each volcanic phenomenon that is associated with each potential source volcano, as each of these phenomena may have a different screening distance values.

An alternative approach to assessing hazards at Stage 3 is to estimate the conditional probability of a specific volcanic phenomenon reaching the site, given an eruption at the source volcano. Multiple methods are available to estimate this probability. These methods are considered further in the discussion on Stage 4. In most circumstances, site characterization data alone likely will be insufficient to determine a robust estimate of this probability, because the geologic record incompletely preserves past activity from volcanoes and because past activity may not have encompassed the appropriate range of phenomena potentially resulting from a future volcanic event.

Using a conditional probability estimate for a specific volcanic phenomenon with accompanying uncertainties can produce a range of likelihood values that can be used in the site assessment. If the potential for a volcanic event to produce any phenomenon that may reach the site is negligibly low, no further analysis is required and volcanic hazards do not represent credible design basis events for this site. If this potential is sufficiently high, the volcano or volcanic field concerned should be considered *capable* and a comprehensive site-specific volcanic hazard analysis should be undertaken (Stage 4).

Complications often arise in the use of both deterministic and probabilistic approaches to screening hazards because some volcanic phenomena may involve coupled processes. For example, tephra fallout on distant topographic slopes sometimes creates new source regions for debris flows and lahars. Water impoundments can be created by debris flows and lava flows. Screening decisions should consider secondary sources of hazards that result from such complexities.

5.3.4 Stage 4: Site-Specific Volcanic Hazards Assessment

Stage 4 seeks to provide a clear technical basis for evaluating site-specific volcanic hazards when considering nuclear installation site selection and design. If one or more *capable volcanoes* are identified, a site-specific volcanic hazard assessment for the nuclear installation should be conducted. Specific outcomes of this hazard assessment should provide sufficient information to determine whether each volcanic hazard is a credible external event. If an event is credible, then the hazard assessment also should provide sufficient information to determine if a design basis or other practicable solution for this event can be established. If a design basis or other practicable solution for this credible external event cannot be resolved, the site will likely be considered unsuitable (*e.g.* IAEA, 2003a).

A combination of deterministic and probabilistic approaches can be used to decide whether or not an acceptability issue exists for the site due to volcanic hazard. Each hazard that is included in the design basis should be associated with a quantified parameter or set of parameters so that its value can be compared with the design basis values of other external events to the extent possible. For some of the hazards it may be possible to demonstrate that design basis parameters derived for other external events envelope those derived for volcanic hazards. Recommendations are provided in this section for volcanic phenomena that should be considered as part of a site-specific volcanic hazard assessment. Relevant volcanological information that should be considered for each of these phenomena is discussed in Connor *et al.* (Chapter 2, this volume).

5.3.4.1 Tephra Fallout

Tephra fallout is the most widespread hazardous phenomena from volcanoes, including the opening of new vents. Hazards associated with tephra fallout include static load on structures, particle impact, potential blockage and abrasion of water circulation systems, mechanical and chemical effects on ventilation and electrical systems, and particle load in the atmosphere. Water can significantly increase the static load of a tephra deposit. Tephra fallout hazard assessments should consider (i) potential sources of tephra; (ii) magnitudes of potential tephra producing volcanic eruptions and the physical characteristics of these eruptions; (iii) frequency of tephra producing eruptions; (iv) meteorological conditions between source regions and the site that will affect tephra transport and deposition; and (v) secondary effects of tephra eruptions.

A deterministic approach should consider the maximum credible thickness for tephra fallout deposits at the site. For example, actual deposits from analogous volcanoes could define the maximal thickness of accumulation at the site from a *capable volcano*. Particle-size characteristics (*e.g.* size distribution and maximum size) could be estimated from these deposits. Analogue deposits or eruptions can also provide information about soluble ions that form corrosive, acidic condensates, which often accompany tephra falls.

A probabilistic approach should use a numerical simulation of tephra fallout at the site. In such an analysis, Monte Carlo simulation of tephra fallout from each *capable volcano* should be conducted, accounting for variation in eruption volume, eruption column height, total grain-size distribution, wind velocity distribution in the region as a function of altitude, and related parameters. Such models produce a frequency distribution of tephra accumulation, commonly presented as a hazard probability of exceedance curve (Hill *et al.*, 1998; Connor *et al.*, 2001; Bonadonna *et al.*, 2005 and Volentik *et al.*, this volume). The uncertainty in the resulting hazard curve can be expressed by confidence bounds, with a stated basis for selection of the reported confidence levels.

