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Volcanic Hazards in Site Evaluation for Nuclear Installations

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(Front inside cover)

IAEA SAFETY RELATED PUBLICATIONS

.FOREWORD

by DG

Director General

VOLCANIC HAZARDS IN SITE EVALUATION FOR NUCLEAR INSTALLATIONS

CONTENTS

1. INTRODUCTION

BACKGROUND

1.1. This Safety Guide was prepared under the IAEA's programme for safety standards. It supplements and provides recommendations for meeting the requirements for nuclear installations in the Safety Requirements publication on Site Evaluation for Nuclear Installations [1] in relation to volcanic hazards. Thus, this Safety Guide complements other Safety Guides that deal with the protection of nuclear installations from external natural and human-induced events through site selection and site evaluation assessments and measures and corresponding design features, Refs [2-7].

1.2. The Safety Requirements for Site Evaluation for Nuclear Installations states that "prehistorical, historical and instrumentally recorded information and records, as applicable, of the occurrences and severity of important natural phenomena or human induced situations and activities shall be collected for the region and shall be carefully analysed for reliability, accuracy and completeness" (see para. 2.17 of [1]). In this regard, volcanism is explicitly mentioned in 3.52 of Ref. [1] indicating that "historical data concerning phenomena that have potential to give rise to adverse effects on the safety of the nuclear installation, such as volcanism, sand storms, severe precipitation, snow, ice, hail and subsurface freezing of subcooled water (frazil), shall be collected and evaluated". Therefore, volcanism shall be considered during the site selection and site evaluation stages of a nuclear installation. Consequently, this Safety Guide provides a basis to meet that requirement – as other IAEA Safety Guides do for other natural and human induced external events – through a comprehensive consideration of all potential volcanic hazards. Such consideration should not be interpreted as a way to encourage the location of nuclear installations in regions of hazardous volcanic activity.

1.3. The present Safety Guide upgrades and supersedes the Provisional Safety Standards Series No. 1 publication on "Volcanoes and associated topics in relation to nuclear power plant siting" published by the IAEA (July 1997). This was the first draft guidance provided by IAEA on this subject, which was still undergoing development at both international and national levels. Since that time many aspects of volcanological science have developed. Simultaneously, there is growing interest in the nuclear community for the construction of additional nuclear power units at existing sites which were not comprehensively assessed in terms of these hazards at the time of the site selection. For new nuclear installations, more regions in the world are now being surveyed and assessed. In particular, some countries are embarking on the development of nuclear installations for the first time, and some of these sites need careful assessment regarding the potential for volcanic hazards. The IAEA Provisional Safety Standards Series No. 1 publication was a unique reference about this subject and has been used both by the scientific and nuclear community to improve volcanic hazard assessments. Feedback from this experience has been used in the preparation of this Safety Guide.

1.4. Volcanic phenomena are the surface manifestations of large scale geological processes that develop at great depths within our planet over large lengths of time. Volcanic activity is due to deep geological phenomena that determine the local rate of magma generation. The recommendations provided in the present Safety Guide reflect the current status of development of the science of volcanology, which has undergone transformative changes during the last thirty years. During this time volcanology has evolved from an essentially descriptive science into a quantitative science that relies on both observations of volcanic systems that were not previously possible, and numerical models of complex volcanic processes. Given this evolution in volcanology, it is appropriate to use these advances to enhance safety assessments for nuclear installations.

1.5. Engineering or operational solutions are generally available to mitigate some potential effects of external events by means of certain design features. However, when such solutions are not practicable or cannot be demonstrated as being adequate for mitigation of the effects of external events, an alternative site should be selected. In this regard, this Safety Guide satisfies the safety principle No. 8 of the fundamental safety objectives [8] on the request to proceed with an adequate site selection as a means of the defence in depth concept, firstly, providing the basis for screening out those sites which are not suitable during the site selection process and, secondly, for assessing the volcanic hazards that can affect a nuclear installation and for which appropriate design bases can be established.

OBJECTIVE

1.6. The objective of this Safety Guide is to provide recommendations and guidance on assessing the volcanic hazards at a nuclear installation site, so as to enable the identification and characterization in a comprehensive manner of all potentially hazardous phenomena that may be associated with future volcanic events. These volcanic phenomena may affect the acceptability of the selected site and some of which may determine corresponding design basis parameters for the installation.

1.7. This Safety Guide is intended for use by regulatory bodies responsible for establishing the regulatory requirements, for designers of nuclear installations and for operating organizations, directly responsible for the safety of their installations through the protection of the people and the environment from the harmful effects of ionizing radiation.

1.8. This Safety Guide is not intended to deal with the response analysis and the capacity evaluations of the volcanic hazards on the nuclear installation (i.e. plant design aspects, capacity or fragility calculations of systems, structures and components).

SCOPE

1.9. This Safety Guide is intended to be used mainly during the site selection process of new nuclear installations. It may also be used for existing nuclear installations for a retrospective assessment of the volcanic hazards external to the installation that may affect it.

Siting or site selection is the process of selecting a suitable site for a facility, including appropriate assessment and definition of the related design bases. The selection of an adequate site is one of the elements of the concept of defence in depth for preventing accidents as required by the Principle 8 of the Safety Fundamentals documents [8].

The siting process generally consists, in a first phase known as site survey, of an investigation of a large region to identify potential available sites and to select and rank one or more candidate sites, followed by a detailed evaluation phase of those candidate sites in order to finally select the one in which the nuclear installation will be located. Once the site is selected, the siting process is thus finished.

Site evaluation is the process that covers from: (a) the last phase of the siting process (i.e. the detailed evaluation phase of the selected candidate sites), to (b) the detailed evalution of the selected site to confirm its acceptability and to derive the site related design bases for the installation, to (c) the confirmation and completion of the assessment during the installation pre-operational stage (i.e. during design, construction, assembly and commissioning phases), and finally to (d) the operational stage of the installation (see paras 1.8 and 1.14 of [1]). Thus, site evaluation covers the complete lifecycle of the installation.

The volcanic hazard assessment may be necessary for performing probabilistic safety assessments for external events to a nuclear installation.

1.10. The volcanic hazards treated in this Safety Guide are obviously considered as external events, which are events unconnected with the operation of a facility or activity and which could have an effect on the safety of the facility or activity. It should also be highlighted that the concept of 'external to the installation' is intended to include more than the external zone (see [9]) since in addition to the area immediately surrounding the site, the site area itself may contain objects that pose a hazard to the installation. The assessment of the volcanic hazards may be also necessary when performing a probabilistic safety assessment (PSA) of the installation considering the full scope of external events as intiating events.

1.11. The Safety Guide discusses the volcanic processes that may cause adverse effects on the performance of safety systems at nuclear installations and provides recommendations for the methods that can be used, and the critical factors involved in the evaluation of volcanic events and of their associated effects. Different types of phenomena associated with volcanism are discussed in terms of their influence on site acceptability and on the derivation of design basis parameters.

1.12. Volcanic phenomena may potentially affect site acceptability and design of nuclear installations. Hazards from volcanoes can occur over a broad scale of time and distance. These hazards are not uniformly distributed worldwide. Approximately 25% of Member States contain potentially active volcanoes. In addition, volcanic hazards can readily extend across international boundaries, and some hazards can occur at inactive volcanoes.

1.13. For the purposes of this Safety Guide, a volcanic hazard is considered to be any phenomenon related to volcanism that may affect site acceptability or operation of a nuclear installation. Volcanism is the natural process by which magma ascends through the earth, erupts or nearly erupts at the earth's surface, and produces phenomena that may have far-reaching and long-term effects. Volcanic hazards are complex and varied. Some phenomena, such as the opening of new volcanic vents, are generally considered to be rejection criteria in the site selection of nuclear installations. Potential for such disruptive phenomena in the site vicinity should be considered early in the site acceptability evaluation. In general, site vicinity is defined as the area extending a few kilometres from the site area, but also considering the topography of the site, and defined in agreement with the regulatory authority. Similarly, the potential for various flow phenomena, such as pyroclastic flows or lava flows, within the site vicinity should be assessed as part of the site acceptability evaluation. The potential for other volcanic phenomena, such as the accumulation of volcanic tephra, may represent design basis external events. As some volcanic phenomena potentially affect sites hundreds of kilometres from erupting volcanoes, it is emphasized that a comprehensive methodology is required to assess volcanic hazards. This Safety Guide discusses the nature of volcanic phenomena in the context of hazard assessment, and outlines frameworks for probabilistic and deterministic approaches to evaluation of volcanic hazards.

1.14. It is noted that the potential for so-called mud volcanoes to form near the site is beyond the scope of this Safety Guide, as this is not strictly a volcanic phenomenon, in which magma reaches the surface. Instead, mud volcanoes occur when overpressure within the earth brings a mixture of sediment, water, and gas to the surface (see Appendix, para. A.10). Although the formation of a mud volcano is not strictly a volcanic phenomenon, hazards associated with mud volcanism may be evaluated using techniques described in this Safety Guide related to the opening of new vents, and using techniques discussed in Ref. [7].

1.15. This Safety Guide addresses an extended range of nuclear installations as defined by Ref.[9]: land based stationary nuclear power plants, research reactors, nuclear fuel fabrication plants, enrichment plants, reprocessing facilities and spent fuel storage facilities. The methodologies recommended for nuclear power plants are applicable to other nuclear installations through a graded approach, whereby these recommendations can be tailored to suit the needs of different types of nuclear installations in accordance with the radiological consequences of their potential failure when subjected to volcanic hazards. The recommended direction of grading is to start with nuclear power plant related attributes and to grade down to installations associated with lesser radiological consequences[1]. Therefore, if no grading is performed the recommendations related to nuclear power plants are applicable to other nuclear installations.

1.16. For the purpose of this Safety Guide, existing nuclear installations are those installations that are either (a) at the operational stage (including long term operation and extended temporary shutdown periods) or (b) at a pre-operational stage for which the construction of structures, manufacturing, installation and/or assembly of components and systems, and commissioning activities are significantly advanced or fully completed. As long as nuclear fuel is present at the facility, the nuclear installation is considered at the operational

[1] For sites at which nuclear installations of different types are collocated, particular consideration should be given to using a graded approach.

stage because the high level of operational safety shall be maintained as required by the revised version of IAEA NS-R-2-Safety of Nuclear Power Plants: Operation [12]. In existing nuclear installations that are at the operational and pre-operational stages, a change of the original design bases, or a change in the regulatory requirements regarding the consideration of volcanic hazards, may lead to a significant impact on original design features and, consequently, to important hardware modifications.

STRUCTURE

1.17. In this Safety Guide, the description of the phenomena associated with volcanism and the collection of required data and information are separated from the criteria for hazard assessment. Thus, Section 2 and the Appendix give the non-specialist a general description of the different types of volcanic phenomena and an overview of the criteria and general methodology to be used for hazard assessment. Section 3 outlines the general recommendations and general procedure to be followed during the site selection and site evaluation stages. Section 4 provides guidance on the acquisition and development of the database for the hazard assessment. Sections 5 and 6 provide guidance on performing the volcanic hazard assessment and on deriving the design basis parameters. Section 7 describes the procedures and criteria to be used for installations other than nuclear power plants using a graded approach, and Section 8 includes information on monitoring and preparation for response in case of volcanic activity. Section 9 provides guidance on management system aspects of the tasks to be performed. As general information for the non-specialist, Annex 1 provides examples of the complex series of events that accompany different types of volcanic eruptions, while Annex 2 gives information on worldwide available sources of data in the subject. Finally, in the same spirit, and recognizing that complete consensus has not been reached within the scientific community on the use and meaning of some terms, a glossary of volcanological terms is provided, applicable only to usages adopted in this Safety Guide.

2. OVERVIEW OF VOLCANIC HAZARD ASSESSMENT

NATURE OF VOLCANIC HAZARDS

2.1. Volcanic events can present significant hazards to nuclear installations. Volcanic hazards arise from phenomena that have broad ranges of physical characteristics. These phenomena 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 Safety Guide to indicate a set of potentially hazardous phenomena that may occur before, during, or after volcanic eruptions.

2.2. Phenomena associated with volcanic events that may pose potential hazards to a site are presented in detail in the Appendix and listed in Table 1.

2.3. 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 are usually considered active. Around the world, there are more than 1500 volcanoes that can be considered active on this basis (see Annex 2). These volcanoes are formally referred to as Holocene volcanoes, i.e. volcanoes that have had erupted during the last 10 000 years (the Holocene). Holocene volcanoes may experience eruptions after long periods of inactivity. Some volcanoes have reactivated after periods of inactivity longer than 10 000 years. Many volcanoes have not been studied in sufficient detail to know whether they have erupted during the Holocene. Therefore, consideration of volcanic hazards should not be limited to Holocene volcanoes.

2.4. Volcanic activity within a geographic region can persist for longer time scales than associated with individual volcanoes. Many volcanic arcs exhibit recurring volcanic activity for longer than 10 Ma[2], although individual volcanoes within the arc itself may remain active only for around 1 Ma. Because such distributed activity can persist for many millions of years, regions that have had volcanic activity during the past 10 Ma are considered to have at least potential for future activity. Straightforward estimate of a regional volcanic recurrence rate of less than 1 event in 10 Ma would imply a current annual probability of future activity of less than 10^{-7}. In hazard assessments from external events for nuclear installations (see Section 4, para. 4.3 of Ref. [2]), a limiting value of the annual probability of occurrence of events with potential radiological consequences is defined as the screening probability level (SPL) for which, in some Member States, a value of 10^{-7} is used. Initiating events with a probability of occurrence lower than this screening probability level should not be given further consideration, regardless of their consequences. During initial screening, an annual probability of 10^{-7} is a reasonable basis to evaluate if a volcano in the region could produce any type of activity in the future, given that hazardous effects at the site due to an eruption are even less likely.

[2] Ma: million years

Table 1. Volcanic phenomena and associated characteristics that could affect nuclear installations, with implications for site selection and evaluation, and design.

Phenomena	Potentially Adverse Characteristics for Nuclear Installations	Considered as exclusion criteria at Site Selection Stage	Can Design[1] and Operation mitigate the effects?
1-Tephra fall	Static physical loads, abrasive and corrosive particles in air and water	No	Yes
2-Pyroclastic density currents: Pyroclastic flows, surges, and blasts	Dynamic physical loads, atmospheric overpressures, projectile impacts, temperatures >300 °C, abrasive particles, toxic gases	Yes	No
3-Lava flows and lava domes	Dynamic physical loads, floods and water impoundments, temperatures > 700 °C	Yes	No
4-Debris avalanches, landslides and slope failures	Dynamic physical loads, atmospheric overpressures, projectile impacts, water impoundments and floods	Yes	No
5-Debris flows and lahars, floods	Dynamic physical loads, water impoundments and floods, suspended particulates in water	Yes	Yes
6-Opening of new vents	Dynamic physical loads, ground deformation, volcanic earthquakes	Yes	No
7-Volcano generated Missiles	Particle impacts, static physical loads, abrasive particles in water	Yes	Yes
8-Volcanic gases and aerosols	Toxic and corrosive gases, acid rain, gas-charged lakes, water contamination	No	Yes
9-Tsunamis, seiches, crater lake failure, glacial burst	Water inundation	Yes	Yes
10-Atmospheric phenomena	Dynamic overpressures, lightning strikes, downburst winds	No	Yes
11-Ground deformation	Ground displacements, subsidence or uplift, tilting, landslides	Yes	No
12-Volcanic earthquakes and seismic events	Continuous tremor, multiple shocks, usually < M 5	No	Yes
13-Hydrothermal systems and groundwater anomalies	Thermal water > 50 °C, corrosive water, water contamination, water inundation or upwelling, alteration, landslides, modification of karst and thermokarst, abrupt change in hydraulic pressure	Yes	Yes

Note: A *Yes* in the site selection stage column indicates that the presence of a significant hazard from this phenomenon in the site vicinity generally constitutes a site exclusion criterion, i.e. the site is not suitable for locating a nuclear installation. The design and operation column indicates the general practicality of mitigating potential hazard associated with particular phenomena, by either facility design or operational planning. A *Yes* in both columns indicates that although a design basis may be achievable, sites with this hazard are usually avoided. Volcanism is a complex process. Specific impacts of volcanic phenomena depend on a range of conditions such as composition of the erupted products, temperature, water contents and related factors. One type of phenomena often gives rise to another.

[1] Design also includes the design of site protection measures for some of the hazards.

2.5. 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 missiles, to high energy events that bury the countryside in tens of metres of hot ash. Thus, a variety of volcanic phenomena can occur with substantially different magnitudes during volcanic events. Even volcanoes located hundreds of kilometres from a site can cause hazardous phenomena such as tephra fallout, long-runout lahars, floods or tsunamis, which may adversely affect the safety and performance of a nuclear installation.

2.6. Non-eruptive phenomena at volcanoes may also produce hazards for nuclear installations. Volcanoes commonly are unstable landforms. Even after long periods of repose, portions of volcanoes may suddenly collapse to form landslides and debris flows. This type of mass wasting is often triggered by extreme weather events, such as tropical cyclones. Such events can impact areas of thousands of square kilometres around the volcano. Some volcanoes are closely linked to tectonic faults or geothermal activity. In such instances seismic activity related to fault movement may also cause collapse of the volcano edifice. These examples demonstrate that a volcanic hazard assessment for a nuclear installation should consider the influence of extreme weather, hydrologic and tectonic processes on the likelihood and characteristics of future volcanic events.

2.7. Volcanic events rarely produce a single hazardous phenomenon. Rather, eruptions can initiate a complex sequence of events and 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 in the analysis.

GEOLOGIC RECORD AND DATA UNCERTAINTY

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

2.9. The geologic record of an individual volcano does not necessarily encompass the potential characteristics and extent of future activity. Hazard assessments 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 both to constrain and to reduce uncertainties arising from interpretations of an incomplete geologic record and also to assess potential changes in volcanic hazards through time.

2.10. The frequency and timing of past events is incompletely understood and 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. Whether a volcano is dormant or extinct is often subjective and difficult to determine.

2.11. At most volcanoes, there is more certainty about the physical characteristics of past events, such as their volume and spatial extent, 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 more certain than one focusing on an estimation of the likelihood of the occurrence of hazardous phenomena. Because of uncertainties in the geologic record, this Safety Guide recommends an initial approach of screening potential volcanic hazards based on their physical characteristics, rather than on likelihood of occurrence. Detailed hazard assessments, if warranted, may need to consider the likelihood of occurrence and associated uncertainties for volcanic phenomena that may reach the site.

ALTERNATIVE CONCEPTUAL MODELS OF VOLCANISM

2.12. A fundamental assumption in volcanic hazard assessment is that the record of past volcanic events provides a reliable indicator of possible future events. Confidence in this assumption requires development of conceptual models to interpret the geologic record in terms of volcanic processes. Such conceptual models can encompass the origin of magmas, the tectonic setting of volcanoes, the rates and volumes of eruptions, and the nature of volcanic hazards. For example, volcanism in the site region may be associated with a tectonic setting that has remained unchanged for millions of years, and therefore the processes interpreted in the geologic record could be assumed to persist in the future. Alternatively, a potential site may be located in an area where tectonic setting has changed through time such that the geologic record of past volcanic activity could poorly represent potential future volcanism. As in this example, a conceptual model of the tectonic setting for volcanism should assess the extent to which past events appropriately represent future events.

