IAEA Safety Standards
for protecting people and the environment

Volcanic Hazards in Site Evaluation for Nuclear Installations

Specific Safety Guide
No. SSG-21

IAEA
International Atomic Energy Agency

IAEA SAFETY STANDARDS AND RELATED PUBLICATIONS

IAEA SAFETY STANDARDS

Under the terms of Article III of its Statute, the IAEA is authorized to establish or adopt standards of safety for protection of health and minimization of danger to life and property, and to provide for the application of these standards.

The publications by means of which the IAEA establishes standards are issued in the **IAEA Safety Standards Series**. This series covers nuclear safety, radiation safety, transport safety and waste safety. The publication categories in the series are **Safety Fundamentals**, **Safety Requirements** and **Safety Guides**.

Information on the IAEA's safety standards programme is available at the IAEA Internet site

http://www-ns.iaea.org/standards/

The site provides the texts in English of published and draft safety standards. The texts of safety standards issued in Arabic, Chinese, French, Russian and Spanish, the IAEA Safety Glossary and a status report for safety standards under development are also available. For further information, please contact the IAEA at PO Box 100, 1400 Vienna, Austria.

All users of IAEA safety standards are invited to inform the IAEA of experience in their use (e.g. as a basis for national regulations, for safety reviews and for training courses) for the purpose of ensuring that they continue to meet users' needs. Information may be provided via the IAEA Internet site or by post, as above, or by email to Official.Mail@iaea.org.

RELATED PUBLICATIONS

The IAEA provides for the application of the standards and, under the terms of Articles III and VIII.C of its Statute, makes available and fosters the exchange of information relating to peaceful nuclear activities and serves as an intermediary among its Member States for this purpose.

Reports on safety and protection in nuclear activities are issued as **Safety Reports**, which provide practical examples and detailed methods that can be used in support of the safety standards.

Other safety related IAEA publications are issued as **Radiological Assessment Reports**, the International Nuclear Safety Group's **INSAG Reports**, **Technical Reports** and **TECDOCs**. The IAEA also issues reports on radiological accidents, training manuals and practical manuals, and other special safety related publications.

Security related publications are issued in the **IAEA Nuclear Security Series**.

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VOLCANIC HAZARDS IN SITE EVALUATION FOR NUCLEAR INSTALLATIONS

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world''.

IAEA SAFETY STANDARDS SERIES No. SSG-21

VOLCANIC HAZARDS IN SITE EVALUATION FOR NUCLEAR INSTALLATIONS

SPECIFIC SAFETY GUIDE

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FOREWORD

by Yukiya Amano
Director General

The IAEA's Statute authorizes the Agency to "establish or adopt… standards of safety for protection of health and minimization of danger to life and property" — standards that the IAEA must use in its own operations, and which States can apply by means of their regulatory provisions for nuclear and radiation safety. The IAEA does this in consultation with the competent organs of the United Nations and with the specialized agencies concerned. A comprehensive set of high quality standards under regular review is a key element of a stable and sustainable global safety regime, as is the IAEA's assistance in their application.

The IAEA commenced its safety standards programme in 1958. The emphasis placed on quality, fitness for purpose and continuous improvement has led to the widespread use of the IAEA standards throughout the world. The Safety Standards Series now includes unified Fundamental Safety Principles, which represent an international consensus on what must constitute a high level of protection and safety. With the strong support of the Commission on Safety Standards, the IAEA is working to promote the global acceptance and use of its standards.

Standards are only effective if they are properly applied in practice. The IAEA's safety services encompass design, siting and engineering safety, operational safety, radiation safety, safe transport of radioactive material and safe management of radioactive waste, as well as governmental organization, regulatory matters and safety culture in organizations. These safety services assist Member States in the application of the standards and enable valuable experience and insights to be shared.

Regulating safety is a national responsibility, and many States have decided to adopt the IAEA's standards for use in their national regulations. For parties to the various international safety conventions, IAEA standards provide a consistent, reliable means of ensuring the effective fulfilment of obligations under the conventions. The standards are also applied by regulatory bodies and operators around the world to enhance safety in nuclear power generation and in nuclear applications in medicine, industry, agriculture and research.

Safety is not an end in itself but a prerequisite for the purpose of the protection of people in all States and of the environment — now and in the future. The risks associated with ionizing radiation must be assessed and controlled without unduly limiting the contribution of nuclear energy to equitable and sustainable development. Governments, regulatory bodies and operators everywhere must ensure that nuclear material and radiation sources are used beneficially, safely and ethically. The IAEA safety standards are designed to facilitate this, and I encourage all Member States to make use of them.