To support the potential development of design bases, results of deterministic or probabilistic assessments of tephra fallout for each *capable volcano* should be expressed in terms of parameters, such as mass accumulation, accumulation rate, and grain-size distribution. In order to estimate potential static loads, the contribution for each *capable volcano* should be integrated into a single, site-specific maximum credible value or single tephra fallout hazard curve (Hobblit *et al.*, 1987; Volentik *et al.*, this volume). This information may be also used to assess particle size distribution and potential for remobilization of tephra deposits to create atmospheric mass loads of particles or debris flows and lahars.

5.3.4.2 Pyroclastic Flows, Surges, and Blasts

Pyroclastic flows, surges, and blasts, known collectively as pyroclastic density currents, accompany both explosive volcanic eruptions and effusive volcanic eruptions that generally form lava domes or thick lava flows. Impacts of pyroclastic density currents are severe for obstacles in their flow paths, because these flows move at high velocities and commonly have high temperatures (*e.g.* more than 300 °C). In addition, these flows are destructive due to the momentum of the massive ground-hugging mixture of hot lava blocks, ash and volcanic gas, and due to their transport of projectiles. Although their main flowage is controlled topographically, surges and blasts are less constrained by topography than pyroclastic flows. All types of pyroclastic density currents are known to surmount topographic obstacles in certain circumstances or to flow across bodies of water.

A deterministic approach should consider the volume and energy of the pyroclastic flow or surge resulting from an eruption and hence its potential maximum travel distance (*i.e.* run out). Screening distance for these phenomena could be determined based on the volume and nature of pyroclastic flow or surge deposits exposed within the geographic region of concern, or by referring to flow events identified at analogous volcanoes. Potential run-out also can be estimated using physics-based numerical models. Pyroclastic surges are generated directly from the vent by a fountain-like collapse of the eruption column, by blast, or from collapse of large domes, and may travel more than 10 km from the vent. Surges or blasts associated with pyroclastic flows may extend several kilometers more beyond the pyroclastic flow front. Thus, a deterministic approach for a pyroclastic surge or blast will be based on a screening distance value generally greater than that for pyroclastic flows.

Probability of pyroclastic flows could be calculated as a conditional probability of an eruption of given intensity, multiplied by conditional probability distributions for (i) the occurrences of flow and surge; (ii) run-outs of these phenomena; and (iii) directivity effects. The value for conditional probability of pyroclastic surge should be representative of the magma's physical properties, the geometry and structure of the volcano, the dynamics of the eruption, and the physics of flow spreading and diffusion. The uncertainty in the resulting probability level can be expressed by confidence bounds, with a stated basis for selection of the reported confidence levels.

Several additional factors should be considered in deriving design basis and in making site acceptability judgments related to hazards from pyroclastic density currents. Hazards related to most pyroclastic density currents can be evaluated empirically and approximately by using the energy cone model (Sheridan, 1979; Malin and Sheridan, 1982) to estimate potential run-out distances. However, more sophisticated numerical models (*e.g.* Wadge *et al.*, 1998; Woods, 2000; Patra *et al*., 2005; Neri *et al*., 2007) coupled with Monte Carlo simulations can generate probabilistic assessments of run-out and destructive effects. Although this is an area of intense research in volcanology, comprehensive dynamic models of pyroclastic flows, surges, and blasts are not yet fully established. Consequently, both deterministic and probabilistic approaches should be considered. Results of analyses of pyroclastic flow, surge, and blast impacts may be presented, for example, in terms of dynamic pressure, temperature, and velocity. Some pyroclastic density currents can give rise to secondary hazards, such as tephra fallout, debris flows, and tsunamis.

5.3.4.3 Lava Flows

Lava flows essentially cause total destruction on their path. The impact of lava flows will depend on the physical characteristics of the lava, the discharge rate, the duration of the eruption, the morphology at the vent and the topography. Lava flows have direct impacts due to their dynamic and static loads, flow thickness, and temperature up to approximately 1200 °C. In order to evaluate hazards associated with lava flows for each *capable volcano*, estimates are needed for (i) potential magnitude (*e.g.* mass discharge rate, areal extent, velocity, thickness) of lava flows; (ii) frequency of future effusive volcanic eruptions; (iii) eruptive scenario, such as individual lava flows, lava tubes, and flow fields; and (iv) physical properties of erupted lava.