2.13. A clear and proper understanding of the processes that affect volcanism, as represented by the conceptual model, makes best use of available geologic data and guides the collection of additional data. Updates to conceptual models occurs as new information becomes available during site investigations. In some cases new data and conceptual models may emerge after the initial site evaluation has been completed.

2.14. Volcanic hazard assessments usually consider alternative conceptual models. These models are to be consistent with available data and current scientific understanding, and should be evaluated for effect on estimated hazard. For example, volcanic systems may vary from primarily effusive with low energy eruptions to higher energy explosive eruptions. A conceptual model for volcanic activity at a volcano that only has the products of low energy eruptions preserved in the geologic record might estimate hazards for this activity alone. In contrast, an alternative conceptual model using information from analogous volcanic systems would include hazards associated with higher energy explosive eruptions.

2.15. The hazard assessment document clearly where alternative conceptual models could result in significant differences in hazard. If alternative models result in significant differences in hazard, these alternative models should be propagated through the hazard assessment.

VOLCANO CAPABILITY

2.16. The concept of the capable volcano is introduced in this Safety Guide to define the potential of a volcano or volcanic field to produce hazardous phenomena that may affect in future the site of a nuclear installation. A capable volcano or volcanic field is one that (1) has a credible likelihood of experiencing future activity during the lifetime of the installation and (2) such an event has the potential to produce phenomena that may affect the site of the installation. Identification of one or more capable volcanoes results in development of a comprehensive, site-specific volcanic hazard assessment. The designation of a volcano as capable is not dependent only on the time elapsed since the most recent eruption of the volcano, but rather is dependent on the credibility of future volcanic eruptions. This distinction is made because: (1) there is often considerable uncertainty about the timing of most recent activity at volcanoes that have no documentation of historical eruptions, and (2) there are multiple methods of establishing the credibility of future eruptions, such as analysis of the eruption recurrence rate, assessment of the current state of activity of the volcano using geophysical and geochemical investigations, analysis of geochemical trends indicative of the magma productivity of the volcano system, and analysis of the tectonic setting of the volcano.

DETERMINISTIC AND PROBABILISTIC APPROACHES

2.17. Both deterministic and probabilistic methods currently are used to assess volcanic hazards. Deterministic methods use thresholds to screen specific phenomena from further consideration. Such thresholds often are based on empirical evidence, such as the maximum volume or lateral extent of pyroclastic flows. Probabilistic methods use density functions to estimate the likelihood of specific volcanic phenomena. Such analyses consider a range of potential event frequencies, magnitudes and characteristics. Both deterministic and probabilistic methods of hazard assessment rely on empirical observations and theoretical understanding of volcanic processes. Volcano capability and site-specific volcanic hazard may be evaluated using, to the extent possible, both deterministic and probabilistic methods because they are of complementary nature.

2.18. In either deterministic or probabilistic approaches, the magnitude and spatial extent of volcanic phenomena need to be evaluated using geologic data gathered in the site region, and in a manner consistent with conceptual models of volcanic processes. These geologic data can be supplemented with information from analogous volcanoes and from numerical simulation of volcanic phenomena. If the likelihood of a phenomenon must be used to assess volcano capability or site-specific volcanic hazards, relative and absolute age determinations should be used to estimate recurrence rates of volcanic events. In either a probabilistic or deterministic approach, uncertainty analysis for data and models are an integral part of the hazard assessment as discussed in detail in following Sections dealing with each of the specific volcanic phenomena.

2.19. If alternative models can explain the available data and differences in these models cannot be resolved by means of additional investigations within a reasonable timeframe, the final hazard evaluation needs to consider all such models. The volcanic hazard assessment are to express the uncertainty represented by the alternative conceptual models, and clearly document the method used to propagate this uncertainty through the hazard assessment. Examples of methods used to propagate this uncertainty include logic trees and bounding analyses based on individual models.

3. GENERAL RECOMMENDATIONS

INTRODUCTION

3.1. This Safety Guide recommends a general procedure for the evaluation of volcanic hazards for a site, as presented in Figure 1. A successful outcome of a volcanic hazards assessment should be a transparent and traceable basis for making decisions about site acceptability and determination of the design basis. Indeed, the recommended approach focuses only on volcanic phenomena that represent credible hazards to the site. This approach recognizes the need for increasing levels of information for increasing levels of potential hazard at the site. This process also recognizes that sites located far from potentially active volcanoes may need to consider only a limited subset of potential hazards, for example, only distant tephra falls and/or volcanogenic tsunamis, whereas sites located closer to potentially active volcanoes may need to consider the full range of potential hazards.

3.2. 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 should be accomplished in four stages, as follows:

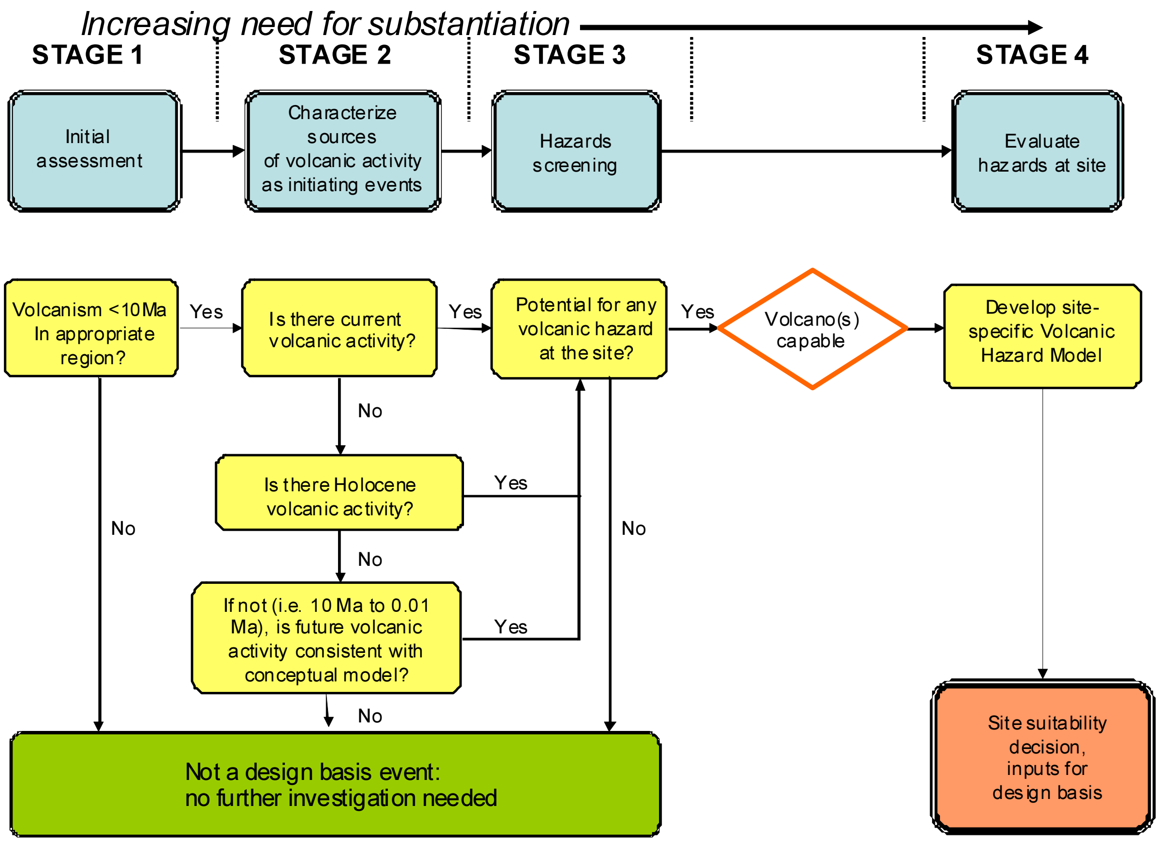
(a) Stage 1: First, an initial assessment should define a geographical region around the site that encompasses all potential sources of volcanic activity occurred during the last 10 Ma.

(b) Stage 2: Second, once these volcanoes are identified, they should be evaluated for the possibility of producing a future eruption or other volcanic event.

(c) Stage 3: Third, the possibility of future volcanic events creating hazardous phenomena that may adversely affect the nuclear installation site should be evaluated. Volcanoes that do not have a credible possibility of producing hazardous phenomena at the site should be screened out from further consideration.

(d) Stage 4: Finally, if a capable volcano is identified, a site-specific volcanic hazard assessment should be completed. This assessment should include each of the specific phenomena that may affect the site, and should consider potential causal relationships among these phenomena.

Figure 1: Methodological approach



Each of these stages is briefly described in the following paragraphs and additional guidance is provided in subsequent sections.

3.3. At each stage of the assessment, a determination should be made whether sufficient information is available to evaluate adequately 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 acceptability, including consideration of volcanic hazards as design basis events.

3.4. During the initial stage of the site selection and evaluation process, relevant data should be collected from available sources (publications, technical reports, and related material) in order to identify volcanic phenomena with the potential for hazardous effects at the site. In this regard, Annex 2 provides worldwide sources of information that can be used for such purposes.

GENERAL PROCEDURE

Stage 1 - Initial Assessment

3.5. The initial stage of the hazard assessment focuses on two primary considerations: definition of an appropriate geographic region that encompasses potential sources of volcanic hazards, and evidence of volcanic activity occurring within that region during the last 10 Ma. The geographic region depends on the nature and type of volcanic phenomena (Table 1), which span orders of magnitude in scale, varying from tens of kilometres for some phenomena which are of the most importance for the selection of the site and the safety of the installation, to thousands of kilometres for others phenomena, such as tephra fallout and tsunami. This stage should include a detailed review of available sources for an appropriate geographic region around the site. This detailed review would typically use geologic maps, results from previous geologic investigations, and other information as discussed in Section 4. The outcome of Stage 1 should be a determination of the presence and distribution of volcanoes and volcanic fields younger than 10 Ma.

Stage 2 - Characterising Potential Sources of Future Volcanic Activity

3.6. If the outcome of the initial assessment in Stage 1 indicates that volcanoes or volcanic fields younger than 10 Ma are present in the selected geographic region, then a conceptual model for volcanic processes in the region should be developed. This conceptual model, or set of alternative conceptual models, includes analysis of the tectonic setting of volcanism, rates of eruptive activity, and similar information about geologic trends. Volcanoes that are consistent with the conceptual model for volcanic processes, and all volcanoes with Holocene activity, should be characterized further. Alternatively, if it can be justified using a conceptual model of volcanism that there is no credible potential for future eruptions, for example if the tectonic setting that gave rise to past activity at these volcanoes has changed appreciably, then these volcanoes should be screened from further consideration. Such justification may be supported using a hierarchical analysis, as described in paras. 5.6-5.16.

Stage 3 – Screening of Potential Volcanic Hazards

3.7. In cases where the potential for future volcanic activity in the site region cannot be ruled out, the potential for hazardous phenomena to affect the site should be considered, given that an eruption or other volcanic event occurs. This analysis should be performed for each of the phenomena associated with each potentially active volcano or volcanic field in the selected geographical site region. Either deterministic or probabilistic methods should be used to evaluate the possibility that potentially hazardous volcanic phenomena may reach the site. It is noted that all potentially active volcano or volcanic field in the selected geographical site region due not necessarily produce all volcanic phenomena listed in Table 1. Volcanoes that do not have a credible possibility of producing potentially hazardous volcanic phenomena at the site should be screened from further consideration in the hazard assessment.

Stage 4 – Hazard Assessment of Capable Volcanoes

3.8. Volcanoes that may possibly erupt in the future and that may produce potentially hazardous volcanic phenomena at the site are considered capable volcanoes. A site specific volcanic hazard assessment should be conducted for capable volcanoes. The outcome of this assessment is a technical basis for decisions about (a) the acceptability of the site if those phenomena listed as "Yes" in Table 1, 3rd Column, do not have a credible potential to occur within the site vicinity (see para. 1.13) or present a potential hazard to the installation, and (b) the design basis for phenomena listed as "Yes" in the 4th Column of Table 1.

Additional Considerations

3.9. If volcanoes within the geographic region are sources of credible hazards at the site, then the characteristics of these capable volcanoes shall be monitored over the lifetime of the installation as required by the safety requirements [1]. In this case, a monitoring programme should be prepared and implemented in coordination with specialized agencies in the country for early warning during the operational state of the installation. Normally, emergency planning requirements for an installation would include this monitoring programme and operating procedures.

4. NECESSARY INFORMATION AND INVESTIGATIONS (DATABASE)

OVERVIEW

4.1. The cogency and robustness of any assessment of volcanic hazards are dependent on a sound understanding of: (i) the character of each individual volcanic source within the appropriate geographic region, (ii) the wider volcanological, geological and tectonic context of such volcanic sources, and (iii) the types, magnitudes and frequencies 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.

4.2. The database should incorporate all the information that is needed to support decisions at each stage of the volcanic hazards assessment. The database structure should be flexible enough to accommodate increasing levels of information, completeness and integration as the analysis progresses through advancing stages of complexity. The database may be based initially 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. This section provides guidance about the types and levels of information required for the assessment of volcanic hazards.

4.3. 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. Any data considered in the assessment but rejected or otherwise not used should also be retained in the database and identified as such. Justification should be provided why these rejected data are not considered in the assessment.

INFORMATION REQUIRED FOR INITIAL ASSESSMENT (Stage 1)

4.4. For the initial assessment stage (see Figure 1), available geological knowledge should be used to determine if any volcanic activity occurred during the last 10 Ma in an appropriate geographic region surrounding the site. If it is judged that the available geological information is insufficient for this purpose, then additional data should be sought, such as that described in paras 4.7-4.9, to provide an adequate basis for initial assessment.

4.5. The geographic region for the assessment does not have predetermined, uniform dimensions, but should consider the types of potentially hazardous phenomena that may have occurred at volcanoes younger than 10 Ma and they may have an impact on the safety of the installation. The most important volcanic phenomena for the site selection and safety of the installation extend for short distances from volcanoes. The region considered for such potential hazards might only extend for tens of kilometres away from the site. For tephra-fall and other atmospheric hazards related to volcanoes, this region should extend for hundreds to thousands of kilometres from the site, giving due consideration to regional wind-field patterns[3]. Assessment of volcanic phenomena induced tsunamis should appropriately consider an entire ocean basin for some coastal sites (see Ref [6])

4.6. A hierarchy of geological maps and volcanological data is needed for initial assessment. At this stage, available geological maps may be adequate if they provide data at various scales. For example, a 1:500,000 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 assessment. Available records of satellite images and aerial photographs can be also useful for this purpose. Data retrieval should include international and national compilations of volcanological data, especially for Holocene and Quaternary volcanoes. Volcanic hazard maps and hazard assessments of specific volcanoes are often conducted as part of national hazard mitigation programmes. If available, such hazard maps and assessments should be included in the initial assessment. All this information may be used to develop thematic mapping through a Geographic Information System (GIS) to be develop during the different stages of the volcanic hazard assessment.

4.7. Volcanism should be characterized in terms of the types of volcanoes and potential volcanic eruptions concerned (see Annex 1). At this initial stage it will be helpful also to consider volcanic activity in terms of age, overall spatio-temporal trends, morphology, eruptive products and associated range of eruptive behaviours, 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 and deposits during initial assessment. This detailed characterization provides the groundwork for determination of the appropriate geographic region for the volcanic hazard assessment. This characterization should be supported by data of appropriate resolution.

4.8. Age determinations are fundamental information for the initial assessment stage. 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. For many cases, available information for initial assessment may not be sufficient for a robust appraisal at this stage of a site evaluation. In

[3] As an example, off the Atlantic coast of South America, a tephra fall deposit of decimetric thickness is reported from an unknown Andean volcano, probably 1000 km distant. Such types of circumstance call for more detailed investigations.

these circumstances, additional geochronological, geological and volcanological data should 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.

INFORMATION REQUIRED FOR HAZARD SCREENING AND SITE SPECIFIC HAZARD ASSESSMENT (Stages 2-4)

4.9. If the findings of the initial assessment indicate the presence of volcanism younger than 10 Ma, the next step should be to examine and, if necessary, gather more detailed information on the timing and characteristics of that volcanism and any associated phenomena in the surrounding region. This information should be added to the volcanological database as indicated in the following paragraphs.

4.10. The database should incorporate statements or records of associated uncertainties, data quality or grading, data sources, and any other related information that can be helpful in assessing the evidential strength and reliability of the data in relation to establishing the robustness of the hazard assessment.

4.11. Because volcanoes often have complex geologic histories, additional information may be required in order to ensure a comprehensive hazard assessment. First and foremost, any information that is specific to a volcanic source found in the geographic region should be included in the database. Additionally, it may need to be recognized that the geologic record of volcanic activity for a given specific source could be incomplete. For such cases, rates of activity at analogous volcanoes may be useful to supplement information collected in the geographic region of the site in order to evaluate the possibility of future eruptions. Similarly, the spatial distributions of volcanic products found at analogous volcanoes may be useful in helping to define screening distance values. Whenever such analogue information is utilized in the hazard assessment, it too should be included in the database.

Geologic Data

4.12. Decisions regarding the characterization of volcanic sources and screening distance values all rely on information about the timing and magnitude of activity at potential volcanic sources. Therefore, the database should document:

(a) the spatial distribution of volcanic sources and geologic controls on the distribution of these volcanic sources (such as relationship to tectonic features);

(b) the number and timings of eruptions at each source;

(c) the repose intervals between eruptions, and durations of eruptive episodes at each source, where it is possible to determine these;

(d) the current topography of each potential source of volcanic activity and relationship to the topography of the site (such as a digital elevation model);

(e) the range of eruption magnitudes, dynamic processes (such as eruption intensity and style) and eruptive products;

(f) information about trends in eruptive activity, such as spatial migration of volcanic sources, or temporal evolution of geochemistry, and changes in the volume of eruption products.

4.13. For volcanic sources with any documented historical activity, the database should contain information relevant to a full understanding of the scale and timing of this activity. Possible volcanological information taken from historical sources should include:

(a) location of the volcanic sources (e.g. latitude, longitude, elevation) and dates and durations of eruptions;

(b) description of the types of eruptive products, including areal extent, volume and composition;

(c) areal extent and magnitude of associated seismic activity, ground deformation, and other geophysical and hydrological activity or anomalies;

(d) description of current activity at the volcano including monitoring programmes and review of monitored data (such as seismic data and ground deformation data), if any.

4.14. The database should include descriptions of any volcanic products younger than 10 Ma. For Holocene and younger volcanoes, including those that are currently active, the entire 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 commonly is 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.

4.15. The information in the database should form the substantive basis on which to assess the potential for specific phenomena to affect the site, and should be used to develop screening distance values for these phenomena. Therefore, data should be compiled on volcanic products that could reach the site from each potential source. Deposits younger than 10 Ma in the geographic region of interest should be identified and evaluated to provide the following information:

(a) type and distribution of the deposits, and identification of the likely source or sources;

(b) ages, volcanological and petrological characteristics of the associated eruptions and their products.

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, complete volcanological information should be collected. In order to compile complete volcanological information, it may be necessary to complete one or more boreholes at the site and to log and sample the stratigraphic section revealed in these boreholes. Rock samples from these boreholes may be characterized petrographically, geochemically, and if appropriate, radiometric age determinations may be made using these samples.