A deterministic assessment should first address the locations of vents and the potential formation of new volcanic vents. Subsequently, assessment for potential lava flow inundation should determine the maximum credible length, areal extent, thickness, temperature and potential speed of lava flows that could reach the site. This assessment can be achieved using data from other volcanoes from the region of concern, from analogue volcanoes, or from empirical lava flow emplacement models. Topography along the path and at the site should be considered. A screening distance value can thus be defined for lava flows beyond which lava incursion is not thought to be a credible event.

A probabilistic approach also should address plausible variations for vent locations, and the potential formation of new volcanic vents. The probabilistic approach likely would entail numerical modeling of lava flows and proceed with numerical simulations from each *capable volcano* to account for a range of values for parameters that control flow length and thickness, using stochastic methods. Lava flow hazard curves could then be determined and combined to express the probability of exceedance of lava flow incursion and thickness at the site. Uncertainty in the resulting hazard curves can be expressed by confidence bounds, with a stated basis for selection of the reported confidence levels.

There are empirical correlations between flow length and effusion rate for many lavas (Walker, 1973), whereas others are volume-limited (Malin, 1980). Assessment of the potential for lava flow inundation usually involves numerical models of maximum lava flow length, area of inundation, speed, and thickness of the flows (Barca *et al.,* 1994; Miyamoto and Sasaki, 1997; Vicari *et al.*, 2007). In these numerical simulations, topography, discharge rate, viscosity of the flow, and duration of the eruption are key parameters that control modeled lava flow emplacement. Probabilistic assessments use numerical models of lava flows emplacement coupled with Monte Carlo simulations. Probabilistic or deterministic approaches should result in estimates of the potential for any lava flows to reach the site, their likely thicknesses, as well as their thermal properties. This assessment would likely include the effects of phenomena associated with lava flows such as tephra fall, generation of floods following interaction with ice and snow fields, water impoundments, and generation of pyroclastic flows from the collapse of viscous lava domes and flows.

5.3.4.4 Debris Avalanches, Landslides and Slope Failures

Debris avalanches resulting from edifice collapse should be considered separately from other slope failures because of the potentially large volumes involved (*e.g.* up to several km^3), high velocities, and the considerable distances that can be reached (*e.g.* 150 km). Other, smaller-scale slope failures can be treated within the scope of non-volcanic geotechnical hazards (*e.g*. IAEA, 2004). The effects of volcanic debris avalanches are predominantly mechanical due to the mass of material involved and associated high velocities. A hazard assessment for debris avalanches, landslides, and slope failures for each *capable volcano* should consider (i) potential source regions of these events; (ii) potential magnitude (volume, aerial extent, thickness) of these events; (iii) frequency of such events; and (iv) their potential flow paths. These assessments should identify potential source regions and areas of potential instability. Modifications of the flow properties along the path, as well as the topography from the source region to the site, also should be considered.

A deterministic approach should determine the maximum credible run-out distance and thickness of avalanche deposits at the site using information collected from actual deposits from analogous volcanoes, and empirical avalanche flow emplacement models. A screening distance value can thus be defined for debris avalanches and other associated mass flows beyond which they are not credible events.

A probabilistic approach should extend the numerical modeling of these flows and proceed with numerical simulations for each *capable volcano* accounting for a range of values for parameters that control flow length, velocity, and thickness using stochastic methods. Hazard curves should then be determined and combined to express the probability of incursion at the site. Uncertainty in the resulting hazard curves can be expressed by confidence bounds, with a stated basis for selection of the reported confidence levels.

Several additional factors should be considered in deriving design basis and in making site acceptability judgments related to debris avalanches, landslides, and slope failures. The results of probabilistic or deterministic approaches should include parameter estimates of potential for incursion of the site, as well as flow thickness and velocity. This assessment likely would consider the other indirect phenomena associated with debris avalanches, landslides, and slope failures such tephra fall, projectiles, pressure waves, debris flows, floods, and tsunamis. Large slope failures are potential non-eruptive volcanic events, and may be triggered by rainfall or tectonic earthquakes.