4.16. If such deposits are identified, additional information should be provided for each distinguishable tephra fall episode that may have impacted the site. For example, tephra fallout from a nearby volcano that did not result in deposition at the site itself – perhaps only because of meteorological conditions during the eruption - should also be included in the database. This information about an individual tephra fall deposit should include:

(a) isopach and isopleth maps showing the extents, thicknesses, volumes, particle sizes and dispersion axes of deposits;

(b) equivalent static load (wet and dry) of the resulting deposits;

(c) derived eruption parameters, such as eruption column height (if not directly observed), mass eruption rate, and eruption duration.

4.17. For each distinguishable deposit produced by pyroclastic flow, pyroclastic surge, or volcanic blast that may have impacted the site vicinity, the following information should be collected:

(a) thicknesses, volumes, densities, areal distribution, and probable velocities and temperatures of emplacement, and estimates of maximum dynamic pressure achieved during flow, if possible and necessary;

(b) data about topographic features that influenced the direction and kinetic energy of flows driven by gravity or directed volcanic blasts (areas over which such flows may have passed without leaving measurable deposits should also be shown);

(c) inferences from such data about the source conditions in each case (e.g. height above vent of a column collapse pyroclastic flow).

4.18. For each distinguishable deposit produced by lava flow, lahar, debris flow, or debris avalanche, the following information should be collected:

(a) areas inundated by these flow phenomena, thickness and volume of the deposits;

(b) probable temperature of emplacement, velocity, and estimates of dynamic pressure, and related criteria to distinguish flows associated with magmatic activity from those not associated with magmatic activity;

(c) data about topographic features that influenced the flowpath from the source, velocity and distribution of the flows, and relationship to current topography.

Geophysical and Geochemical Survey Data

4.19. Data collected using instrumental methods at individual capable volcanoes within the region of interest can improve the overall hazard assessment. There are several reasons to survey such volcanoes:

(a) to help reduce the level of uncertainty in the understanding of particular volcanic phenomena;

(b) to provide an objective basis for detecting changes in the level of activity of the volcano and prospects for future eruptive phenomena;

(c) to take advantage of new emerging or improved technologies or techniques to strengthen information (i.e. the database) about the specific volcano; and

(d) for capable volcanoes, to comply with safety requirements for monitoring [1].

4.20. 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 stage of the process. In addition to surface measurements, geophysical and geochemical observations made in boreholes in the site vicinity may provide valuable data about water and gas chemistry (e.g., the presence of magmatic gases), temperature, state of stress, and related observations relevant to volcanic hazard assessment. Survey data should be interpreted and integrated with other data that contributes to the site evaluation process, and included in the database.

4.21. In the following paragraphs brief reviews of some of the various recognized ways of surveying volcanoes for the evaluation of volcanic activity are provided. For the design, implementation, and analysis of these techniques, specialist advice should be obtained. Close co-operation with institutions that operate existing monitoring systems, such as national programmes for prediction of volcanic eruptions and mitigation of disasters, should be sought. Survey planning and design should consider the possibility that data collection activities might evolve into a monitoring programme for constructed installations [1].

Volcano-seismic signals

4.22. Instrumental monitoring of volcano-seismic signals is generally recognized as being one of the best methods for detecting volcanic activity and changes in the state of a volcano. Unrest of a volcano with the potential for eruptive activity can be discerned by certain patterns and types of volcano-seismic signals occurring within or near the volcano, and dedicated seismic monitoring is needed to detect these signals.

4.23. A seismographic network for volcano monitoring should be capable of recording all types of volcano-seismic signals (e.g. tremor, as well as transient events) and its technical capabilities should allow for the appropriate characterization of the properties of these signals. Recent developments in seismic tomography techniques and deep tremor detection, for instance, have demonstrated their usefulness for investigating subsurface volcanic systems.

Ground deformation

4.24. Ground deformation and changes in volcanic topography may reflect surface instability or underground movement of magma, ground water, and gas. Typically, ground deformation techniques will provide repeated measurements of variations in elevation, angles, and distances between points in a network. These measurements can be acquired by various techniques on the ground or by remote sensing. Because ground deformation may be extremely subtle, or obscured by confounding effects, it is recommended that ground deformation monitoring networks be deployed at an early stage in site evaluation.

Geomagnetism and Geoelectricity

4.25. Measurements of geomagnetic and geoelectrical parameters may be useful to understand underground structure, the position of magmatic bodies or groundwater systems, and to detect changes in them. Results from these methods can enhance understanding of volcanic structures and the large-scale geophysical properties of the volcanic edifice, such as zones of hydrothermal alteration.

Gravity

4.26. Measurements of gravity should be made over volcanic terrain to give useful information about rock properties such as porosity and mass density, and about geologic structure, such as the distribution of faults in volcano edifices. When detailed measurements of temporal variations of gravity can be made in conjunction with precise measurements of ground deformation, it may be possible to detect movement of volcanic fluids or other internal mass transfer processes.

Gases

4.27. The composition and the flux of gases discharged from a volcano via craters, fumaroles, or passively through the ground or into crater lakes should be obtain to provide useful clues as to the degree and character of volcanic activity. Multiple chemical species and variations of isotopic composition of gases can provide indication of the predominance of a juvenile magmatic origin or a hydrothermal or meteoric source. For hazard assessment purposes it is important to establish the area affected by such degassing, either by direct emanations through the soils of the area, or by mass loading of the atmosphere. Variations in gas output can also be diagnostic of a change in the state of the volcano.

Geothermal anomalies and geothermal fluids

4.28. Changes in the temperature, composition, and location of thermal anomalies related to fumaroles, vents, crater lakes, hot and cold springs, soils, and snow and ice fields are often good indicators of variations in volcanic activity. Hence a programme of inspection, monitoring or repeated measurements on the ground or by remote sensing should be considered.

Ground water circulation

4.29. Significant changes in ground water conditions can be induced by volcanic activity, sometimes acting over large distances. Fluctuations in water level and discharge, changes in chemical composition, temperature, conductivity, and dissolved gas content of hot or cold springs and crater lakes should be monitored. In addition, other more specialized techniques such as bathymetric measurements and acoustic monitoring of crater lakes may be appropriate.

Other Phenomenological Observations

4.30. Detailed and regular visual observations and inspection provide the most fundamental primary data to assess the state of activity of a volcano. Sometimes, the earliest signs of unrest can be detected by basic observations, such as anomalous sounds, felt earthquakes and ground vibrations, temperature variations and fluctuations in the activity of fumaroles and hotsprings, patterns of snow melting, drying up of wells, springs and lakes, and changes in the state of vegetation. Visual observations of the flux, intensity, colour and other features of gas or steam venting should be made because they may be informative and can be easily undertaken and reported. If such visual observations are possible, the installation of visible wavelength or infrared cameras for remote surveillance may be warranted, for instance.

4.31. Initially, many simple phenomenological observations may be anecdotal but, if verified, these should be formalized and integrated in the database, together with any information collected by more formal means.

4.32. The database should also contain the following additional information:

(a) statistics on seasonal wind directions and velocities as a function of altitude, where available;

(b) rainfall or snowfall data;

(c) data with which to identify potentially unstable slopes on volcanoes that could result in landslides and debris avalanches, such as digital elevation models, topographic maps, and drainage patterns.

4.33. A satisfactory interpretation of volcano monitoring data should include integration with counterpart meteorological data. This may be obtained by cooperation with surveillance undertaken for other purposes at the nuclear installation, as well as from regional national or international weather services.

4.34. Water courses that could become involved with transport of volcanic products towards, or sedimentation near, the site should be characterised and measurements programmes instituted. Real-time early-warning monitoring systems may be warranted in certain conditions.

Unrest and Eruption Monitoring

4.35. Since capable volcanoes should be subjected to a monoitoring programme (see paragraph 3.9), unrest and eruption monitoring data should be documented in the database. Many of the methods discussed previously, such as volcano seismology, are frequently used for monitoring purposes. Monitoring is often improved by utilizing multiple methods. If a capable volcano starts erupting, a programme of systematic sampling of products (e.g. lava, ash, aerosols) should be implemented to provide detailed information on the eruptive process and potential for further hazardous phenomena. Such data gathering and documentation related to unrest and monitoring should be coordinated with national programmes for volcano monitoring when possible.

Emerging Techniques

4.36. New and improved techniques for volcano monitoring and for geophysical and geochemical surveying of volcanic systems will continue to emerge. In terms of informing a site-specific volcanic hazard assessment, or for the determination of volcano capability, the fundamental test of any new monitoring or surveying technique must be that it provides substantive data or evidence in context. If this is satisfied, such data should be incorporated in the database. Advantage should be taken also of data arising from work undertaken for other purposes (e.g., for the assessment of other types of hazard at the site, for operational safety requirements, or as part of national or regional hazard mitigation programmes).

5. SCREENING VOLCANIC HAZARDS

5.1. Stages 1-3 of the volcanic hazard analysis (Figure 1) provide steps in the process to identify capable volcanoes. This should be accomplished using a hierarchy of screening decisions based on the potential of future volcanic activity and the location of the site relative to sources of hazardous phenomena. In this Section, criteria are developed for decision-making at each stage in this hierarchical assessment.

STAGE 1: INITIAL ASSESSMENT

5.2. This stage should focus on two primary considerations: 1) definition of an appropriate geographic region for the initial assessment of volcanic hazards; and 2) collection of evidence of volcanic activity occurring within the last 10 Ma. Stage 1 includes a detailed review of available sources for an appropriate geographic region around the site. This detailed review should typically include geologic maps, results from previous geologic investigations, and other information as discussed in Section 4. Criteria for defining the geographic region for the assessment is provided in paras 4.4 and 4.5.

5.3. 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 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 low-energy surface flows from volcanoes located much closer to the site. Nevertheless, high-energy surface flows, such as volcanic blasts, may readily overcome steep topography. The definition of the appropriate geographic region should be justified, to ensure that potentially hazardous volcanoes have been duly considered in the assessment.

5.4. Initial assessments should evaluate the evidence of volcanic activity occurring within the last 10 Ma. As described in para. 2.4, 10 Ma encompasses the timescales of regional volcanic activity in many volcanic arcs and intraplate volcanic settings. In addition, lack of volcanism in the last 10 Ma implies that probabilities of future eruptions are less than 10^{-7} per year. Finally, modern radiometric age determinations are generally quite good at distinguishing igneous rocks that are older than or much younger than 10 Ma, minimizing the potential for data uncertainties confusing the outcome of the initial hazard assessment.

STAGE 2: CHARACTERISING POTENTIAL SOURCES OF FUTURE VOLCANIC ACTIVITY.

5.5. If the outcome of the initial assessment in Stage 1 indicates that volcanoes or volcanic fields younger than 10 Ma are present in the selected geographic region, then these volcanic sources should be further characterized by additional investigations.

5.6. If there is evidence of current volcanic activity then future eruptions are possible and the hazard assessment should proceed to Stage 3. Evidence of current volcanic activity includes: historic volcanic eruptions, ongoing volcanic unrest, an active hydrothermal system (e.g., presence of fumaroles), and related phenomena.

5.7. Evidence of an eruption during the last 10 000 yr (i.e., the Holocene) is a widely accepted indicator that future eruptions are credible. Because the Holocene is often a readily recognized geologic boundary, national and international databases usually differentiate between volcanoes that have been active in the Holocene and older volcanoes. Information for determining if Holocene volcanic activity has occurred may come from multiple sources. Radiometric dating of volcanic products provides the most direct evidence that volcanic eruptions occurred within the Holocene.

5.8. 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.

5.9. 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 should be classified as Holocene(?)[4], which is consistent with established volcanological terminology. From a safety perspective, future eruptions should be considered credible for Holocene volcanoes (i.e., those with an questionable record of eruptions in the Holocene) and the analysis should proceed to Stage 3.

5.10. If evidence of current or Holocene activity does not exist, additional consideration should be given to assessing the timing of older activity in the region. Evidence of an eruption during the last 2 Ma 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 Ma 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 Ma have a potential for a future eruption.

5.11. At this step a probabilistic analysis of the potential for future volcanic events can be used. The event may be a volcanic eruption, or non-eruptive activity such as slope failure resulting from previous eruption. Probabilistic methods for this assessment may include frequency based 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 of eruptive products.

5.12. As indicated in para. 2.4, in some States, a value for the annual probability of 10^{-7} is used in the hazard assessment for external events as one acceptable limit on the probability value for interacting events having radiological consequences [2]. As volcanism is an external hazard, an annual probability of renewed volcanism in the region around the site (i.e. occurrence of an eruption) at or below 10^{-7} could be considered a reasonable criterion for

[4] Holocene(?): the query sign is explained as consistent with volcanic terminology where questionable Holocene age is indicated by Holocene(?).

initial screening. Because there is some smaller likelihood that a hazardous phenomena would reach the site if an eruption occurred, the value of 10^{-7} is a reasonable basis for initially screening potential volcanic sources of initiating events.

5.13. Deterministic approaches also may be used. For example, analogous volcanoes might be investigated to determine the maximum duration of gaps in eruptive activity and use this maximum duration of gap in activity as a threshold. For a volcano with an ongoing period of quiescence, the possibility of return to activity could be compared with this threshold value. Such a deterministic analysis should include discussion of the volcanic processes that drive volcanic activity and document why the volcanoes are truly analogous in terms of these processes.

5.14. 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, it may be argued that renewed volcanism is not possible. In cases where a resolution based on these other criteria is not achieved, a deterministic approach should simply assume that future eruptions are possible for any volcano younger than 10 Ma.

5.15. It may be found 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, lacking sufficient evidence, or if future volcanic events in the region of interest appear to be possible, additional analyses are warranted and the hazard assessment should proceed to Stage 3.

STAGE 3: SCREENING VOLCANIC HAZARDS

5.16. In cases where potential for future volcanic activity in the site region is identified, or cannot be precluded, 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, etc., see the Appendix). 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 scenarios that comprise complex sequences of volcanic events (Annex 1).

5.17. A deterministic approach to assessing hazards at this step can be based on screening distance values for specific phenomena. These screening distance values are thresholds beyond which the volcanic phenomena cannot reasonably be expected to extend. 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 nature of topography 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 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 examples from analogous volcanoes.

5.18. 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 to be 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 site-specific hazard assessment should be undertaken (i.e., Stage 4). This analysis should be completed for each volcanic phenomenon that is associated with each potentially active volcano, as each of these phenomena may have a different screening distance value.

5.19. A complementary approach to assessing hazards at this step is to estimate the conditional probability of a specific volcanic phenomenon reaching the site, given an eruption at the source volcano. Several methods are available to estimate this probability. These methods are discussed further in Section 6. In some circumstances, site characterization data alone may 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 full range of potential phenomena resulting from a future volcanic event.

5.20. Using a conditional probability estimate for a specific volcanic phenomenon with accompanying uncertainties can produce a range of probability values, which 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 conditional hazard alone is insufficient to support screening, volcano capability must be considered.

5.21. As indicated in para. 2.4, in some States a value for the annual probability of 10^{-7} is used in the hazard assessment for external events as one acceptable limit on the probability value for interacting events having serious radiological consequences [2]. Thus, an annual probability of hazardous phenomena affecting the site, given that an initiating volcanic event occurs, at or below 10^{-7} could be considered a reasonable criterion for screening decisions. This is calculated, for example, multiplying the probability of a volcanic event by the probability that phenomena associated with this event will reach the site, given that the event occurs. This multiplication of probabilities for initiating event by the conditional hazard also is an appropriate basis for identifying a capable volcano. The site specific hazard assessment (Stage 4) should be conducted for phenomena from capable volcanoes.

5.22. Note that there is a relationship between the magnitude of volcanic eruptions, and hence their potential to affect a site, and the certainty with which the probability of volcanic events can be estimated. Small eruptions often leave little or no geologic record. Therefore, there may be great uncertainty about the frequency of small eruptions. Alternatively, if only large magnitude eruptions can affect the site, it is the probability of these large magnitude eruptions that is of most interest in determining volcano capability. As large magnitude eruptions generally leave a significant geologic record, there may be more certainty in estimating the probability of large magnitude eruptions based on the geologic record of past activity. The conceptual model of the volcano, encompassing the nature and evolution of volcanic processes, should inform the estimate of the probability of these large magnitude volcanic events.

5.23. Many volcanic phenomena involve coupling between different processes, so that deterministic and probabilistic approaches should not consider individual processes only in isolation and should explicitly allow for coupled and compounded effects. 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 (see the Appendix and Annex 1).

6. SITE SPECIFIC VOLCANIC HAZARD ASSESSMENT

6.1. This section provides guidance for evaluating site specific volcanic hazards when one or more capable volcanoes are identified. This guidance is needed for conducting the assessment of specific volcanic hazards at the installation site as requested for the Stage 4 (Figure 1).

6.2. The volcanic phenomena listed in Section 2 and described in the Appendix are initially screened in Stages 1-3. Volcanic phenomena that were not screened out as part of Stages 1-3 require further consideration during the site-specific volcanic hazard assessment to determine the frequency, nature and magnitude of potential hazards The assessment should further provide sufficient information to determine if a design basis or other practicable solution for this volcanic hazard can be established. If a design basis or other practicable solution for this volcanic hazard cannot be established, the site shall be deemed unsuitable [1].

6.3. As in screening decisions in Stages 2-3, a combination of deterministic and probabilistic approaches may be needed to assess volcanic hazards in Stage 4. In deterministic methods, threshold values are defined based on empirical observations of past volcanic activity, analogous information from other volcanoes, and/or numerical simulation of volcanic processes. Site acceptability and design bases decisions are based upon whether these thresholds are exceeded or not. Probabilistic methods also may use a range of empirical observations, analogous information from other volcanoes, and/or numerical simulation to develop a distribution for the likelihood that hazardous phenomena will exceed any magnitude. Site acceptability and design basis decisions are derived from analysis of these probability distributions. In either method, both the potential for volcanic events to occur and their potential impacts on the nuclear installation should be evaluated. This evaluation is the topic of the site specific volcanic hazard assessment.

6.4. Each volcanic hazard that is included in the design basis should be quantified so that it can be compared with the design basis characteristics of other external events to the extent possible. For some of the volcanic hazards it may be possible to demonstrate that design basis derived for other external events envelope those derived for volcanic hazards. For example, physical loads resulting from tephra fallout may be enveloped by physical loads derived for other external events.

6.5. Guidance is provided in the following regarding 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 provided in the Appendix.

TEPHRA FALLOUT

6.6. Tephra fallout is the most widespread hazardous phenomenon from volcanoes. Even minimal tephra accumulation has the potential to disrupt normal operations at nuclear installations. 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 particles commonly have adsorbed acid leachates (e.g., SO_4, F, Cl) on their surfaces and so can cause chemical corrosion as well as pollution of water supplies.

6.7. Tephra fallout hazard assessments should consider: (i) the potential sources of tephra, (ii) the magnitudes of potential tephra-producing volcanic eruptions and the physical characteristics of these eruptions, (iii) the 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, such as increased likelihood of lahars, potential for pollution and chemical corrosion, which may have adverse affects on site operations.

Deterministic assessment

6.8. A deterministic approach should develop a threshold for the maximum credible thickness for tephra fallout deposits at the site. For example, actual deposits from analogous volcanoes could define the maximum thickness of accumulation at the site from a capable volcano. Particle size characteristics (grain-size distribution and maximum clast size) could be estimated from these deposits. Analogue deposits or eruptions can also provide information about soluble ions that form acid condensates, which accompany tephra fallout processes. Numerical models of tephra fallout may also be used to derive a threshold, based on tephra accumulation at the site associated with specific eruption and meteorological conditions. The uncertainty in the different parameters should be properly taken into account.

Probabilistic assessment

6.9. 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. The uncertainty in the resulting hazard curve should be expressed by confidence bounds, with a stated basis for the selection of the reported confidence levels.

Factors to Consider in Design Basis and Site Evaluation

6.10. The 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. This information may be also used to assess particle size distribution and potential for remobilisation of tephra deposits, creating atmospheric mass loads of particles or debris flows and lahars. Tephra hazards may also result from the opening of new vents.

PYROCLASTIC DENSITY CURRENTS: PYROCLASTIC FLOWS, SURGES AND BLASTS

6.11. Pyroclastic flows, surges and blasts, known collectively as pyroclastic density currents, accompany not only explosive volcanic eruptions but also effusive volcanic eruption forming lava domes or thick lava flows. The impacts of pyroclastic density currents are very severe for obstacles in their flowpaths, because these flows move at high velocities, commonly at high temperatures (e.g., more than 300 °C). In addition, they 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. Deposits resulting from pyroclastic density currents can exceed tens of metres in thickness. The effects of pyroclastic density currents may exceed many common design bases, and, thus, often represent site acceptability issues.

6.12. Although flow can be controlled topographically, surges and blasts are less constrained by topography than pyroclastic flows, and commonly overcome most topographic obstacles. All types of pyroclastic density currents are known to surmount topographic obstacles in some circumstances or to flow across large bodies of water.

6.13. Hazard assessments for pyroclastic density current should consider: (i) the potential sources of explosive volcanic events and lava domes and flows that may collapse, (ii) the magnitudes of potential volcanic eruptions and the physical characteristics of these eruptions that result in pyroclastic density currents, (iii) the frequency of explosive volcanic eruptions or dome collapse events that lead to different types of pyroclastic density currents, (iv) topography between source regions and the site that can affect the flowpath and extent of pyroclastic density currents, and (v) secondary effects of deposition of pyroclastic density currents, such as increased likelihood of lahars and debris flows.

Deterministic assessment

6.14. A deterministic approach should consider the volume and energy of the pyroclastic density current resulting from an eruption and hence establish a threshold based on the potential maximum travel distance (runout). Screening distance for these phenomena could be determined based on the volume and nature of pyroclastic density current deposits exposed within the geographic region of concern, or by referring to flow events identified at analogous volcanoes. Potential runout also can be estimated using numerical models. The uncertainty in the different parameters should be properly taken into account.

6.15. The threshold values specified for pyroclastic flows, surges, and blasts are not necessarily the same. Surges, for example, may also form from pyroclastic flows and may extend several kilometres beyond the pyroclastic flow front. In this circumstance, pyroclastic surges may have a screening distance value generally greater than that for pyroclastic flows.

Probabilistic assessment

6.16. Probability of pyroclastic density currents should be calculated as a conditional probability of an eruption of given intensity, multiplied by conditional probability distributions for: (i) the occurrences of pyroclastic density currents, (ii) runouts of these phenomena; and (iii) directivity effects. The value for conditional probability of pyroclastic density currents should be representative of the magma's physical properties, the dynamics of the eruption including interaction with hydrothermal and groundwater systems, and the physics of flow spreading and diffusion. In many circumstances the past frequency and nature of pyroclastic density currents from the capable volcano, and from analogous volcanoes, can inform the estimate. The uncertainty in the resulting probability should be expressed by confidence bounds, with a stated basis for selection of the reported confidence levels.

Factors to Consider in Site Selection

6.17. Several additional factors should be considered in making site acceptability judgements related to hazards from pyroclastic density currents. Both threshold values and probability estimates related to most pyroclastic density currents might be evaluated using the energy cone model, an empirical model commonly used to estimate potential runout distances.

More sophisticated numerical models of pyroclastic density currents coupled with Monte Carlo simulations can generate probabilistic assessments of runout and destructive effects. Although this is an area of intense research in volcanology, comprehensive dynamic models of pyroclastic flows and surges are not yet fully established. Consequently, a variety of observations and modelling approaches should be considered in both deterministic and probabilistic approaches. Pyroclastic density currents can give rise to secondary hazards, such as tephra fallout, debris flows, and tsunamis.

LAVA FLOWS

6.18. Lava flows commonly destroy or bury engineered structures in their path. The impact of lava flows depends primarily on two factors:(i) the physical characteristics of the lava, and (ii) the discharge rate and duration of the eruption. The morphology of the vent and the topography across which lava flows move are also factors in controlling lava flow length. Lava flows have direct impacts due to their dynamic and static loads, flow thickness, and their elevated temperature (up to 1200 °C). The effects of lava flows usually exceed many common design bases, and, thus, often represent site acceptability issues.

6.19. In order to estimate hazard associated with lava flows for each capable volcano, it is necessary to estimate: (i) the potential magnitude (e.g., mass discharge rate, areal extent, velocity, thickness) of lava flows, (ii) the frequency of future effusive volcanic eruptions, (iii) the eruptive scenario (individual lava flows, lava tubes, flow fields), and (iv) the physical properties of erupted lava.

Deterministic assessment

6.20. 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 threshold values based on the maximum credible length, areal extent, thickness, temperature and potential speed of lava flows that could reach the nuclear installation. This can be achieved using data from other volcanoes from the region of concern, from analogue volcanoes, or from empirical or numerical models of lava flow emplacement. Some empirical lava flow emplacement models rely on correlations between lava flow length and effusion rate, whereas others are volume-limited. Topography along the path and at the nuclear facility 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. The uncertainty in the different parameters should be properly taken into account.

Probabilistic assessment

6.21. A probabilistic approach should also address the locations of vents and the potential formation of new volcanic vents. The probabilistic approach should entail numerical modelling 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. In these numerical simulations, vent location, topography, discharge rate, viscosity of the flow, and duration of the eruption are key parameters that control modelled lava flow emplacement. Probabilistic assessments use models of lava flows coupled with Monte Carlo simulations. Empirical observations from the capable volcano and analogous volcanoes can be used to inform the probabilistic analysis. Lava flow hazard curves should then be determined and combined to express the probability of exceedance of lava flow incursion and thickness at the nuclear installation. Uncertainty in the resulting hazard curves should be expressed by confidence bounds, with a stated basis for the selection of the reported confidence intervals.

Factors to Consider in Site Selection

6.22. Several additional factors should be considered in making site acceptability judgements related to lava flow hazards. The probabilistic or deterministic approaches should result in estimates of the potential for any lava flows to reach the nuclear facility, their likely thicknesses, as well as their thermal properties. This assessment should consider the effects of phenomena associated with lava flows such as generation of floods following interaction with ice and snow fields, water impoundments, opening of new vents and generation of pyroclastic flows from the collapse of viscous lava domes and flows.

DEBRIS AVALANCHES, LANDSLIDES AND SLOPE FAILURES

6.23. Debris avalanches resulting from edifice collapse should be considered separately from other slope failures mainly because of the potentially very large volumes involved (possibly exceeding several tens of km^3), high velocities, and the considerable distances that can be reached (e.g., possibly exceeding 150 km). Other, smaller-scale slope failures can be treated within the scope of other (i.e. non-volcanic) geotechnical hazards [7]. The impact of volcanic debris avalanches is predominantly mechanical due to the mass of material involved and its velocity, and the great thickness to which these deposits can accumulate. Given the wide range of volumes, and hence consequences for a site, the effects of debris avalanches, landslides, and slope failures should be considered in deriving design bases and often represent site acceptability issues.

6.24. A hazard assessment for debris avalanches, landslides, and slope failures for each capable volcano should consider: (i) the potential source regions of these events, (ii) the potential magnitude (volume, aerial extent, thickness) of these events, (iii) the frequency of such events, and (iv) their potential flowpaths. These hazard 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 nuclear facility should be considered, noting that during some eruptions topography is altered during the eruption so that flow paths may be altered significantly.

Deterministic assessment

6.25. A deterministic approach should determine the threshold value for the maximum credible volume, runout distance and thickness of avalanche deposits at the site using information collected from actual deposits from analogous volcanoes, and 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. The uncertainty in the different parameters should be properly taken into account.

Probabilistic assessment

6.26. A probabilistic approach should extend the numerical modelling of these flows and proceed with numerical simulations for each capable volcano accounting for a range of values for parameters that control geometry of the source region, flow length, velocity, volume and thickness using stochastic methods. Probabilistic methods can be informed by the record of volcanic events at the capable volcano and by analysis of similar events at other volcanoes. Hazard curves should then be determined and combined to express the probability of incursion at the site. Uncertainty in the resulting hazard curves should be expressed by confidence bounds, with a stated basis for the selection of the reported confidence intervals.

Factors to Consider in Site Selection

6.27. Several additional factors should be considered in making site acceptability judgements 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 should 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.

VOLCANIC DEBRIS FLOWS, LAHARS AND FLOODS

6.28. Debris flows, lahars, and associated floods of volcanic origin should be considered separately from other ordinary floods mainly because of the short time of warning 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. possibly more than 150 km from the source). In addition to the impacts associated with ordinary flooding, debris flows and lahars produce mechanical effects due to the mass of material involved and its velocity and its erosive power. The occurrence and effects of debris flows and lahars can persist for months to decades following volcanic eruptions as volcanic products, such as pyroclastic density current and tephra fallout deposits, are remobilized through time. Deposits of debris flows and lahars may reach significant thickness (e.g., tens of meters). Given the wide range of volumes, and hence consequences for a site, the effects of debris flows, lahars, and floods should be considered in deriving design bases and often represent site acceptability issues. Floods associated with volcanic events should be treated in a manner consistent with floods of non-volcanic origin [6].

6.29. 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 including snow-cap and glaciers, (ii) estimate the potential magnitude and flow characteristics, (iii) consider modification of the flow properties along the path, the sources of water, and topography from the source region to the nuclear facility, (iv) 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.

Deterministic assessment

6.30. A deterministic approach should determine a threshold based on the maximum credible volume, runout distance and thickness for debris flow and lahar deposits for the site using information about actual deposits from nearby, analogous volcanoes, and debris flow emplacement models. A screening distance value can thus be defined for these flows beyond which they are not thought to be credible events. Floods of volcanic origin should be evaluated in a manner consistent with the IAEA safety guide on flood hazard [6]. The uncertainty in the different parameters should be properly taken into account.

Probabilistic assessment

6.31. A probabilistic approach should entail the numerical modelling of these flows 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. These models can be informed by observations of debris flow and lahar deposits at the capable volcano and similar observations made at analogous volcanoes. Hazard curves should then be derived that express the probability of exceedance for flow incursion and discharge at the site. Uncertainty in the resulting hazard curves should be expressed by confidence bounds, with a stated basis for the selection of the reported confidence intervals.

Factors to Consider in Design Basis and Site Evaluation

6.32. Several additional factors should be considered in deriving design basis and in making site acceptability judgements related to debris flows, lahars, and associated floods. The probabilistic or deterministic approaches should result in estimates of their potential to reach the nuclear facility as well as their likely flow geometry and discharge. It is fundamental to consider indirect event sequences such as tephra fall on neighbouring non-capable snow clad volcanoes that could act as sources for debris flows, to consider floods generated by eruption under ice or snow, and to consider the sudden release of water and debris from breakage of volcanic dams in craters or valleys filled with volcanic debris.

OPENING OF NEW VENTS

6.33. The opening of new vents is a geologically rare phenomenon but one that can produce significant flow, tephra fallout, ballistic, and ground deformation hazards for a nuclear installation located close to the site of a new volcano (e.g., scoria cone). These new vents may be circular in form, or highly elongate fissures. Vents generally form clusters within volcanic fields, or are closely associated with large volcanic systems, such as shield and composite volcanoes and calderas. Multiple new vents form during some volcanic eruptions. Therefore hazard assessment of a capable volcano or volcanic field should consider that volcanic phenomena, such as tephra fallout, lava flows and pyroclastic flows, may originate from new vents, as well as existing vents, during a volcanic eruption. Opening of new vents at the site would exceed most design bases, and, thus, is a site acceptability decision. In addition, site evaluation and design bases should consider the potential for products erupted from new vents to affect the site.

6.34. Assessment of the likelihood of formation of new vents requires information about the distribution and ages of volcanic vents in the region. Additional information, such as geophysical surveys of the region, is often 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.

Deterministic assessment

6.35. 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. In addition to the formation of a new vent, this deterministic analysis should consider the distance eruptive products might travel from the new vent. The uncertainty in the different parameters should be properly taken into account.

Probabilistic assessment

6.36. Modern analyses of volcanic hazards associated with new vent formation normally involve probabilistic assessment. Probabilistic assessments should 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. In addition to the formation of a new vent, this probabilistic analysis should consider the distance eruptive products might travel from the new vent. Uncertainty in the resulting hazard curves should be expressed by confidence bounds, with a stated basis for the selection of the reported confidence intervals.

Factors to Consider in Site Selection

6.37. Several additional factors should be considered in making site acceptability judgements related to the opening of new volcanic vents. Results of this analysis could be expressed as the probability of a 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 should 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., metres), volcanic seismicity, and gas flux may occur in the site vicinity. During many volcanic eruptions, the formation of a new vent may involve phreatic or phreatomagmatic activity, which is generally highly explosive.

In such circumstances the opening of a new vent in water or shallow groundwater systems may result in a significantly more explosive eruption than represented by the products of past eruptions.

VOLCANO GENERATED MISSILES

6.38. Volcano generated missiles can be compared with impacts due to tornado-borne missiles or aircraft crashes but the potential number of missiles that may fall on a nuclear installation as generated by volcanic activity can be very high. At the vent, the particles have velocities in the range of 50 to 300 m/s, and the distance travelled is a function of their size and aerodynamic drag, which can be reduced behind shock waves produced by large eruptions. These factors mean that even large, dense particles, one metre in diameter, can travel kilometres from the volcanic vent. For hazard estimates for each capable volcano, it is necessary to estimate the source locations, potential magnitude, and frequency of future explosive eruptions. The fallout of volcano generated missiles often accompanies the formation of new vents. Furthermore, missile fallout commonly occurs when lava flows or pyroclastic flows enter bodies of water, producing secondary (rootless) vents. Missile fallout would disrupt normal operations at nuclear installations and could result in damage to structures at the facility. Design bases can be derived for most volcano generated missile fallout.

Deterministic assessment

6.39. A deterministic approach should define a threshold value using information from the maximum distance and size of missiles in previous explosive eruptions from analogous volcanoes. Missile transport models could also be used to determine a screening distance as a function of the exit speed, density of particles, exit angle, and wind field parameters. The analysis should consider the effect of topographic barriers between the nuclear installation and the vent, and the possibility of missiles from secondary vents. The uncertainty in the different parameters should be properly taken into account.

Probabilistic assessment

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

Factors to Consider in Design Basis and Site Evaluation

6.41. Several additional factors should be considered in deriving design basis and in making site acceptability judgements related to volcano generated missiles. Probabilistic and deterministic approaches may be used together. Results of this analysis could be expressed as the probability of potential impacts beyond a screening distance. The potential for volcano generated missiles should be considered as part of the hazard assessment of potential opening new vents and as impacts related to tephra fallout. Because missile fragments are commonly hot, they can initiate fires and the potential for such fires in or around the nuclear installation should be considered. Results of the analysis should be consistent with similar external hazards, such as missiles generated by human induced events or extreme meteorological phenomena (see Refs. [2] and [5]).

VOLCANIC GASES

6.42. Volcanic gases may be released in very large quantities during explosive volcanic eruptions, they can be released from volcanic vents at some volcanoes even during periods of non-eruptive activity, and can diffuse through soils and along fracture systems on and adjacent to volcanoes. Large lava flows are also a significant source of volcanic gases. The adverse effects of volcanic gases include asphyxiation, toxicity and corrosion, often associated with condensation of acids from volcanic gases and dry deposition, and heavy acid loading. The effects of volcanic gases on mechanical systems and personnel should be considered in deriving the design bases of nuclear installations.

6.43. 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.

Deterministic assessment

6.44. A deterministic approach should consider defining, using information from analogous volcanoes or gas concentration measurements at the capable volcano, 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 modelling should provide some indication of the extreme gas concentrations and acid loading that might occur at the site. The uncertainty in the different parameters should be properly taken into account.

Probabilistic assessment

6.45. A probabilistic approach should 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 resulting hazard curves should be expressed by confidence bounds, with a stated basis for the selection of the reported confidence intervals.

Factors to Consider in Design Basis and Site Evaluation

6.46. Several additional factors should be considered in deriving design basis and in making site acceptability judgements related to volcanic 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 should 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 should also evaluate the potential for catastrophic degassing of gas-charged (e.g., CO_2, CH_4) water bodies (e.g., crater or fault-bounded lakes) or hydrothermal systems to affect the site.

TSUNAMIS AND SEICHES

6.47. 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, lakes and reservoirs, normally consider tsunami and seiche hazards as part of the site assessment (see Refs. [5] and [6])... Nevertheless, specialist knowledge is needed to fully evaluate the likelihood and source characteristics of volcanogenic tsunamis. The effects from volcanically induced tsunamis and seiches are the same as those from seismically induced tsunamis and seiches. Inundation by tsunamis and seiches has the potential to disrupt normal operations and damage nuclear installations. Therefore tsunamis and seiche hazards are considered in both site evaluation and design.

6.48. Currently, tsunami and seiche hazards are evaluated using deterministic numerical models that should 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 [6]. 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.

ATMOSPHERIC PHENOMENA

6.49. Explosive volcanic eruptions can produce atmospheric phenomena that have potentially hazardous characteristics. Overpressures from air shocks can often extend for kilometres 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. Such atmospheric phenomena should be considered in derivation of design bases for nuclear installations.

6.50. Because explosive volcanic eruptions would be considered rare events for atmospheric phenomena [5], hazards assessment should consider a deterministic approach to model the potential maximum hazard for each phenomena associated with a potential volcanic eruption.

6.51. Volcanoes can be considered as stationary sources of explosions when considering air shocks in the hazards analysis [2]. Hazards analyses described in Ref. [2] for stationary sources of explosions are generally applicable to the analysis of air shocks from explosive volcanic eruptions. The air-shock analysis should focus on determining the potential maximum explosion for the volcanic source and a simplified analysis for shock attenuation with distance from that source.

6.52. Volcanically induced lightning has the same hazardous characteristics as lightning from other meteorological phenomena but is a frequent phenomena 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 [5]. A deterministic hazard assessment for volcanically-induced lightning strikes should consider the screening criteria used in hazard assessment of rare atmospheric phenomena [5] but consider that there is a potential for a large number of column-to-ground lightning strikes during an explosive eruption.

GROUND DEFORMATION

6.53. 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. Ground deformation also accompanies the opening of new volcanic vents. The magnitude of ground deformation varies considerably, from millimetric vertical and horizontal displacements at great distances from the volcano (e.g., > 10 km) to metres of displacement near some volcanic centres (e.g. a new vent or a restless caldera). Thus, most significant potential deformation in site locations is associated with the opening of new vents. Therefore, volcano deformation associated with distant capable volcanoes can be within design bases of nuclear installations. Near-vent deformation within the site vicinity area (i.e. about 5 km around the site), however, can exceed most design bases, and therefore, the potential for large volcanic deformation is a site acceptability issue.

6.54. The potential magnitude of ground deformation should be estimated in terms of displacement and results should be superimposed on topographic maps or digital elevation models in order to assess the potential for secondary impacts, such as landslides.