5.3.4.5 Volcanic Debris Flows, Lahars and Floods

Debris flows, lahars, and floods of volcanic origin should be considered separately from other ordinary floods (*e.g.* IAEA, 2003b) mainly because of the short warning time available after the onset of the flow, high flow velocities and discharge rates, high flow volumes, and the considerable distances that can be reached (*e.g.* 150 km from the source). Their impact is mechanical due to the mass and velocity of material involved, erosive power, and other effects related to flooding by water with a high sediment load. Modifications of the flow properties along the path, the sources of water, and topography from the source region to the site should be considered. The hazard assessment for debris flows should also consider the fact that potentially adverse effects can persist over a time period that greatly exceeds the duration of an eruption. A hazard assessment for lahars, debris flows and floods of volcanic origin for each *capable volcano* should (i) identify regions of potential source for volcanic debris and for water; (ii) estimate the potential magnitude and flow characteristics; (iii) determine the frequency of such events in the past; and (iv) acquire meteorological data at the source region and along the potential path of such potential flows.

A deterministic approach should consider the maximum credible distance for debris flows and lahar deposits at the site using information from *capable* and analogous volcanoes, and empirical debris flow emplacement models. A screening distance value should be defined for debris flows, lahars, and other associated floods beyond which they are not credible events.

A probabilistic approach could use numerical modeling of these flows (*e.g.* Iverson *et al.,* 1998; Pitman *et al.*, 2003) and proceed with numerical simulations for each *capable volcano* to account for a range of values for parameters that control flow geometry and discharge rate, using stochastic methods. Hazard curves could then be derived that express the probability of exceedance for flow incursion and discharge at the site. The uncertainty in the resulting hazard curves can be expressed by confidence bounds, with a stated basis for selection of the reported confidence levels.

Several additional factors should be considered in deriving design basis and in making site acceptability judgments related to debris flows, lahars, and floods. Probabilistic or deterministic approaches should result in estimates of the potential for these phenomena to reach a site as well as their likely flow geometry and discharge. Indirect event sequences, such as tephra fall on neighboring non-*capable*, snow-clad volcanoes, could act as sources for debris flows. Debris flows also can occur from floods generated by eruption under ice or snow, and from the sudden release of water and debris from breakage of volcanic dams in craters or valleys filled with volcanic debris. Other, smaller-scale floods can be treated within the scope of floods of non-volcanic origin (IAEA, 2003b).

5.3.4.6 Opening of New Vents

The opening of new vents is a geologically rare phenomenon but one that can produce significant flow, ballistic, and ground-deformation hazards for a nuclear installation located close to the site of a new volcano (*e.g.* scoria cone). Vents generally form clusters within volcanic fields, or are closely associated with large volcanic systems, such as shield volcanoes and calderas. Assessment of the likelihood of formation for new vents requires information about the distribution, type, and age of volcanic vents in the region. Additional information, such as geophysical surveys of the region, often is used to identify vents buried by subsequent activity or that are otherwise obscured. In addition, geological and geophysical models of the site region often provide important information about geological controls on vent distribution, such as the relationship between vents and faults or similar tectonic features.

A deterministic assessment of the possibility of new vent formation should determine a screening distance value for the site, beyond which the formation of a new vent is not thought to be a credible event. Additional information, such as significant changes in tectonic regime with distance from an existing volcanic field, should also be considered in a deterministic analysis.

Modern analyses of volcanic hazards associated with new vent formation normally involve probabilistic assessment (Connor and Connor, this volume). Probabilistic assessments could estimate a spatial probability density function describing the spatial, or spatio-temporal, intensity of volcanism in the region. Additional geological or geophysical information should be incorporated into the analysis. Uncertainties in the resulting probability density functions can be expressed by confidence bounds, with a stated basis for selection of the reported confidence levels.

Several additional factors should be considered in deriving design basis and in making site acceptability judgments related to the opening of new volcanic vents. Probabilistic and deterministic approaches may be used together. Results of this analysis could be expressed as the probability of a specific type of new vent forming within a specified time period (*e.g.* one year) and specific area (*e.g*. the area of the site vicinity). The potential for new vent formation likely would be considered as part of the hazard assessment of potential sources of other volcanic coupled phenomena, such as lava flows, ballistics, tephra fallout, and surges. In the case of opening of new vents, ground deformation of large magnitude (*e.g*. meters), volcanic seismicity, and gas flux may occur in the site vicinity.