Deterministic assessment

6.55. In a deterministic assessment, a threshold value should be derived that reflects the maximum potential magnitude of ground deformation at the site. This threshold value may be estimated using information from analogous volcanoes where deformation has been directly observed and models of ground deformation that consider the movement and pressurization of magma bodies of various geometries and with various rock mechanical properties. The uncertainty in the different parameters should be properly taken into account.

Probabilistic assessment

6.56. Probabilistic assessment of potential ground deformation may simply link the magnitude of ground deformation estimated using models to the likelihood of such events, and to a range of potential intrusion geometries. As in deterministic approaches, models of ground deformation should consider the movement and pressurization of magma bodies of various geometries and with various rock mechanical properties. This probabilistic analysis may be informed by information from analogous volcanoes where ground deformation has been observed.

Factors to Consider in Site Selection

6.57. 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, should 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 (i.e. landslides and debris avalanches) 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 should be considered as part of the flood hazards assessment [6].

VOLCANIC EARTHQUAKES AND SEISMIC EVENTS

6.58. 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. Volcanic earthquakes can be large enough or numerous enough (hundreds to thousands per day) collectively to represent a potential hazard. Thus a specific volcano-seismic hazard assessment should be considered and, where appropriate, undertaken using similar methods to those set out in Ref. [4].

Deterministic assessment

6.59. In line with the approach to tectonic earthquake (i.e., seismic) hazard assessment, a deterministic method for assessing volcano-seismic ground motions should determine the combination of volcano-seismic event magnitude, depth of focus and distance from site which produces maximal ground motion at the site, with account taken of local ground conditions at the site. (It may be necessary to demonstrate that the volcano-seismogenic source structure cannot be construed a capable fault - see Section 6 of Ref. [4]). Suitable relationships for volcano-tectonic earthquakes should be derived for alternative ground motion parameterizations, such as peak acceleration, duration of shaking or spectral content. (specific ground motion characteristics of volcano-tectonic earthquakes may differ from those considered in paras 5.20–5.35 of Ref. [4], but the same principles should be applied). The uncertainty in the different parameters should be properly taken into account.

Probabilistic assessment

6.60. A probabilistic assessment of volcano-seismic hazard at a site should follow similar principles as those outlined in Ref. [4]. Allowance should be made for uncertainties in the parameters as well as alternative interpretations. Application of the probabilistic method should include the following steps: (i) construction and parameterisation 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 (for example, peak acceleration and an appropriate range of response spectral accelerations), for both horizontal and vertical motions.

Factors to Consider in Design Basis and Site Evaluation

6.61. In many cases a site close to a capable volcano will also lie in a region of significant seismic hazard from faults and fault zones and it may be possible to demonstrate that volcano-seismic hazards at a site are significantly lower than those associated with other sources of seismic activity. It should be recognized that the occurrence of volcanic activity may alter regional patterns in seismicity. For example, volcanic activity may result in pressurization of pore fluids along regional tectonic faults. When such an analysis does not provide a clear margin of difference, a deterministic or probabilistic volcano-seismic hazard assessment should be undertaken.

6.62. Volcano-seismic events may result in increased possibility of slope failure and may alter loads on structures (e.g., in tandem with tephra loading). Such effects should be considered and assessed for their potential influence on design basis and site evaluation.

HYDROTHERMAL SYSTEMS AND GROUNDWATER ANOMALIES

6.63. Hydrothermal systems can generate steam explosions, which eject rock fragments to a distance of several kilometres and can create craters up to hundreds of meters in diameter and result in the formation of new vents. Hydrothermal systems also alter rock to clays and other minerals, which creates generally unstable ground that can be highly susceptible to landslides. These factors make it questionable whether design bases can be derived for a nuclear installation located in an active hydrothermal system. Thus, the occurrence of a hydrothermal system and the potential for such a system to develop affects site acceptability. Active hydrothermal systems and groundwater perturbations due to volcanic events at capable volcanoes can create conditions that result in lahar formation and slope instabilities.

6.64. Factors that should be considered in evaluating the development and possible impacts of hydrothermal systems include: (i) knowledge of the lateral extent and nature of active hydrothermal systems associated with capable volcanoes, (ii) understanding of the patterns of groundwater circulation that may give rise to hydrothermal systems, and (iii) distribution of features, such as faults, that may influence the location and development of hydrothermal systems.

Deterministic assessment

6.65. A deterministic assessment would identify a threshold value for the distance from an existing hydrothermal system beyond which the hydrothermal system would not expand, and beyond which the possibility of a new hydrothermal system developing is negligible. Determination of this threshold value should consider the lateral extent and nature of hydrothermal systems at capable volcanoes, the lateral extent of hydrothermal systems at analogous volcanoes, and the hydrogeology of the site and surrounding area. The uncertainty in the different parameters should be properly taken into account.

Probabilistic assessment

6.66. A probabilistic assessment could consider numerical models for the development of hydrothermal systems in specific geologic settings, given changes in volcanic activity at capable volcanoes, and in conjunction with the opening of new vents. Such probabilistic models can be informed by information from analogous volcanoes. Output from the probabilistic model should be likelihood of a hydrothermal system developing at the site, given a range of input parameters related to the thermal state of the volcano and the properties controlling flow and transport in the hydrologic system.

Factors to Consider in Site Selection

6.67. Currently, it is difficult to determine the likelihood for steam explosions to occur at specific locations within most hydrothermal systems. Hazards associated with specific phenomena, such as the development of fumaroles or opening of new vents during steam explosions, are less important to consider explicitly than the development and lateral extent of the hydrothermal system itself. Rather, the presence of a hydrothermal system is a primary site acceptability issue. The effects of groundwater anomalies on potential for lahars, debris flows and slope stability should be assessed as part of analyses of those phenomena.

A COMPREHENSIVE VOLCANIC HAZARD MODEL

6.68. A comprehensive, site-specific volcanic hazard model involves a large number of complex interacting phenomena. Development of such models will require assistance from informed volcanological experts, preferably through a formal process designed to consider all expert judgement in relation to volcanic hazard at the site. 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 has been considered in the assessment.

6.69. 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.

6.70. Non-volcanic events, such as regional earthquakes or tropical storms, can initiate the occurrence of hazardous phenomena at a volcano. A comprehensive model of 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 the nuclear installation. For example, debris flows may persist in a region for years following explosive volcanic eruptions. Although such debris flows may not damage a nuclear installation directly, they may render normal operation of the installation impossible due to extensive or devastating impacts on the population and infrastructure of the surrounding region.

6.71. Overall, development of a site-specific volcanic hazard model should inform decisions about site acceptability and installation design. In reaching these decisions, it is strongly recommended that the potential for future volcanism and assessment of its potential effects be considered from the perspectives of the impact on: (i) the site, resulting in potential loss of containment and 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.

7. NUCLEAR INSTALLATIONS OTHER THAN POWER PLANTS

7.1. This section provides guidance for the volcanic hazard assessment for a broad range of nuclear installations other than nuclear power plants. This Safety Guide addresses an extended range of nuclear installations as defined by Ref.[9]: land based stationary nuclear power plants, research reactors, nuclear fuel fabrication plants, enrichment plants, reprocessing facilities and spent fuel storage facilities..

7.2. For the purpose of volcanic hazard assessment, these installations should be graded on the basis of their complexity, potential radiological hazards, and hazards due to other materials present. Volcanic hazard assessment should be done in accordance with this grading.

7.3. Prior to categorizing an installation, a conservative screening process should be applied based on the assumption that the complete radioactive inventory of the installation is released by an accident initiated by a volcanic event. If the result of this simulated release is that no unacceptable consequences would result for workers, the public (i.e., doses to workers or the public due to the release of the inventory would be below the limits established by the regulatory body) and/or the environment, and no other specific requirements have been imposed by the regulatory body for such an installation, the installation may be screened out from further volcanic hazard assessment.

7.4. If the results of this conservative screening process show that the consequences of the release are ‘significant’, a volcanic hazard assessment and safety evaluation for the nuclear installation should be carried out according to the steps indicated from paras 7.5 to 7.14.

7.5. The likelihood that a volcanic event will give rise to radiological consequences depends on characteristics of the nuclear installation (e.g. its use, design, construction, operation and layout) and on the nature of the volcanic event itself. Characteristics of the nuclear installation that warrant consideration include the following factors:

(a) The amount, type and status of radioactive inventory at the site (e.g. solid, fluid, processed at the installation or only stored, etc.);

(b) The intrinsic hazard associated with the physical processes (e.g. criticality) and chemical processes that take place at the installation;

(c) The thermal power of the nuclear installation, if applicable;

(d) The configuration of the installation for activities of different kinds;

(e) The concentration of radioactive sources in the installation (e.g. for research reactors, most of the radioactive inventory will be in the reactor core and fuel storage pool, while at processing and storage plants the radioactive inventory may be distributed throughout the plant);

(f) The changing nature of the configuration and layout for installations designed for experiments (such activities have an associated intrinsic unpredictability);

(g) The need for active safety systems and/or operator actions to cope with mitigation of postulated accidents; characteristics of engineered safety features for preventing accidents and for mitigating the consequences of accidents (e.g. the containment and containment systems);

(h) The characteristics of the processes or of the engineering features that might result in a cliff edge effect in the event of an accident;

(i) The characteristics of the site relevant to the consequences of the dispersion of radioactive material to the atmosphere and the hydrosphere (e.g. size, demographics of the region, etc.);

(j) The potential for on-site and off-site radiological contamination resulting from the volcanic event.

7.6. Volcanic hazard at the site should be evaluated in accordance with the procedures described in this Safety Guide.

7.7. Although most nuclear installations are located at surface sites, some nuclear installations may be located in the subsurface. Most hazards from surface volcanic processes, such as lava flows, have limited potential to affect the safety of a subsurface installation. Surface flow phenomena from volcanoes may impact ventilation and water circulation systems associated with such subsurface facilities. Direct intrusion of magma, or other igneous processes that accompany the opening of new vents, including volcanic gases, ground deformation, volcanic earthquakes and circulation of geothermal fluids, are of principle concern for the volcanic hazard assessment of subsurface installations. Analyses of volcanic hazard for subsurface installations may need to consider the transport and release of radioactive material in the biosphere by volcanic processes, such as tephra fallout and lava flows, if there is potential for eruptive conduits to develop through the installation.

7.8. Depending on the criteria of the regulatory body, some or all of the above factors should be considered. For example, fuel damage, radioactive releases or doses may be the conditions or metrics of interest.

7.9. The grading process should be based on the following information:

(a) The existing safety analysis report of the installation should be the primary source of information;

(b) If a comprehensive volcanic hazard assessment has been performed (Stages 1-4), the results of this study should also be used in the grading process;

(c) The characteristics of the installation specified in Para 7.5.

7.10. The grading of the installation leads to its categorization. This grading may have been performed at the design stage or later. If this grading has been performed, the assumptions on which it was based and the resulting categorization should be reviewed and verified. In general, the criteria for categorization should be based on the radiological consequences of the releases of the radioactive material contained in the installation, ranging from very low radiological consequences to potentially severe radiological consequences. As an alternative, the categorization may range from radiological consequences limited within the borders of the installation itself, to radiological consequences limited within the site boundary of the installation, to radiological consequences to the public and the environment outside the site.

7.11. As a result of this process for grading of the installation, three or more categories of installations may be defined on the basis of national practice and criteria as indicated in para. 7.9. As an example, the following categories may be defined:

(a) The lowest hazard category includes those nuclear installations for which national building codes for conventional facilities (e.g. essential facilities, such as hospitals) or for hazardous facilities (e.g. petrochemical or chemical plants), as a minimum, should be applied.

(b) The highest hazard category contains installations for which nuclear power plants standards and codes should be applied.

(c) There is often one or more intermediate categories of hazardous installations, for which, as a minimum, codes dedicated to hazardous facilities should be used.

7.12. The volcanic hazard assessment should be performed using the following guidance:

(a) For the least hazardous installations, the volcanic hazard may be estimated from national volcanic hazard maps or similar volcano-specific hazard assessments.

(b) The installations in the highest hazard category should use all of the methodologies for volcanic hazard assessment described in this Safety Guide, i.e. recommendations applicable for nuclear power plants.

(c) For installations categorized as in the intermediate hazard category, the volcanic hazard assessment is typically performed using the methodologies described in this Safety Guide, but higher probabilities of volcanic events or higher thresholds of activity in deterministic analyses may be acceptable for site selection and evaluation, and design of such installations. For such intermediate hazards category installations simplified methods may be appropriate, in cases where the database and the methods recommended in the Safety Guide are found to be excessively complex and time/effort consuming for the nuclear installation in question. Such analyses may be based on national or similar regional databases of volcanic eruptions (Annex 2), and simplifying assumptions might be used to assess the potential of specific volcanic phenomena to affect the site.

7.13. Unless national regulations require otherwise, the volcanic hazard assessment for nuclear installations of the lowest hazard category should be based on existing volcanic hazard maps applied to the site, including appropriate factors for rates and nature of volcanism and topography of the site region. In cases where no such volcanic hazard maps exist, such hazard maps should be prepared and applied to the site following national standards for volcanic hazard assessments.

7.14. The recommendations relating to volcano monitoring of capable volcanoes in the geographic region of interest (see paras. 3.9 and 4.36) should be reduced in a way commensurate with the category of the installation defined in para. 7.11.

8. MONITORING AND PREPARATION FOR RESPONSE

8.1. As required by Ref. [1] para. 5.1, the characteristics of the natural and human induced hazards as well as the demographic, meteorological, and hydrological conditions of relevance to the nuclear installation shall be monitored over the lifetime of the nuclear installation. Considering that capable volcanoes represent natural induced hazards, if a nuclear installation is constructed that has an associated capable volcano, that volcano should be monitored over the lifetime of the nuclear installation. Thus, if a volcano monitoring programme is not present during the site acceptability stage, such a programme should be developed by the time the start of construction of the installation and maintain and keep update during the operational stage.

8.2. Since volcanic hazards can originate from well beyond the boundaries of the installation, monitoring should be conducted in collaboration with appropriate national and international institutions whose mission is to observe and monitor volcanoes. It may be the case that capable volcanoes are not currently monitored or are given comparatively low monitoring priority by national and international volcano observatories tasked with volcanic hazard reduction on a national scale. Therefore all stakeholders (e.g., operators, regulators and other government organizations) should work with these volcano observatories to achieve an appropriate level of monitoring, commensurate with the nature of the capable volcano and with the hazards posed to the nuclear installation. In the absence of an established volcano observatory, the stakeholders themselves may need to install such observatory as part of the monitoring programme.

8.3 Some of the data collection activities performed during the site characterization stage (Section 4) may involve assessing the current state of activity at volcanoes that might be capable. As the personnel who made these assessments may be from volcano observatories, and the instrumentation required to monitor capable volcanoes may be in place during this stage, a monitoring programme should be developed using these personnel and infrastructure to the extent practical. Involvement of personnel from volcano observatories early in the site characterization will facilitate development of an appropriate monitoring programme for capable volcanoes.

8.4 The emergency plan for the nuclear installation should consider how results or alerts from the volcano monitoring program will be used in operational responses. A detailed procedure should be prepared to consider and respond to changes in the potential for volcanic hazards that are detected by the monitoring system. Most volcanic systems show a systematic increase in indicators of unrest prior to potential eruption, which allows for the development and use of a graded level for alert. Most volcano observatories around the world are responsible for establishing the level of alert based on information from the monitoring system. The levels of response in the emergency plan should be based on the levels of alert identified by the volcano observatory. Development of the emergency plan should be coordinated with appropriate representatives of volcano observatories to ensure a clear operational response to alert information provided during periods of volcanic activity.

9. MANAGEMENT OF VOLCANIC HAZARDS EVALUATION

9.1. An adequate management system, that includes quality assurance programme [10], [11] should be established and implemented to cover all activities related to data collection, data processing and interpretation, field and laboratory investigations, numerical modelling and technical evaluations that are within the scope of this Safety Guide. At each step in the hazard assessment, documentation should be provided to support outcomes of the assessment.

9.2. In view of the complexity of the volcanic hazard assessment, an independent peer review should be conducted by a peer review panel. The peer reviewer(s) should not have been involved in other aspects of the volcanic hazard assessment and should not have a vested interest in the outcome. The level and type of peer review can vary depending on the nature of the volcanic hazard. The peer review should address all parts of the volcanic hazard assessment, including the process for the volcanic hazard assessment, all technical elements (e.g. determination of volcano capability, geological and geophysical investigations, assessment of rates of past volcanic activity), methods used for the volcanic hazard assessment (e.g. use of numerical models), and quantification and documentation. The peer review panel should include the multidisciplinary expertise to address all technical and process related aspects of the study.

9.3. The purpose of the peer review is to provide assurance that a proper process has been duly followed in conducting the volcanic hazard assessment, that the analysis has addressed and evaluated epistemic uncertainties, and that the documentation is complete and traceable.

9.4. Two methods for peer review can be used: (1) participatory peer review and (2) late stage peer review. A participatory peer review is carried out during the course of the study, allowing the reviewer(s) to resolve comments as the volcanic hazard assessment proceeds and as technical issues arise and decreasing the likelihood of the study being rejected at a late stage. A late stage and follow-up peer review is carried out towards the end of the study.

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APPENDIX - DESCRIPTION OF TYPES OF VOLCANIC PHENOMENA

A.1. A brief description of the physical characteristics of each volcanic phenomenon and an indication of the order of magnitude of representative parameters associated with each phenomenon are presented. However, a comprehensive volcanic hazard assessment should quantify specific parameter values for a given site. Additional information about volcanological terms used in the following is provided in the Glossary.

Tephra Fallout

A.2. The fall and deposition of pyroclastic material such as ash, pumice and scoria occur when these particles are lofted by an explosive eruption to altitudes of several to tens of kilometres (generally < 40 km above sea-level). This material is transported in the atmosphere by wind. Volcanic eruptions produce widely varying volumes of tephra, but total mass released in explosive volcanic eruptions commonly exceeds 10^{11} kg (approximately 10^8 m^3 tephra by volume). On falling, pyroclasts normally reach a constant velocity (so-called terminal velocity), which is determined by the size, shape, density of the falling particle, air density, and air viscosity. Their distribution is governed by the velocity and direction of the wind and by the nature of the eruption column. Thickness and mass per unit area of tephra deposited generally decrease with distance from the volcano, each in a roughly exponential manner. Thus tephra fallout may occur more than 100 km from the vent, and mass per unit area may vary from less than 10 kg/m^2 far from the vent to more than 1000 kg/m^2 close to the vent. When wet, these loads may be more than double. Tephra particles can range in size from microns to decimetres and average particle size decreases with distance from the volcano. Substantial tephra fallout is generated by Plinian volcanic eruptions. Vulcanian and Strombolian –style volcanic eruptions also generate tephra fallout. Tephra fallout is common at all types of volcanoes, but most voluminous fallout is normally associated with caldera-forming eruptions and composite volcanoes.

Pyroclastic flows, surges, and blasts

A.3. Pyroclastic flows are high-temperature mixtures of rock fragments, volcanic gases and air that flow down slopes at high speeds. These flows form from gravitational collapse of eruption columns, boil-over of vent rims by dense eruption columns, or avalanching of dome and viscous lava flow fronts. Flow velocities reach 10 to 100 m/s. The temperature can be close to that of the original magma (around 1000 °C in many cases) ranging down to ambient temperatures depending on the degree of mixing with air. Rapid downslope movement of the pyroclastic flow is driven largely by gravitational forces. The high mobility of the flow indicates that internal friction is very low. Pyroclastic flows may have sufficient momentum to deviate from drainage lines, surmount topographic obstacles, and can rapidly reach tens of kilometres from the volcano, depending on eruption volume and flow thickness. Dynamic pressure generated in pyroclastic flows may exceed 100 kPa, and the thickness of individual flow deposits may range from tens of metres to a few millimetres. These flows carry projectiles that may inflict significant damage on some structures.

A.4. Pyroclastic surges and blasts are dilute gas-solid suspensions that flow over the ground surface at high velocities with less influence of topography than pyroclastic flows. Estimated densities of pyroclastic surges range from 1 to 6 kg/m^3. Ground surges are generated by many of the same processes that form pyroclastic flows and often over-ride or precede pyroclastic flows. Ground surges have many of the characteristics of pyroclastic flows but are more dilute, lower volume, and leave thinner deposits in general. Base surges originate from hydromagmatic explosions in which interaction occurs between shallow ground water or surface water and magma. Base surges typically contain water and/or steam and have temperatures at or below the boiling point of water. Base surges can extend up to 10 km from the vent. A volcanic blast is a laterally directed pressure waves associated with ash-laden clouds. Surges and blasts pose a variety of hazards including burial and impact by rock fragments. Hot pyroclastic surges present several additional hazards including incineration, toxic gases, and asphyxiation. Pyroclastic flows, surges, and blasts are capable of travelling over bodies of water for tens of kilometres. In some cases, entrance of dense pyroclastic flows into water may generate tsunamis.

A.5. Pyroclastic flows, surges, and blasts are most commonly associated with explosive volcanic activity, such as Vulcanian and Plinian eruptions at calderas and composite volcanoes. Nevertheless, all types of volcanoes, including monogenetic tuff rings and scoria cones, may be the locus of such activity.

Lava flows and domes

A.6. Flows of lava are driven by gravity and follow the drainage lines of the topography. Lavas are viscous, dense (approximately 2000 kg/m^3) fluids, usually with a semi-solid crust on the surface, and flow at speeds of less than 1 m/s to around 20 m/s in extreme cases. The morphology and velocity of lava flows depend on the viscosity, eruption rate, temperature, composition, vent geometry and topography. Thick lava flows can inundate and change topography. Lava flows can travel tens of kilometres from the vent, and in unusual cases up to several hundred kilometres, and range in thickness from less than one metre to more than 100 m. The temperatures of lavas can range from 1200°C to around 800°C or less. Lavas may erupt from the main volcanic conduit, or from multiple vents located on the flanks of volcanoes, up to tens of kilometres from the location of the main vent. Lava flows typically inundate areas of 0.1-1000 km^2. Effusive activity from a single vent can sometimes continue unabated for several years.

Depending on their nature lava flows can create their own topography by vertical expansion, enabling the lava flows to invade new areas initially not connected to the lava source. Flowage of low viscosity lava over dense vegetation will likely ignite vegetation and trigger explosion from trapped CO_2 and CH_4 gas. Explosive activity and degassing is possible upon entry of lava flows into water bodies or the sea. Eruption of lava under snow or ice can generate massive floods such as happens in Iceland (jökulhlaups).

The extrusion of viscous lavas can last a few days to years or decades, leading to formation of lava domes associated with degassing (SO_2, CO_2, H_2O, HCl, HF) which can have significant environmental impact. Eruption of viscous lava typically produces voluminous pyroclastic material from the gravitational collapse and explosive disintegration of the lava dome or lava flows. This material is emplaced at the base and on the volcano where it can be remobilized (i.e. lahars) for many years to decades after cessation of the eruption. Repeated, frequent magma intrusions such as those that feed long-lived lava flow also promote the development of hydrothermal systems that can be active years to decades, even centuries. The dynamics of the hydrothermal system will govern in part processes of magma ascent, eruptive style, and contribute in turn to slope instability of altered parts of the edifice.

Debris avalanches, landslides, and slope failures

A.7. Steep-sided volcanic edifices such as volcanic domes and composite volcanoes may become unstable as a result of rock alteration, volcanic eruption, ground deformation, and erosion. Partial or complete failure of the slopes can produce debris avalanches, which are high-speed flows of rock fragments, ranging in size from a few centimetres to tens of metres in diameter, and entrapped air. Individual blocks of very large diameter can cause significant damage because of their momentum. The mode of movement of debris avalanches is therefore similar to that of pyroclastic flows in that both phenomena are fluidised flows accelerated downslope by gravity with high velocities (up to 50-70 m/s). Volumes of debris avalanches from composite volcanoes may exceed 10 km^3, and deposits of these avalanches can extend more than 100 km from the volcano. Sometimes volcanic avalanches are hot (up to 100 °C). Although not as large as debris avalanches, detachment and collapse of unstable slopes of the volcanic edifice may lead to landslides and other types of sudden slope failures, triggered by igneous intrusion, earthquake, or heavy rainfall. Edifice collapse can trigger hydrothermal explosions or initiate volcanic eruptions, including lateral blasts. These mass movements may have sufficient volume to dam river drainages. In some cases, entrance of debris avalanches and landslides into water may generate tsunamis.

A.8. As noted above, debris avalanches, landslides, and slope failures are common on steep topography. Nevertheless, very large debris avalanches (100-1000 km^3 in scale) have occurred on shield volcanoes in oceanic settings, resulting in tsunami generation. These phenomena also occur on long dormant volcanoes.

Debris flows, lahars, and floods

A.9. Volcanic debris flows and lahars are mixtures of volcanic rock fragments ranging in size from a 10^{-6} to 10^{2} m in diameter mixed with varying proportions of water as well as other rocks, soil and vegetation. Sometimes volcanic debris flows are hot (up to 100 °C). They range from flows containing many large boulders cascading down steep slopes to muddy currents sweeping over wide areas at the base of the volcano following river courses. Debris flows and lahars grade into torrential streams, heavily loaded with suspended sand and clay particles. These flows may occur at any stage during volcanic activity, including the earliest stages of an eruption. Debris flows can occur throughout a region for decades following voluminous explosive volcanic eruptions. Flow velocities may reach 10-50 m/s with discharge rates up to 10^5 m^3/s for jökulhaups. Large debris flows and lahars may travel 150 km or more and have volumes of more than 10^7 m^3 (up to a few km^3 for jökulhlaups and those transformed from debris avalanches). Debris flows may surmount topographic barriers, especially near the base of volcano edifices.

A.10. Floods can be generated in association with volcanic activity. These may be the result of complex processes. For example, floods may be created by the catastrophic draining of crater lakes, the formation of jökulhlaups, which are floods resulting from subglacial eruptions of lavas, breakage of temporary dams formed by volcanic debris avalanches and related mass flow deposits, and entrance of these flows into existing bodies of water.

Debris flows and related phenomena are common on composite volcanoes, sometimes occurring many years after volcanic eruptions. Such flows are much less common on other types of volcanoes, except in unusual circumstances. For example, rivers have been known to dam at topographic restrictions, causing flooding, following pyroclastic eruptions from monogenetic volcanoes. Flooding of nearby lowlands also is common after explosive eruptions if sediment from the volcano reduces channel capacity of rivers in these areas.

Opening of new vents

A.11. A new vent forms when magma ascends through the Earth's crust along a new pathway, erupting magma at a new location at the surface. New volcanoes can form at locations up to tens of kilometres away from sites of previous eruptions. New vents may initiate along fissure zones that are up to several kilometres long, but normally eruptive activity localizes as the eruption continues, resulting in the formation of pyroclastic cones, such as cinder cones, lava domes, eruptive fissures, and similar structures. Secondary vents may form when lavas or pyroclastic flows enter bodies of water. These are sometimes referred to as rootless vents. Eruptions from these new vents may last from several hours to months, or eruptions may occur sporadically over many decades with significant gaps in eruptive activity. Where associated with larger volcanic structures, such as shield volcanoes and calderas, new vents often form along rift zones or other major structures on the volcano. New vents also form in volcanic fields, consisting of tens to hundreds of individual volcanoes that are not associated with larger volcanic structures. These vents can be the source of significant pyroclastic fall and voluminous lava flows. Occurrence of a non-volcanic phenomenon like a so-called mud volcano may also be considered as similar to the opening of a new vent. Mud volcanoes form by eruption of a suspension of rock particles with water and gas (often, methane). They may be more than 100 m in radius and 20 m height. Although they may occur in volcanic areas, they are more usually found in non-volcanic areas that are underlain by clayey to sandy bedrock. Mud volcanoes form because of underground fluid overpressure, usually associated with slightly elevated temperatures, that may cause fracturing and fluidisation of the rock formation. The gases, which may contain relevant amount of methane, may be flammable in contact with the air. Eruptions of mud volcanoes have persisted for years and have resulted in long and voluminous flows of mud. Soil fluidisation and mudflows associated with mud volcanoes may constitute a potential hazard relevant to surface stability (see Ref. [7]). Mud volcano phenomena are not addressed specifically in this Safety Guide and the criteria for determining capability and the related volcanic hazards should not be applied. Nevertheless, some of the methods in current practice for evaluating the probability of occurrence of opening of new volcanic vents and for characterizing mudflows on volcanoes may be applicable to mud volcano hazard assessment.

Volcano generated missiles

A.12. Ejection of missiles such as blocks, bombs and other solid fragments is caused by explosions occurring within craters, domes, or vents. These objects are propelled by high-pressure gas and follow trajectories under gravity. The speeds of the missiles can be more than 300 m/s and the maximum horizontal distances they may travel can be up to 5 km from the origin. Large blocks or bombs can be thrown farther than expected due to the decrease of the influence of drag forces. When their size is sufficiently small, the friction of air decelerates them enough to affect the trajectory. Typically, volcano generated missiles larger than 1 m in diameter are not significantly affected by drag forces.

Volcano generated missiles can be associated with a wide variety of eruptions, but are especially notable products of strombolian and vulcanian style eruptions, and thus with eruptions on composite volcanoes, shield volcanoes, and at monogenetic volcanoes. Ejection of missiles nearly always accompanies the opening of new vents and secondary vents associated with lava flows and pyroclastic flows.

Volcanic gases

A.13. Volcanic gases make up a significant fraction of the total mass of material emitted by volcanoes. Gases exhaled from volcanic vents, fumaroles, solfataras mofettes and hydrothermal systems may be highly reactive and hazardous to humans and property. Although volcanic gases consist mainly of H_2O, they also include CO_2, SO_2, H_2S, CO, HCl, HF, and form low pH condensates. Gases may be discharged in large quantities either from established vents or from new fissures unrelated to established vents, or through soils on volcanoes, well before or after an eruption. For example, SO_2 release on volcanoes not in eruption may be on order a few tons per day to a few thousand tons per day and can be transported by wind for great distances. Large quantities of magmatic gases, especially CO_2, may also be released suddenly from lakes in volcanic craters and tectonic rifts. Because CO_2 is heavier than air, dense gas flows may follow drainage systems and collect in topographical depressions, displacing air and causing asphyxiation. Interaction of volcanic gases with water in the atmosphere also results in acid rain, and potential pollution of surface water.

A.14. Volcanic gas emission may occur from lava flows during volcanic eruptions, as these lava flows continue to cool and crystallize as they flow across the Earth's surface. Changes in hydrothermal systems may result in increases or decreases in volcanic gas emissions. Investigation of the state of the hydrothermal system of the volcano may provide important information about the potential for volcanic gas emissions. Widespread and persistent gas emissions are common at calderas and composite volcanoes. Such emissions also occur at some shield volcanoes, especially from rift zones on these volcanoes.

Tsunamis and Seiches

A.15. Volcanogenic tsunamis and seiches may be generated when voluminous (e.g., 10^6 to greater than 10^9 m^3) landslides, pyroclastic flows, or debris avalanches rapidly enter the sea or large lakes, or by submarine eruption of volcanoes. Collapse of a volcano edifice triggered by volcanic eruptions or earthquakes may lead to large displacement of the slopes, which in turn can generate tsunamis in proximal bodies of water.

Because steep-sided volcanoes are unstable structures, any such volcano located near water is a potential source of these phenomena. In addition, bathymetric surveys reveal that shield volcanoes in oceanic settings have been the sites of submarine debris avalanches. Such phenomenon potentially result in basin-wide tsunamis. In addition, even moderate eruptions at island volcanoes have generated tsunamis, although generally it is the larger, explosive eruptions that provoke these effects in extreme cases.

Atmospheric phenomena

A.16. Explosive eruption of a volcano, such as vulcanian and phreatic explosions, can generate air pressure waves powerful enough to break windows at distances of several kilometres. Air shocks may accompany lateral volcanic blasts, and thus may affect areas tens of kilometres from the volcano, depending on the interaction of the blast and topography. They are accompanied by projection of bombs and blocks as discussed in the previous section but the radius of the shock wave effects may be greater than that of the projected material.

A.17. Lightning often accompanies many types of volcanic eruptions, and may involve hundreds of ground strikes. In some cases, lightning and high static charges occur up to several kilometres from the erupting volcano.

A.18. Locally violent weather may accompany volcanic eruptions. Heavy rainfall may accompany the development of explosive eruption columns, as ash particles in the atmosphere cause sudden nucleation of raindrops. Heavy rainfall during tephra fallout may result in the generation of lahars. Downbursts (locally very strong winds) can occur as a result of explosive columns or the emplacement of hot lava flows. These winds may cause damage beyond the extent of the lava flows themselves.

Although such atmospheric phenomena may occur during any volcanic eruption, they most commonly are associated with large explosive eruptions, such as phreato-Plinian eruptions.

Ground Deformation

A.19. Some of the largest amplitude natural ground deformations ever observed have occurred on volcanoes. Prior to volcanic eruptions, ground deformation can involve rapid uplift of several meters or more. More generally, ground displacements of millimetres to centimetres may occur over broad areas in response to igneous intrusion into volcanoes. Deformation typically occurs around volcanoes through syneruptive faulting or shallow intrusion of magma. Modes of deformation include uplift, subsidence and extension. For example, vertical displacements of more than 100 m were produced by the 1977 eruption of Usu volcano in Hokkaido (Japan). Even the slow deformation of slopes may, with time, lead to considerable horizontal and vertical displacement manifested as faults, cracks and undulations of the surface. Ground deformation in calderas may result in significant vertical movements over large areas on different time scales. Large scale ground deformation is common at virtually all types of volcanoes.

Volcanic Earthquakes and Seismic Events

A.20. Volcanic earthquakes and seismic events normally occur as a result of stress releases associated with the rise of magma toward the surface. There are two principal forms of volcano-seismic activity which could give rise to potentially hazardous ground motions at a site and, for convenience, these can be grouped into two types: the first are transient events, such as volcano-tectonic and volcanic earthquakes. These transient seismic disturbances last a few seconds or tens of seconds, at most. The second category is usually denoted generically as "tremor", which is of a much more continuous and prolonged nature and may last hours or days. The effects of tremor are generally small and localized to the volcanic centre, whereas volcano-tectonic earthquakes can occur 10 km or more from the centre. These volcanic tremors are best characterised by their limited frequency content and long durations. They occur due to resonance phenomena involving systems with large dimensions (i.e., hundreds of meters to a few kilometers) and hence involve frequencies of a few Hertz, and are associated with fluid motion.

Generally speaking, the largest volcanic earthquakes have smaller magnitudes than the largest earthquakes of tectonic origin in a geodynamically active region. The characteristics of volcano-seismic events may differ considerably from tectonic earthquakes. Moreover, volcanic earthquakes can be large enough or numerous enough (hundreds to thousands per day) to warrant consideration as part of a seismic hazard assessment (see Ref.[4]).

Such volcanic earthquakes accompany every type of volcanic eruption and are present in all types of volcanoes.

Hydrothermal systems and ground water anomalies

A.21. Extensive hydrothermal systems sometimes are associated with volcanoes. Hydrothermal systems create elevated near-surface temperatures that can boil water and alter solid rock to clays. The presence of active hydrothermal systems or hydrothermal alteration can indicate a propensity for large mass movements, such as landslides or edifice collapse. Additionally, hydrothermal systems can produces steam explosions that hurl rock fragments for several kilometres and form explosion craters up to hundreds of meters in diameter. The interaction of rising magma with the groundwater table may cause a phreatic or phreatomagmatic eruption. Volcanic activity or igneous intrusions, such as dykes, may change ground water flow patterns and cause fluctuations in the depth of the water table. Unexpected discharges of water and mud from the interior of volcano edifices and unrelated to rainfall can occur. These discharges generate lahars that are attributed to the disturbance of the hydrothermal or groundwater system by volcanic intrusions. Magma intrusions also can trigger explosions in the hydrothermal system. Changes in the groundwater system may cause subsidence in karst terrains. In arctic areas, phenomena such as thermokarst may develop in response to changes in groundwater flow, or due to the development of hydrothermal systems. Changes in the hydrogeology of the site due to volcanic activity may also result in change of the hydraulic pressure in soils and water bearing horizons. Development of hydrothermal systems and groundwater anomalies are most common at calderas, but may be associated with all types of volcanoes.

ANNEX 1: VOLCANIC HAZARD SCENARIOS

A.1-1. Volcanic activity often involves a complex series of events and may involve development of a series of hazardous volcanic phenomena. Volcanic activity often begins with a period of unrest which may continue for a long period of time (e.g., decades) and which often is not followed by eruption. Once eruptions begin, they can persist for just a few minutes up to many years. This duration of activity and uncertainty means that volcanic events are varied and complex, often best treated as a combination of possible scenarios. Consideration of such scenarios is an important part of volcanic hazard assessment. The following three hypothetical scenarios are used to illustrate the complexity of volcanic eruptions and consequently the complexity of hazard assessment.

Scenario 1: Eruptions characteristic of composite volcanoes

A.1-2. Composite volcanoes are steep-sided conical volcanoes built by effusion of lava flows and domes, and by explosive eruption of pyroclastic material that forms pyroclastic flows and tephra falls. Although some composite volcanoes have patterns of past activity that can be used to assess the likelihood of hazardous phenomena occurring, composite volcanoes can be unpredictable in their development, and appropriate consideration should be given to a broad range of potentially hazardous explosive and effusive phenomena. The geologic record at many composite volcanoes shows that abrupt changes in composition or eruptive character are common, and that eruptive centres can suddenly emerge kilometres away from the central (summit) vent.

A.1-3. A typical eruption generally commences with the onset of volcanic unrest, such as changes in the background seismicity, deformation of the volcano edifice, or increased emission of magmatic gas, all of which may be detected by monitoring activities. Potentially precursory unrest can be as short as hours or as long as decades. The onset of unrest does not necessarily mean that there will be an eruption. Indeed, periods of unrest without eruption are more common than periods of unrest that lead to eruption.

A.1-4. The ensuing eruption can produce a wide range of simultaneous hazards over a period of hours to years, often with long gaps of inactivity. Initial activity can start with the gentle effusion of lavas from a flank vent, with the sudden emergence of explosive activity from the summit vent occurring later. In other examples, large explosions herald the onset of the eruption. Pyroclastic flows and falls can characterize days of sustained activity, followed by cessation of the eruption or a prolonged period of dome or lava effusion. Debris flows commonly occur if pyroclastic flows invade active drainage systems, or in response to heavy rainfall. Throughout the eruption, volcanogenic earthquakes occur and the potential for landslides or slope failure is enhanced. The high elevations of the composite volcano edifice represent a significant energy potential for debris flows and landslides triggered by large-scale (e.g., cubic kilometres) edifice collapse. Although not all phenomena will necessarily occur during a composite volcano eruption, the potential for multiple hazards to occur during a single eruption is extremely high for such a volcano.