5.3.5.7 Ballistic Projectiles

Ballistic projectiles can be compared with impacts due to tornado-borne missiles, but the potential number of volcanic projectiles that may fall on a site within 5 km of a volcano can be very high. At the vent, ballistic projectiles have velocities in the range of 150 to 800 m s^{-1}. Hazard estimates for ballistics from each *capable volcano* need to consider the source locations, potential magnitude, and frequency of future explosive eruptions.

A deterministic approach should consider the definition of a screening distance using information from the maximum distance and size of ballistics in previous explosive eruptions from analogous volcanoes. Empirical explosion models could also be used to determine a screening distance as a function of the exit speed, density of ballistics, exit angle, and wind field parameters. The analysis should consider the effect of topographic barriers between the site and the vent.

A probabilistic approach could consider a numerical simulation of ballistic trajectories at the site. In such an analysis, a stochastic analysis of ballistic trajectories from each *capable volcano* would be conducted, accounting for variation in explosion pressure, density of ballistics, exit angle, and related parameters. Such models produce a frequency distribution of ballistic accumulation, commonly presented as a hazard curve. Uncertainty in the resulting hazard curve can be expressed by confidence bounds, with a stated basis for selection of the reported confidence levels.

Several additional factors should be considered in deriving design basis and in making site acceptability judgments related to ballistic projectiles. Probabilistic and deterministic approaches may be used together. Results of this analysis could be expressed as the probability of potential ballistic impacts beyond a screening distance. The potential for ballistics likely would be considered as part of the hazard assessment of potential opening new vents and as impacts related to tephra fallout. Temperature effects from ballistic fragments also may need to be considered. Results of the analysis should be consistent with similar external hazards, such as tornado-borne missiles (*cf*. IAEA, 2002b).

5.3.4.8 Volcanic Gases

Volcanic gases can be released in very large quantities during explosive volcanic eruptions, but also can be released from some volcanoes even during periods of non-eruptive activity and can diffuse through soils and along fracture systems on and adjacent to volcanoes. Adverse effects of volcanic gases include toxicity and corrosion, often associated with condensation of acids from volcanic gases and dry deposition, and heavy acid loading. Estimation of hazards due to volcanic gases relies on accurate estimation of the potential flux of such gases in volcanic systems, and the meteorological and topographical data used to model the dispersion, flow and concentration of gases in the atmosphere.

A deterministic approach should consider using information from analogous volcanoes or gas concentration measurements at the *capable volcano* to define an offset distance between potential volcanic gas sources and the site. Alternatively, assuming that degassing will occur from a *capable volcano*, a deterministic approach could estimate the impact of this degassing using an atmospheric dispersion model, assuming a conservative value for the mass flux of volcanic gases. This modeling should provide some indication of the extreme gas concentrations and acid loading that might occur at the site.

A probabilistic approach could consider the expected variation in mass flux from the volcano, including the possibility of degassing pulses at otherwise quiescent volcanoes, and the variability of meteorological conditions at the site. These probability distributions would be used as input into a gas dispersion model to estimate acid loading and related factors. Uncertainty in the models can be expressed by confidence bounds, with a stated basis for selection of the reported confidence levels.

Several additional factors should be considered in deriving design basis and in making site acceptability judgments related to gases. Probabilistic and deterministic approaches may be used together. Results of this analysis are generally expressed in terms of the expected atmospheric concentration of volcanic gases and expected dry deposition in the site vicinity. This analysis likely would consider hazard from direct degassing from volcanic vents and eruptive plumes as well as from indirect passive degassing of erupted products, through the ground, the hydrothermal system, and crater lakes. The analysis also may need to evaluate the potential for catastrophic degassing of gas-charged (*e.g*. CO_2, CH_4) water bodies (*e.g.* crater or fault-bounded lakes) to affect the site.

5.3.4.9 Tsunamis and Seiches

Massive amounts of rock can abruptly enter large bodies of water during an eruption. Furthermore, volcano slopes can become unstable and collapse without warning or eruptive activity. Underwater volcanic eruptions also can displace large volumes of water, from both slope collapse and the release of volcanic gases, and should be considered in site-specific hazard assessments. Coastal sites, or sites located near large bodies of water, normally consider tsunami and seiche hazards as part of the site assessment (*e.g.* IAEA, 2003b). Nevertheless, specialist knowledge will be needed to fully evaluate the likelihood and source characteristics of potential volcanogenic tsunamis. The effects from volcanically induced tsunamis and seiches on sites are the same as those from seismically induced tsunamis and seiches.

Currently, tsunami and seiche hazards are evaluated using deterministic numerical models that consider the locations of potential sources, volume and rate of mass flow, the source and characteristics of water displacement, and the resulting propagation of waves based on location-specific bathymetry (*e.g.* IAEA, 2003b). For sites located in areas potentially affected by volcanically induced tsunamis or seiches, consideration should be given to the potential for large volumes of rock from volcanic eruptions or unstable volcanic slopes to enter water bodies, as part of analysis of the potential distribution of tsunami sources.

5.3.4.10 Atmospheric Phenomena

Explosive volcanic eruptions can produce atmospheric phenomena that have potentially hazardous characteristics. Overpressures from air shocks can often extend for kilometers beyond the projection of volcanic material. Eruptions that produce tephra columns and plumes commonly are associated with frequent lightning and occasionally with strong downburst winds. Because explosive volcanic eruptions would be considered rare events for atmospheric phenomena (*e.g.* IAEA, 2003c) and involve exceptional conditions, hazard assessments should consider a deterministic approach to model the potential maximum hazard for each phenomena associated with a potential volcanic eruption.

Volcanoes can be considered as stationary sources of explosions when considering air shocks in the hazards analysis (*e.g.* IAEA, 2002b). Hazards analyses described in, for example, IAEA (2002b) for stationary sources of explosions are generally applicable to the analysis of air shocks from explosive volcanic eruptions. The air-shock analysis would likely focus on determining the potential maximum explosion for the volcanic source and a simplified analysis for shock attenuation with distance from that source.

Volcanically induced lightning has the same hazardous characteristics as lightning from other meteorological phenomena but is a widespread feature associated with tephra columns formed by explosive volcanic eruption. The likelihood for ground strikes is high and may exceed the strike rate for extreme meteorological conditions (*e.g.* IAEA, 2003c). A deterministic hazard assessment for volcanically-induced lightning strikes should consider the screening criteria used in hazard assessment of rare atmospheric phenomena (IAEA, 2003c) but consider that there is a potential for a large number of column-to-ground lightning strikes during an explosive eruption.

5.3.4.11 Ground Deformation

Ground deformation typically occurs prior to, during, and following volcanic activity. Hazards associated with ground deformation take several forms. In the case of ground deformation at an existing *capable volcano*, ground deformation associated with intrusion of magma may have indirect effects, such as increase potential of landslide, debris flow or related phenomena, and increase potential for volcanic gas flow. The potential magnitude of ground deformation could be estimated in terms of displacement and results could be superimposed on topographic maps or digital elevation models in order to assess the potential for secondary impacts.

In a deterministic assessment, the potential magnitude of ground deformation at the site should be estimated using analytical solutions for deformation associated with magma movement of various geometries and from various source regions. Probabilistic assessment of potential ground deformation may simply link the magnitude of ground deformation estimated using models to the likelihood of such events, and a range of potential intrusion geometries.

Results of this analysis should include the estimation of the potential ground displacement to occur at the site as a result of volcanic activity, such as the opening of new vents. The most significant impact of the ground deformation analysis, however, would likely involve coupling this analysis with analysis of potential for other volcanic phenomena. In particular, it is critical to assess the potential of ground deformation in landslide and volcanic debris avalanche source regions, as ground deformation in these zones may greatly change the potential volume of such geophysical flows and consequently their potential for reaching the site of the nuclear installation. Volcanic activity or subsurface intrusions of magma may change ground-water flow patterns or cause fluctuations in the depth of the water table. The potential hazards associated with such changes likely would be considered as part of the flood hazards assessment (*e.g.* IAEA, 2003b).

5.3.4.12 Volcanic Earthquakes and Seismic Events

Volcanic earthquakes and seismic events normally occur as a result of stress and strain changes associated with the rise of magma toward the surface. The characteristics of volcano-seismic events may differ considerably from tectonic earthquakes, and volcanic earthquakes can be large enough or numerous enough (*i.e*. hundreds to thousands per day) collectively to represent a potential hazard. Volcano-seismic events may result in an increased possibility of slope failure and may compound loads on stressed structures (*e.g.* in tandem with tephra loading). Thus, a specific volcano-seismic hazard assessment could be undertaken using similar methods to those set out in IAEA (2002a).