A.1-5. A nuclear installation constructed within tens to hundreds of kilometres of a composite volcano experiencing such eruptive activity might face multiple potentially hazardous phenomena, possibly for an extended period of time. For example, tephra fallout at the site might continue for weeks, months, or longer. Explosive volcanic activity might contribute to the occurrence of debris flows, as waterways transport much higher sediment loads as a result of such eruptive activity for years following the eruption. In other words, such a nuclear installation could face multiple hazard scenarios resulting from a single volcanic eruption.

Scenario 2: Effusive eruptions characteristic of shield and composite volcanoes

A.1-6. An effusive eruption of fluid lava will generally begin with formation of eruptive fractures associated with locally felt seismicity, ground deformation, gaseous emanations and anomalous heat flux. In general, eruptions are preceded by months to years of non-eruptive phenomena or activity which, in ideal cases, shows marked variations in some parameters as magma rises towards the surface. However, with effusive systems that produce fluid lava, the rise of magma to the surface can be very quick and sometimes only a few hours separate the onset of high levels of pre-eruption seismicity from the actual eruption of lava. Thus, there might be only a short time to implement safety procedures at a nearby nuclear installation in the event of an effusive eruption.

A.1-7. On shield volcanoes and some composite volcanoes, such effusive eruptive activity may be localized tens of kilometers from the central vent of the volcano. Once magma reaches the surface, lava fountains can reach several tens to hundreds of meters in height above the vent and stretch over several hundreds of meters (i.e. curtain of fire). Eventually, the vent will reduce to a more cylindrical shape and may continue to erupt for hours to days generating potentially copious amounts of tephra transported downwind by relatively low eruption columns (e.g., less than a few kilometres in height) and gases (SO_2, CO_2, H_2O, HCl, HF) that can trigger acidic rains downwind and problems of toxicity to humans, animals, and corrosion to infrastructures, and perturb civil aviation. Lava flows will be emitted from this vent and the eruption of these lavas could last for hours to months from the same vent.

A.1-8. Fluid lava flows can move at speeds of 1-20 m/s. They form potentially extensive lava flow fields, single individual flows, or both at different spatio-temporal scales. The formation of crusted lava flows often leads to formation of lava flow tubes through which lava can flow with little thermal loss and thus can reach areas relatively far from the vent. Sudden breakage of lava tubes or of secondary lava pools formed along the flow, or lava lateral flow fronts (i.e. levées) can generate additional rapidly-moving flows moving with different characteristics and in different directions than the main flow.

A.1-9. Effusive volcanoes can have styles of eruptive behaviour that persist for long periods of time and then suddenly change to a different style (crater-centered eruptions switching to flank lateral eruptions), or they can oscillate from one style to the other from eruption to eruption or within the same eruption. Eruptions can also occur simultaneously from central vents as well as lateral vents located low down on the flanks of volcanic rift zones. Tephra producing lava fountains can coexist with long-lived lava flows from the same edifice and during the same eruption.

A.1-10.Thus, a nuclear installation located near a volcano experiencing such effusive activity would face hazardous phenomena resulting from potential incursion of the site by lava flows, opening of new vents, tephra fallout, gas emissions, and seismicity. Some of these phenomena are considered to be beyond the design basis of nuclear installations and therefore must be avoided through the site evaluation process. Therefore it is critical to evaluate the capability of a volcanic system of producing such effusive flows that may impact the site. In the event that such capability is identified, a volcanic hazard model for the site would necessarily consider the nature of coupled volcanic phenomena, such as a scenario in which new vents open and effusive lava flows from these flank vents.

Scenario 3: Eruptions characteristic of volcanic fields

A.1-11. Not all volcanism occurs from the central vents of existing composite or shield volcanoes. In many circumstances, volcanism is distributed and renewed volcanic activity results in the formation of new vents. On large volcanoes, such as Mt. Fuji or Mt. Etna, the process of new vent formation is clear from the distribution of hundreds of scoria cones and related volcanic features that dot the landscape for tens of kilometres about the volcano. In other areas, volcanism builds volcanic fields, sometimes consisting of hundreds of individual vents distributed over hundreds or thousands of square kilometres, each of which opened separately as an individual batch of magma ascended to the surface.

A.1-12. Activity associated with the opening of new vents begins with the ascent of magma through the crust. Often this magma ascends as a sheet-like dyke, commonly less than one meter in width and perhaps kilometres in length, ascending through the earth's crust at a rate on the order of one meter per second. At a hypothetical nuclear installation in the area, the first sign of this activity would likely be a series of low magnitude earthquakes. Hundreds to thousands of earthquakes per day have been observed to occur associated with magma ascent of this nature. If seismic network observations are sufficiently precise, these earthquake hypocentres might be observed to gradually rise as the tip of the magma dyke ascends to ever shallower levels, although this migration of seismic hypocentres is only rarely observed. In some cases, this ascent is arrested by natural processes and the dyke freezes within the earth, never forming a new vent.

When a new vent does form, the first manifestation at the surface is usually ground deformation. This ground deformation often consists of fracture zones that are up to approximately ten metres in width and hundreds of metres to kilometres in length, comparable to the length of the dyke itself. When magma reaches the surface it often does so at intermittent locations along the entire fracture system. Over a period of hours, however, this activity generally localises into one or a few new vents. Mass flow of magma from these vents increases rapidly with time, creating a fire-fountain of incandescent rock that jets hundreds of metres into the air, and rains particles down on the surrounding terrain. Where abundant water is present at or near the surface, this initial activity may become highly explosive, creating volcanic phenomena such as pyroclastic surges, and excavating craters that may exceed one kilometre is diameter. In some circumstances, buoyant volcanic plumes develop that carry tephra to kilometres or tens of kilometres height above the new vent. Scoria cones grow quickly as a result of this type of volcanic activity, commonly achieving heights of more than one hundred metre and basal diameters of hundreds of metres. Often lava flows develop as the eruption progresses. Depending on the composition and rate of effusion of lavas, these flows can reach tens of kilometres from the new vent. At any time new vents may form along the original fracture. Such eruptions have been observed to persist for less than one month, others have lasted as long as a decade. In some cases, intermittent activity has been known to continue at new vents for more than one hundred years. Thus, the opening of a new vent and the precursory phenomena that herald this type of event represent a complex sequence that may produce a wide array of hazardous phenomena for a nuclear installation located in the region.Although the preceding examples are for illustrative purposes only, they do indicate the complexity of volcanic hazards and the need for development of comprehensive volcanic hazard models where volcanoes capable of affecting the site of a nuclear installation are identified. As shown by these examples, multiple volcanic hazards can occur during a single volcanic event. Volcanic events can continue for an extended period of time (sometimes years), and can affect large areas.

ANNEX 2: WORLDWIDE SOURCES OF INFORMATION

A.2-1. Assessment of potential sources of volcanic activity is complex, even during the initial assessment (Stage 1). Expertise in volcanic hazard assessment and confidence in data sources is needed. Internationally, the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI, Ref. [A.2.1]) is the primary organization dedicated to the study of volcanoes and the mitigation of volcanic hazards. Commissions within IAVCEI that are particularly relevant to volcanic hazard assessments for nuclear facilities include the World Organization of Volcano Observatories (WOVO, Ref. [A.2.2]), the Cities on Volcanoes Commission (Ref. [A.2.2]), and the Commission on Statistics in Volcanology (COSIV, Ref. [A.2.3]). IAVCEI and these IAVCEI Commissions provide essential information concerning the state-of-the-art in volcanic hazard assessments, access to specific information about volcanism by region, and access to specific techniques required to quantitatively assess volcanic hazard. Several databases exist that may be of great utility in volcanic hazard assessments, especially in the initial assessment (Stage 1).

A.2-2. The Smithsonian's Global Volcanism Program (GVP) is dedicated to gathering and verifying data on Holocene volcanic activity worldwide (Ref. [A.2.4; A.2.5]), see Figure A.2-1. While insufficient alone for performing initial assessments for nuclear installations, the GVP database is an excellent resource that can support these assessments. A database of historical volcanic unrest, worldwide, also is under construction by WOVO.

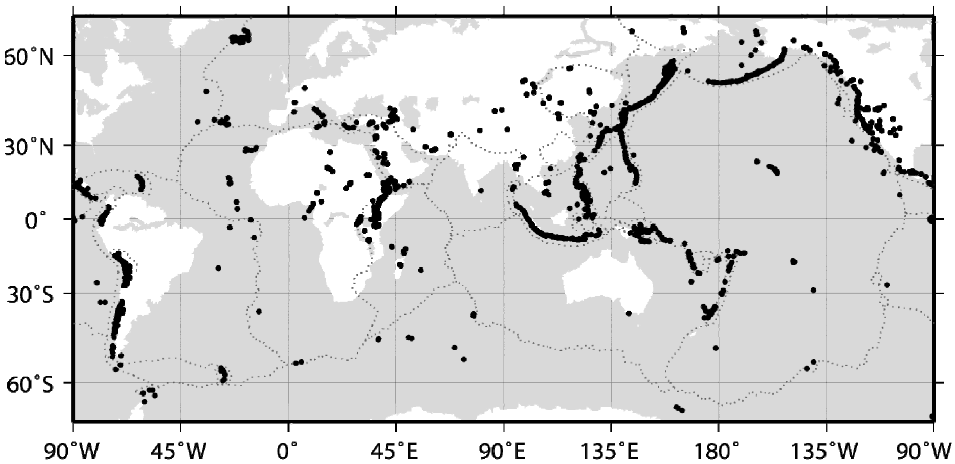

Figure A.2-1: Map shows the global distribution of subareal volcanoes, and some submarine volcanoes, active during last 10 000 years including major plate boundaries (dotted lines). Data from the GVP.

A.2-3. Many States have national databases for Holocene volcanism. (e.g., Russia, Ref.[A.2.6] and USA, Ref.[A.2.7]). For Quaternary volcanoes, the Geological Survey of Japan maintains a detailed database on active (Ref. [A.2.8]) and Quaternary volcanoes (Ref. [A.2.9]) of Japan, including detailed geological maps of specific volcanoes and records of recent volcanic activity. Such resources provide a useful model for development of a site-specific database for the initial assessment.

A.2-4. An important source of information on updated criteria and methodologies for volcanic hazard assessment for nuclear power facilities is available in Ref.[A.2.10].

REFERENCES TO ANNEX 2

[A.2.1.] International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI). http://www.iavcei.org.

[A.2.2.] World Organization of Volcano Observatories (WOVO). http://www.wovo.org.

[A.2.3.] Commission on Statistics in Volcanology (COSIV). http://www.cas.usf.edu/cosiv.

[A.2.4.] Simkin, T., and L. Seibert, 1994. *Volcanoes of the World*. Second edition. Tucson, AZ, USA: Geoscience Press.

[A.2.5.] Smithsonian Global Volcanism Program (GVP). http://www.volcano.si.edu.

[A.2.6.] KVERT: Active Volcanoes of Kamchatka and Northern Kuriles. http://www.kscnet.ru/ivs/volcanoes/index_eng.html

[A.2.7.] Volcanoes, U.S. Geological Survey. http://vulcan.wr.usgs.gov/Volcanoes/framework.html

[A.2.8.] Database of Japanese Active Volcanoes. http://riodb02.ibase.aist.go.jp/db099/index-e.html.

[A.2.9.] Quaternary Volcanoes in Japan. http://riodb02.ibase.aist.go.jp/strata/VOL_JP/EN/index.htm

[A.2.10.] Volcanic and Tectonic Hazard Assessment for Nuclear Facilities, C. Connor et al, Cambridge, 2009.

GLOSSARY OF VOLCANOLOGICAL TERMS

andesite. A type of volcanic rock that is common at many composite volcanoes. Andesite composition (52 to 63 wt. % SiO_2) is intermediate between basalt and dacite magma. It often forms thick rubbly lava flows. However the magma usually contains moderate amounts of dissolved water and can thus produce violent explosive eruptions generating high pumice and scoria-rich eruption columns, pyroclastic flows and surges. Andesite is generally erupted at temperatures between 900 °C and 1100 °C.

ash. A fragment of volcanic rock that is < 2mm in mean diameter resulting from different processes of eruptive fragmentation. By far the most common variety is vitric ash (glassy particles formed by gas bubbles bursting through liquid magma). Also see tephra, pyroclast.

basalt. A type of dark-coloured volcanic rock that often forms lava flows and low-lying volcanoes. Basalt composition has <52 weight percent silica, which gives it a low viscosity and allows dissolved gases to escape from the magma. Although this type of magma often behaves in a less explosive manner than more viscous magmas, basaltic magmas do erupt explosively, especially if interaction with groundwater or seawater occurs. Basalt is erupted at temperatures generally between 1100 °C and 1250 °C.

Bayesian statistics. A paradigm for probabilistic inference that depends on the specification of prior distributions for all unknown parameters, followed by an application of Bayes theorem to incorporate the extra information included in data. The principle can be used in volcanology as a method to help constrain the results and uncertainty estimates of statistical and numerical modeling, taking advantage of as much data and other relevant information as is available. In contrast, "frequentist statistics" relies on patterns of past events to model the likelihood that an event will occur in the future. Bayesian methods can incorporate more geological information into a probability of occurrence estimate than is possible with a frequentist approach.

blast (directed blast). A volcanic explosion of old or juvenile magma with a laterally-directed low-angle component resulting from sudden depressurization of a volcanic dome, a volcanic shallow-depth magmatic body, or a shallow-depth hydrothermal system. Volcanic blasts can produce a dilute mixture of gas and volcanic fragments (blocks and smaller) that moves generally as a laterally expanding highly turbulent pyroclastic surge at considerable speeds (up to 500 km/h) causing devastation in a wide sector. See also pyroclastic surge

block. An angular fragment of volcanic rock > 64mm in mean diameter, which does not deform during transport even if hot. Blocks often break on impact with the ground surface. Also see tephra and bomb.

block and ash flow. A type of pyroclastic flow that is generally concentrated in particles including blocks of dense lava (decimetric to metric in diameter) set in a mixture of finer grained particles. These flows result from the gravitational collapse of lava domes and viscous lava flow fronts. See pyroclastic flow.

bomb. A pyroclast (fragment of volcanic rock) > 64mm in mean diameter ejected during a volcanic explosion and that is sufficiently hot to undergo ductile deformation during transport. Also see tephra and block.

caldera. A large basin-shaped depression, normally larger than a kilometre in diameter, which may form in several ways: (i) removal of magma from a shallow chamber by powerful explosive activity spreading volcanic ash falls and pyroclastic flows over large areas ; (ii) magma withdrawal from a shallow chamber and subsidence of the overlying rock; (iii) sector collapse of a volcano due to edifice instability. A great number of calderas have long periods of repose, episodes of unrest, and eruptions of varying scales. Their geological history often testifies to a very long life, often lasting millions of years.

capable volcano or volcanic field. A volcano or volcanic field that is defined in this Safety Guide as one that may experience volcanic activity during the performance period of the nuclear installation and produce hazardous phenomena, including non-eruptive phenomena, that may potentially affect the site. As discussed in Sections 3 and 5, hierarchical criteria for determining if a volcano or volcanic field is capable are: (i) evidence of contemporary volcanic activity or active near-surface processes associated with magmatism for any volcano in the geographic region; (ii) Holocene volcanic activity for any volcano within the geographic region; (iii) some evidence of potential for activity, such as recurrence rates of volcanism greater than 10^{-7} per year, and potential to produce hazardous phenomena which may impact the site vicinity.

cinder cone (syn. scoria cone). A small conical volcano, typically less than one kilometre in diameter and no more than a few hundred metres high, formed by the accumulation of lava fragments as scoria and bombs around the vent, when they fall back to earth after a moderate explosion. Often they are surrounded by lava flows erupted from the same vent. The cinder cones commonly grow rapidly and soon approach their maximum size. They occur in groups and they often occur on the flanks of large composite volcanoes and shield volcanoes. Examples of cinder cones include Paricutin, Mexico, and Cerro Negro, Nicaragua.

clast (volcanic). An individual solid volcanic fragment or grain that formed as a result of mechanical disruption of the magma or fracturing of rocks from the conduit or the host-rock surrounding the magma reservoir as a result of eruptive processes.

composite volcano (syn. stratovolcano). A large volcano, typically more than one kilometre in diameter at its base and greater than a few hundred metres in height, principally formed from eruption of tephra and lava from a central vent. The history of some composite volcanoes can involve the collapse of its summit forming a caldera or the sliding of an entire flank of the volcano forming a large debris avalanche. Episodes of eruption followed by years to centuries (or longer) of inactivity can recur at composite volcanoes over hundreds of thousands of years. Examples of composite volcanoes include Mt. Vesuvius, Italy, and Mount St. Helens, USA.

conduit. The pathway along which magma reaches the surface at a volcano. Conduit geometries vary from tabular dyke-filled fractures to nearly cylindrical sub-vertical tubes, but complex geometries are possible. The opening of the conduit at the surface is a vent. (see also vent).

co-pyroclastic-flow plumes. Any buoyant ash plume generated from elutriation above pyroclastic flows, irrespective of how the pyroclastic flow originally formed. Co-pyroclastic-flow plumes can detach from the underlying pyroclastic flow and travel over hills and into adjacent valleys, creating a separate hazard from the main pyroclastic flow. The volcanic eruption style influences the volumes of ash and condensed volatiles produced, their dispersion, the concentrations of particles and gases in the plume, the ratio of particles to gases, and the transport time of the ash in the plume.

crust. The outermost solid layer of the Earth. It represents less than 1% of the Earth's volume and varies in thickness from approximately 6 km beneath the oceans to approximately 60 km beneath mountain chains.

dacite. An igneous rock intermediate in composition between andesite and rhyolite These rocks are 63 to 68 wt. % SiO_2. Because of their high SiO_2 contents, dacite magmas can have high viscosity and erupt explosively, generating eruptive phenomena like pyroclastic flows. Generally, dacite magmas erupt at temperatures of 800 °C - 1000 °C.

debris avalanche. A large mass (less than 1 km^3 to more than 100 km^3) of rock debris resulting from the disintegration of a volcanic edifice by partial or complete collapse that slides and/or flows downslope under the force of gravity at rapid speeds (200 km/h). Debris avalanches often excavate a significant part of the hydrothermally altered portions of a volcanic edifice. Debris avalanches contains a mixture of small fragments of mm size to large blocks of the former volcano hundreds of meters in size that move as coherent entities deforming with flow and eventually fragmenting in smaller particles. They can contain significant amount of water or mix with water bodies inflow to transform into more mobile mudflows. Edifice collapse can generate large explosive depressurization of the shallow depth magma-hydrothermal system interface (see blast).

debris flow. A dense, slurry-like mixture of rock debris and water moving rapidly downslope on volcanoes due to gravity and formed from a variety of processes, often with sufficiently high energy to sweep away buildings and trees along the flowpath. They can form from water-saturated landslide blocks, or when water from heavy rain, rapid snowmelt, a crater lake, or from water squeezed out of the edifice, remobilizes ash-rich volcanic deposits. Remobilization of fragmental material by heavy rain can occur for years or even longer after an eruption. Debris flows exhibit significant yield strength and usually contain >60% sediment by volume. See also: hyperconcentrated flow, lahar.

degassing n (degas v.). The process by which volatiles that are dissolved in magma form a separate gas phase and escape from the magma. Slow degassing forms bubbles in lava flows, whereas rapid degassing can tear the magma apart explosively and form pyroclasts. Efficiency of degassing from magma before reaching the surface is one control on the explosivity of eruptions.