In line with the approach to tectonic earthquake (*i.e.* seismic) hazard assessment, a deterministic method for assessing volcano-seismic ground motions should evaluate the combination of volcano-seismic event magnitude, depth of focus, and distance from site that produces maximal ground motion at the site, with account taken of local ground conditions at the site. The analysis may need to consider that a volcano-seismogenic source structure cannot be construed a capable fault (*e.g.* IAEA, 2002a). Suitable relationships for volcano-tectonic earthquakes should be derived for alternative ground motion parameterizations, such as peak acceleration, duration of shaking or spectral content, because specific ground motion characteristics of volcano-tectonic earthquakes may differ from those considered in other seismic hazards assessments (*e.g.* IAEA, 2002a).

A probabilistic assessment of volcano-seismic hazard at a site should follow similar principles as those outlined in, for example, IAEA (2002a). Allowance should be made for uncertainties in the parameters as well as alternative interpretations. Application of the probabilistic method should include steps for (i) construction and parameterization of a volcano-seismic source model, including uncertainty in source locations; (ii) evaluation of event magnitude-frequency distributions for all such sources, together with uncertainties; and (iii) estimation of the attenuation of seismic ground motion for the site region and its stochastic variability. With these steps, the results of a probabilistic ground motion hazard computation should be expressed in terms of the probability of exceedance of different levels of relevant ground motion parameters (*e.g.* peak acceleration and an appropriate range of response spectral accelerations), for both horizontal and vertical motions. The uncertainty in the resulting probability level can be expressed by confidence bounds, with a stated basis for selection of the reported confidence levels.

In many cases a site close to a *capable volcano* will also lie in a region of significant seismic hazard from tectonism. Simple scoping calculations may demonstrate that volcano-seismic hazards at a site are significantly lower than those associated with other sources of seismic activity. When such an analysis does not provide a clear margin of difference, a deterministic or probabilistic volcano-seismic hazard assessment should be undertaken.

5.3.4.13 Hydrothermal Systems and Groundwater Anomalies

Hydrothermal systems can generate steam explosions, which eject rock fragments to a distance of several kilometers and can create craters up to hundreds of meters in diameter. Hydrothermal systems also alter rock to clays and other minerals, which creates generally unstable ground that can be highly susceptible to landslides. Currently, it is not possible to determine the likelihood for steam explosions to occur in most hydrothermal systems. Hazard evaluations for these systems are deterministic, and likely would consider evaluating the potential maximum ballistic or air shock hazard for the hydrothermal source zone.

5.3.5 A Comprehensive Model

A comprehensive, site-specific volcanic hazard model is almost certainly complex. Such models will depend on assistance from informed volcanological experts, preferably through a formal expert elicitation process designed to consider all aspects of volcanic hazard at the site (*e.g.* U.S. Nuclear Regulatory Commission, 1996; Aspinall, 2006). Furthermore, external peer review of the technical basis and application of the hazard model should be undertaken to increase confidence that an appropriate range of models and data have been considered in the assessment.

Volcanic events can give rise to multiple hazardous phenomena (*e.g*. tephra loading and seismic loading). In combination, these hazards can exacerbate the risk at an installation, even though the risk stemming from each hazard may be relatively minor on its own. A comprehensive model of volcanic hazard phenomena should therefore account for combined effects of volcanic phenomena.

Non-volcanic events such as regional earthquakes or tropical storms can initiate the occurrence of hazardous phenomena at a volcano. A comprehensive model for volcanic hazards should consider the likelihood of such hazards, which are coupled to non-eruptive initiating events. Additionally, in comparison to many external hazards, volcanic activity may persist for longer periods of time and may affect larger areas around a nuclear installation. For example, debris flows may not damage a nuclear installation directly, but may render normal operation of the installation temporarily impossible due to extensive or devastating impacts on the population and infrastructure of the surrounding region.

Overall, development of a site-specific volcanic hazard model should inform decisions about site suitability and installation design. In reaching these decisions, the potential for future volcanism and assessment of its potential effects should be considered from the perspectives of the impact on (i) the site, resulting in uncontrolled release of radionuclides into the biosphere; (ii) the site, resulting in controlled shutdown or other emergency response; and (iii) the surrounding communities, which may adversely affect safe operation of the installation or the capability of the installation to deliver energy to the community, especially in a time of adverse circumstances.

5.4 Concluding Remarks

Although volcanic events rarely occur, they can create a range of phenomena that could present potentially significant hazards to nuclear installations. The proposed approach to assess volcanic hazards provides a transparent technical basis to support risk-informed decision making for site suitability and consideration of design bases. The initial volcanic hazards assessment first considers the possibility of future eruptions from sites of past eruptions during the last 10 Myr. For volcanoes with the potential for future eruptions, the hazard assessment then evaluates the ability for future eruptions to produce phenomena that could reach the site of a nuclear installation. Identification of such *capable volcanoes* warrants the development of a site-specific volcanic hazards assessment, which more explicitly evaluates the likelihood of future eruptions and the specific characteristics of hazardous phenomena. Although deterministic methods can successfully support this evaluation, probabilistic methods provide a more transparent basis to consider data and model uncertainties and determine a range of potential hazards in addition to maximum credible events. Probabilistic methods also permit direct comparison of risks from volcanic hazards to risks from other external natural hazards, which allows for straightforward development of design bases for external and internal hazardous events at an installation. Incompleteness in the geologic record generally requires the use of numerical and statistical modeling to ensure that an appropriate range of potentially hazardous volcanic phenomena have been considered in the assessment. Although such process-level models are available for most volcanic phenomena, no model currently represents an explicitly validated methodology. Thus, models that are used to support public health and safety decisions will need to be supported by objective comparisons to well-studied analogous volcanoes, field observations, detailed process models, and laboratory experiments (*e.g.* ASTM Standard C1174-07).

5.5 Suggested Further Reading

Hoblitt *et al.* (1987) and Chung *et al*. (1990) provide good examples of comprehensive volcanic hazards assessments for several nuclear installations in the western United States. Karakhanian *et al.* (2003) and McBirney *et al*. (2003) discussed volcanic and associated hazards at an existing nuclear power plant in Armenia and a proposed site in Indonesia, respectively. These early studies relied primarily on deterministic methods to develop screening arguments for volcanic hazards. The assessment approach developed herein represents an enhancement of concepts originally expressed in McBirney and Godoy (2003), which resulted from an earlier IAEA project to develop a safety guide for volcanic hazards.

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Table 5.1 Table of volcanic phenomena and associated hazards for nuclear installations, with implications for installation design and siting.

Phenomenon	**Primary Hazards**	**Design**	**Siting**
Tephra fall	Static physical loads, abrasive and corrosive particles in air and water	Yes	No
Pyroclastic flows, surges, and blasts	Dynamic physical loads, atmospheric overpressures, projectile impacts, temperatures >300°C, abrasive particles, toxic gases	No	Yes
Lava flows	Temperatures >700°C, dynamic physical loads, water impoundments and floods	Yes	Yes
Debris avalanches and slope failures	Dynamic physical loads, atmospheric overpressures, projectile impacts, water impoundments and floods	No	Yes
Debris flows and lahars	Dynamic physical loads, water impoundments and floods, suspended particulates in water	Yes	No
Opening of new vents	Dynamic physical loads, ground deformation, continuous seismic tremor	No	Yes
Ballistic projectiles	Projectile impacts, static physical loads, abrasive particles in water	Yes	No
Volcanic Gases	Toxic and corrosive gases, water contamination, gas-charged lakes	Yes	No
Tsunamis and Seiches	Water inundation	Yes	Yes
Atmospheric phenomena	Dynamic overpressures, lightning strikes, downburst winds	Yes	No
Ground deformation	Ground displacements >1 m, landslides, volcanic gases	No	Yes
Volcanic earthquakes	Continuous tremor, multiple shocks (usually <M5)	Yes	No
Geothermal fluids	Thermal water >50°C, adverse chemical compositions, water inundation or upwelling	No	Yes

Design represents the general practicality of mitigating potential hazard from this phenomenon by either facility design or operational planning. *Siting* indicates the presence of a credible hazard from this phenomenon generally constitutes a site suitability criterion. A *Yes* in both categories indicates that although a design basis may be achievable, sites with this hazard usually are avoided.

Figure 5.1. Flow chart for an approach to determine volcano capability and subsequent needs for a more detailed volcanic hazards assessment.