dome. A steep-sided pile of rock formed due to an extrusion of lava. Domes are frequently, but not exclusively, composed of andesite to rhyolite magma. Domes usually form when the magma is very viscous or extrudes slowly, so it accumulates at the vent rather than flowing away. Pyroclastic flows can be generated by collapse of lava domes. Recent eruptions producing lava domes include the recent eruptions of the Soufrière Hills volcano, in Montserrat, the 1991-1995 eruption of Mount Unzen, in Japan and the 1994 and 2006 eruptions of Mount Merapi, in Indonesia.

dyke. A sheet-like, often vertical or near-vertical body of igneous rock resulting from solidification of magma-filled fractures that cut across pre-existing rocks and geologic structures. Dykes which transport magma from deep reservoirs towards the surface can become arrested at shallow depths in the crust, feed the volcanic conduit, or erupt themselves at the surface. Shallow-depth emplacement of dykes can cause ground-surface deformation or trigger the collapse of volcano slopes.

effusive eruption. A volcanic eruption in which coherent magma is extruded from the vent to form lava flows. Also see explosive eruption and extrusive flow.

elutriation. A process in which finer volcanic ash particles are separated from coarser by the action of a current of gas, air or water, carrying lighter particles upwards while heavier particles sink.

eruption (volcanic). Any process on a volcano or at a volcanic vent that involves the explosive ejection of fragmental material, the effusion of molten lava, the sudden release of large quantities of volcanic gases (e.g., CO_2), or a process by which buried regions of the volcanic systems from various depths such as the hydrothermal system are brought to the surface during edifice collapse. Eruptions are magmatic if newly solidified magma is present in the eruptive products, and are non-magmatic (phreatic) if they involve only recycled rock fragments. Eruptions can occur on widely varying timescales (seconds to years). See phreatic eruption, phreatomagmatic eruption, plinian eruption, strombolian eruption, Hawaiian-style eruptions, vulcanian eruption, explosive eruption, effusive eruption.

eruption cloud. A cloud of tephra and gases that forms above a volcanic vent during explosive volcanic eruptions. The vertical pillar of tephra and gases that form during most explosive activity is referred to as an eruption column, or strong plume, and includes a momentum-dominated region and a buoyant-dominated region. Eruption clouds may rapidly spread laterally by gravitational spreading, especially in the most energetic eruptions, and may drift thousands of kilometres downwind. Large eruption clouds can encircle the Earth within days.

eruptive fissure. A linear fracture on the Earth's surface through which lavas, pyroclasts, and gas are erupted.

explosive eruption. A volcanic eruption in which gas bubble expansion or explosive interaction between magma and water is rapid enough to break the magma apart (i.e., fragment the magma). Explosive eruptions also occur when pressurized hydrothermal gases and superheated fluids suddenly break the host rock in a volcanic edifice (see phreatic eruptions). Pyroclastic flows, falls, and volcano generated missiles are characteristic of explosive eruptions.

extrusive flow. A non-explosive (i.e., non-pyroclastic) eruption of magma from a volcanic conduit that forms lava flows and domes.

fire fountain. A mildly-explosive, pressure-driven eruption of gas and magma with sufficient velocity to fling bits of magma hundreds of meters above the vent. Fire fountain eruptions often feed lava flows and are characteristic of Hawaiian basaltic eruptions.

fumarole. A fracture or small vent (typically centimetres in diameter) from which volcanic gases or water vapour is emitted at elevated temperatures. Fumarole temperatures vary from only slightly above ambient to magmatic temperatures. A solfatara denotes a fumarole that emits sulphurous gases (sulphur dioxide, hydrogen sulphide). A mofette denotes a fumarole that emits mainly carbon dioxide at temperatures below the boiling point of water.

geologic record. See stratigraphic record.

Hawaiian-style eruption. A type of volcanic eruption characterized by eruption of pyroclasts to heights of < 500 m above the vent, often from fissure or vent systems that may extend for one kilometre or more. Effusion rate and lava volume from Hawaiian eruptions can be quite large when integrated across an entire fissure zone and these eruptions can be sustained for a long time, commonly > 1 yr.

Holocene. The most recent epoch of the geological Quaternary period, defined as the interval from 10000 yr before present to the present.

Holocene volcano or volcanic field. A volcano or volcanic field that has erupted within the last 10,000 yr (the Holocene Epoch). Reported historical activity and radiometric dating of volcanic products provide the most direct evidence of volcanic eruptions within the Holocene. In some circumstances, especially in the early stages of site investigations, the exact age of most recent products may be difficult to determine. In such circumstances additional evidence may be used to consider a volcano as Holocene, following the methods used by the Smithsonian Institution[5]. Such evidence includes: 1) volcanic products overlying latest

[5] Simkin, T., and L. Siebert, Volcanoes of the World, Second Edition, Geoscience Press, 1994

Pleistocene glacial debris, (2) youthful volcanic landforms in areas where erosion should have been pronounced in many thousands of years, and (3) vegetation patterns that would have been far richer if the volcanic substrates were more than a few thousand (or hundred) years old, (4) ongoing fumarolic degassing, or the presence of a hydrothermal system at the volcano. In addition, some volcanoes may be classified as Holocene(?) volcanoes. Volcanoes are denoted as Holocene(?) volcanoes when authorities disagree over the existence of Holocene volcanism, or when the original investigator expresses uncertainty about the most reliable age estimate of the most recent eruption. Under these circumstances it is reasonable to consider such volcanoes as Holocene for the purposes of this *Safety Guide* and proceed with the hazard assessment.

hot spot. A location at the earth's surface that has experience volcanism as a result of a thermal or compositional perturbation or plume in the earth's mantle. Many hot spots are located in intraplate tectonic settings, far from tectonic plate boundaries that often host volcanism.

hyperconcentrated flow. A flowing mixture of sediment and water, intermediate in character and sediment concentration between muddy stream flow and debris flow. Hyperconcentrated flow has no appreciable yield strength, and typically contains 20-60% sediment by volume.

igneous. Adjective used to describe characteristics pertaining to rocks that have formed from a magma. Igneous rocks are typically divided into four basic types according to the amount of SiO_2 in the rock. These types are basalt, andesite, dacite, and rhyolite.

ignimbrite (syn. ash-flow tuff). A pyroclastic flow deposit that consists mainly of pumice and ash. Ignimbrites can range in appearance from loose accumulations of pyroclasts, to strongly compacted (i.e., welded) deposits resembling bricks.

jökulhlaup. A flood or debris flow generated by the melting of ice or snow from a glacier in response to subglacial volcanic eruptions.

lahar. A debris flow or hyperconcentrated flow originating on a volcano and composed mainly of volcanic fragments. See also debris flows..

lapilli. A type of pyroclast (i.e., fragment of volcanic rock) > 2mm and < 64mm in mean diameter. Also see tephra. Lapilli are sometimes formed in eruption columns by the accretion of ash-sized particles, termed accretionary lapilli.

lava. Molten rock erupted at the Earth's surface by a volcano or by an eruptive fissure, as an effusive dome or flow. Lava, when first emitted from a volcanic vent is a liquid at very high temperature, typically from 700° to 1200°C. Lava flows vary by many orders of magnitude in viscosity and this strongly influences their flow properties.

magma. A mixture of molten rock (800–1200 °C) that also can contain suspended crystals, dissolved gases, and sometimes gas bubbles. Magmas form by melting existing rock in the Earth's crust or mantle. Magma composition and gas content generally control the style of eruption at a volcano. In general terms, hotter, less viscous magmas (e.g., basalt) allow gas to separate more efficiently, limiting the explosivity of eruption, while cooler, more viscous magmas (e.g. andesite, dacite, and rhyolite) are more likely to fragment violently during eruption.

magma chamber. An underground reservoir that is filled with magma and tapped during a volcanic eruption. Magma in these reservoirs can partially crystallize or mix with new magma, which can change the eruption composition or hazard through time.

mantle. A solid layer of the Earth that is located between the crust and core, which is approximately 2300 km thick. Basalt magmas form from partial melting of mantle rocks.

monogenetic volcano. A volcano constructed from one or numerous eruptions over a period of months to perhaps several centuries. After this period of activity ends, the monogenetic volcano will not erupt again. Most cinder cone volcanoes are thought to be monogenetic. Also see *volcanic field*.

mudflow. A general term for a flow of water and earth material possessing a high degree of fluidity during movement. (see *debris flow* and *lahar*).

phreatic eruption. A type of eruption caused by rapid volume expansion of water, or water vaporization, in the subsurface, without magma erupted at the surface. Phreatic eruptions are usually steam explosions that occur when hot water is suddenly depressurized, but may occasionally be non-explosive explusions of pressurized or heated aquifer waters and/or hydrothermal fluids at a volcano. Phreatic eruptions are common where rising magma interacts with groundwater, commonly in the interior of a volcano edifice. Although commonly small in scale, phreatic eruptions may be followed by larger scale phreatomagmatic or magmatic eruptions. Phreatic eruptions may generate debris flows and hot lahars.

phreatomagmatic eruption. A type of explosive eruption that involves subsurface interaction of magma and water, which produces explosive mixtures of rock, steam, and magma that often form pyroclastic flows and surges. Surtseyan and Phreato-Plinian eruptions are phreatomagmatic eruptions involving the interaction of hot pyroclasts and water as the magma is erupted from the vent into bodies of water. (also see eruption and phreatic eruption)

plinian eruption. An explosive pyroclastic eruption characterized by a sustained eruption column that generally rises 10–50 km above ground level. Plinian eruptions may produce thick tephra falls over areas of 500–5,000 square kilometres, and/or pyroclastic flows and surges that travel tens of kilometres from the volcano. The 1991 eruption of Mt. Pinatubo, Philippines, was a modern Plinian eruption.

Pliocene. The Pliocene Epoch is an interval of geologic time extending from 5.3 to 2.6 million years ago.

polygenetic volcano. A volcano constructed from multiple eruptions, some of which follow long periods of inactivity. Because many polygenetic volcanoes can remain active for 10,000 to 1,000,000 years and have long periods of repose, it may be very difficult to distinguish between extinction and inactivity at a Quaternary polygenetic volcano. Most composite volcanoes are polygenetic.

pumice n. (pumiceous adj.). A light-coloured, extremely vesicular (typically 60-80% volume void fraction) pyroclastic rock that is formed in explosive eruptions and can float in water. Pumice often forms from rhyolite or dacite magmas, and occasionally forms from andesite magmas. It resembles a foam because it consists of a network of gas bubbles frozen amidst fragile volcanic glass and minerals. During an explosive volcanic eruption, volcanic gases dissolved in the liquid portion of magma expand rapidly to create a foam. In the case of pumice, the liquid part of the foam quickly solidifies to glass around the gas bubbles.

pyroclast A particle of any size or composition produced from a volcanic eruption, generally produced in explosive eruptions.

pyroclastic density current. A generic term for mixtures of volcanic gas, pyroclasts, and rocks that flow across the ground as a result of a volcanic eruption (i.e. pyroclastic flows, surges and blasts).

pyroclastic flow. A ground-hugging concentrated flow of pyroclasts and hot gas. These hot flows generally form by collapse of an eruption column or a dome, and flow rapidly down slopes. Pyroclastic flows can transport large clasts (blocks, bombs) and generally follow topographic gradients. The temperature within a pyroclastic flow is often greater than 500° C.

Velocities depend on how and where the flow originates and the slopes over which it travels, but typically are >50 km/hr and sometimes > 100 km/hr.

pyroclastic surge. A type of pyroclastic flow that is relatively dilute, high velocity and more turbulent than most pyroclastic flows. Pyroclastic surges can form from dome and eruption column collapses, and can also separate and move away from a more dense pyroclastic flow. Pyroclastic surges are less constrained by topographic gradients than most pyroclastic flows.

repose interval. The time elapsed between successive volcanic eruptions at the same volcano. Ideally, repose interval would be the time elapsed from the end of one volcanic eruption to the beginning of the next. Unfortunately, eruption duration can rarely be determined. Therefore repose interval is the best estimate of time elapsed from one eruption to the next.

rhyolite. A type of light-coloured volcanic rock that often forms glassy domes or pyroclastic deposits. Rhyolite composition has >68 weight percent silica, which gives it a high viscosity and traps gases in the magma. Thus, rhyolite eruptions often are explosive and form pyroclastic deposits, although lavas and domes can occur. Rhyolite is generally erupted at temperatures of 700 °C to 850 °C. Obsidian is a special type of rhyolite that looks like glass.

scoria A dark, vesicular pyroclastic rock that is formed in basaltic to andesitic eruptions. Unlike pumice, scoria sinks in water. Scoria forms cinder cones and can occur at fire-fountain eruptions.

shield volcano. A volcano resulting from Hawaiian-style eruptions that tend to produce a broad, low-angle cone, e.g., Kilauea volcano, Hawaii, USA., which resembles an ancient warriors shield in profile..

sill. A sheet-like igneous intrusion that is concordant with pre-existing geologic structure, often horizontal or nearly horizontal (see dyke).

stratigraphic record. The sequence of rock layers in a vertical section of the Earth. Oldest layers are deposited at the base of the section, with successively younger layers deposited on top of the underlying layer. Geologists use the stratigraphic record to assign relative ages to deposits. Volcanic stratigraphy often is complex, with deposite having relatively limited lateral extent, rapid facies changes, and multiple episodes of erosion and refilling of valleys.

stratovolcano. See composite volcano.

strombolian eruption. A type of volcanic eruption that is intermediate in explosivity between fire-fountain and Plinian eruptions. Magma is less fragmented than in a Plinian eruption and gas often is released in coalesced slugs rather than in a continuous jet. The eruptions are commonly discrete events, punctuated by intervals of relative quiescence ranging from few seconds to several hours. Strombolian eruptions, usually basaltic to andesitic in composition, form weak eruption columns that rarely exceed 5 km height, and the volume of lava flows is generally equal to or greater than the volume of pyroclastic rocks. Such eruptions are characteristic of Stromboli volcano, Italy, and Izalco volcano, El Salvador.

tephra. Any type of pyroclastic material erupted from a volcano, regardless of size, shape, composition or method of formation, although the term is most often used for pyroclasts that fall, rather than flow.

vent. An opening in the Earth's crust where volcanic products (magma, solid rocks, gas, liquid water) is erupted. Vents may be either circular structures (i.e. crater) or elongate fissures or fractures, or small cracks in the ground.

volatile. A dissolved component in a magma at high pressure and temperature, which forms a separate gas phase at lower pressure or temperatures. The most common volatile in magma is water, followed by carbon dioxide and sulfur dioxide. Rapid expansion of gas released from magma in the volcanic conduit expels fragments of magma (lava, pumice, scoria, ash, etc.) explosively from the vent into the air.

volcanic activity. A feature or process on a volcano or within a volcanic field that is linked to the presence of magma, and/or heat, and/or gases emanating from the earth and its interaction with nearby crustal rocks or groundwater, including: seismicity, fumarolic activity, high rates of heat flow, emission of ground gases, thermal springs, deformation, ground cracks, pressurization of aquifers, ash venting. The term includes *volcanic unrest* and *volcanic eruptions*.

volcanic earthquake A seismic event caused by and directly associated with processes in a volcano. Volcanic earthquakes and seismic activity come in many forms and types (e.g. volcano-tectonic earthquakes; long period events; hybrid events; tremor; swarms) before, during, and after eruptions, and their characteristics and patterns are used to infer what is happening within the volcano at different times. Seismic monitoring is the most fundamental method to forecast the onset of eruptions and to assess potential for volcanic eruption.

Increasing seismicity, continuous tremor, shift in hypocenters toward the surface with time, and occurrence of shallow long-period (or low-frequency) events imply a high possibility that the onset of eruption is very close. Tremor also can reflect and continue through eruptions.

volcanic event. Any occurrence, or sequence of phenomena, associated with volcanoes that may give rise to volcanic hazards. Volcanic events may be formally defined as part of a hazard assessment in order to provide meaningful definition of repose intervals and hazards. Volcanic events may include eruptions and will typically include the occurrence of non-eruptive hazards, such as landslides.

volcanic field. (or volcano group). Any spatial cluster of volcanoes. Volcanic fields range in size from a few volcanoes to over 1,000 volcanoes. Volcanic fields may consist of monogenetic volcanoes (e.g., the Cima volcanic field, California, USA), or both polygenetic and monogenetic volcanoes (e.g., the Kluchevskoy volcano group, Kamchatka, Russia).

volcanic hazard. A volcanic process or phenomena that can cause an adverse effect on people or infrastructure. In the more restricted context of risk assessment, the probability of occurrence, within a specific period of time in a given area, of a potentially damaging volcanic event of given intensity.

volcanic unrest. Variation in the nature, intensity, spatio-temporal distribution, and chronology of geophysical, geochemical, and geological activity and phenomena as observed and recorded on a volcano, from a base-line level of activity known for this volcano or for other similar volcanoes outside periods of eruptive activity. Volcanic unrest can be precursory and culminate in an eruption but in most cases rising magma or pressurized fluids that cause unrest do not breach the surface and erupt.

volcano. A naturally occurring vent at the Earth's surface through which magma, solid rock, and associated gas and liquid water can erupt. A volcano is also the edifice that is built by the explosive or effusive accumulation of these products over time.

Volcano Explosivity Index (VEI). A classification scheme for the explosive magnitude of an eruption, primarily defined in terms of the total volume of erupted tephra, but in some cases the height of the eruption column and the duration of continuous explosive eruption are used to determine the VEI value. VEI index varies from VEI 0 (non-explosive eruption, less than 10^4 m^3 tephra ejected) to VEI 8 (largest explosive volcanic eruptions identified in the geologic record, more than 10^{12} m^3 tephra ejected). Each magnitude of increasing explosivity on the VEI scale corresponds to an increase in volume of erupted tephra by a factor of ten. The only exception is the transition from VEI 0 to VEI 1, which represents an increase in the volume of tephra erupted by a factor of one hundred.

volcano generated missile. A pyroclastic particle, often of large size, that is forcefully ejected, follows a high-angle trajectory from the vent to the surface as a result of explosive activity at the vent and falls under gravity. Any material, such as rock fragments, trees, and structural debris, that is rapidly transported by flow phenomena with significant momentum and that may impact structures, causing considerable damage, even beyond the extent of the main flow itself.

volcano monitoring. Geophysical, geochemical and geological monitoring to evaluate the potential of forthcoming eruption, forecast the onset of eruption, to understand an ongoing eruption, and evaluate the potential volcanic hazards from an eruption. Instruments such as seismometers, GPS receivers, tiltmeters, magnetometers, gas sensors, cameras, and/or related instruments are installed on and around the volcano to evaluate volcanic activity, identify volcanic unrest, and evaluate the potential for volcanic eruption. Remote sensing using satellites is sometimes very effective to monitor temporal thermal, topographical and geological changes in volcanoes.

vulcanian eruption. A type of volcanic eruption characterized by discrete explosions, which produce shock waves and pyroclastic eruptions. Vulcanian eruptions typically occur when volcanic gas accumulates in a solidifying shallow conduit or dome, which pressurizes the magma to the point of brittle failure. Andesite and dacite magmas are most often associated with vulcanian eruptions. Volcanoes with recent vulcanian eruptions include Sakurajima volcano, Japan, the Soufrière Hills volcano, Montserrat, and Colima volcano, Mexico.

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