NOTE BY THE SECRETARIAT

The IAEA safety standards reflect an international consensus on what constitutes a high level of safety for protecting people and the environment from harmful effects of ionizing radiation. The process of developing, reviewing and establishing the IAEA standards involves the IAEA Secretariat and all Member States, many of which are represented on the four IAEA safety standards committees and the IAEA Commission on Safety Standards.

The IAEA standards, as a key element of the global safety regime, are kept under regular review by the Secretariat, the safety standards committees and the Commission on Safety Standards. The Secretariat gathers information on experience in the application of the IAEA standards and information gained from the follow-up of events for the purpose of ensuring that the standards continue to meet users' needs. The present publication reflects feedback and experience accumulated until 2010 and it has been subject to the rigorous review process for standards.

Lessons that may be learned from studying the accident at the Fukushima Daiichi nuclear power plant in Japan following the disastrous earthquake and tsunami of 11 March 2011 will be reflected in this IAEA safety standard as revised and issued in the future.

THE IAEA SAFETY STANDARDS

BACKGROUND

Radioactivity is a natural phenomenon and natural sources of radiation are features of the environment. Radiation and radioactive substances have many beneficial applications, ranging from power generation to uses in medicine, industry and agriculture. The radiation risks to workers and the public and to the environment that may arise from these applications have to be assessed and, if necessary, controlled.

Activities such as the medical uses of radiation, the operation of nuclear installations, the production, transport and use of radioactive material, and the management of radioactive waste must therefore be subject to standards of safety.

Regulating safety is a national responsibility. However, radiation risks may transcend national borders, and international cooperation serves to promote and enhance safety globally by exchanging experience and by improving capabilities to control hazards, to prevent accidents, to respond to emergencies and to mitigate any harmful consequences.

States have an obligation of diligence and duty of care, and are expected to fulfil their national and international undertakings and obligations.

International safety standards provide support for States in meeting their obligations under general principles of international law, such as those relating to environmental protection. International safety standards also promote and assure confidence in safety and facilitate international commerce and trade.

A global nuclear safety regime is in place and is being continuously improved. IAEA safety standards, which support the implementation of binding international instruments and national safety infrastructures, are a cornerstone of this global regime. The IAEA safety standards constitute a useful tool for contracting parties to assess their performance under these international conventions.

THE IAEA SAFETY STANDARDS

The status of the IAEA safety standards derives from the IAEA's Statute, which authorizes the IAEA to establish or adopt, in consultation and, where appropriate, in collaboration with the competent organs of the United Nations and with the specialized agencies concerned, standards of safety for protection of health and minimization of danger to life and property, and to provide for their application.

With a view to ensuring the protection of people and the environment from harmful effects of ionizing radiation, the IAEA safety standards establish fundamental safety principles, requirements and measures to control the radiation exposure of people and the release of radioactive material to the environment, to restrict the likelihood of events that might lead to a loss of control over a nuclear reactor core, nuclear chain reaction, radioactive source or any other source of radiation, and to mitigate the consequences of such events if they were to occur. The standards apply to facilities and activities that give rise to radiation risks, including nuclear installations, the use of radiation and radioactive sources, the transport of radioactive material and the management of radioactive waste.

Safety measures and security measures[1] have in common the aim of protecting human life and health and the environment. Safety measures and security measures must be designed and implemented in an integrated manner so that security measures do not compromise safety and safety measures do not compromise security.

The IAEA safety standards reflect an international consensus on what constitutes a high level of safety for protecting people and the environment from harmful effects of ionizing radiation. They are issued in the IAEA Safety Standards Series, which has three categories (see Fig. 1).

Safety Fundamentals

Safety Fundamentals present the fundamental safety objective and principles of protection and safety, and provide the basis for the safety requirements.

Safety Requirements

An integrated and consistent set of Safety Requirements establishes the requirements that must be met to ensure the protection of people and the environment, both now and in the future. The requirements are governed by the objective and principles of the Safety Fundamentals. If the requirements are not met, measures must be taken to reach or restore the required level of safety. The format and style of the requirements facilitate their use for the establishment, in a harmonized manner, of a national regulatory framework. Requirements, including numbered 'overarching' requirements, are expressed as 'shall' statements. Many requirements are not addressed to a specific party, the implication being that the appropriate parties are responsible for fulfilling them.

Safety Guides

Safety Guides provide recommendations and guidance on how to comply with the safety requirements, indicating an international consensus that it is necessary to take the measures recommended (or equivalent alternative measures). The Safety

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[1] See also publications issued in the IAEA Nuclear Security Series.

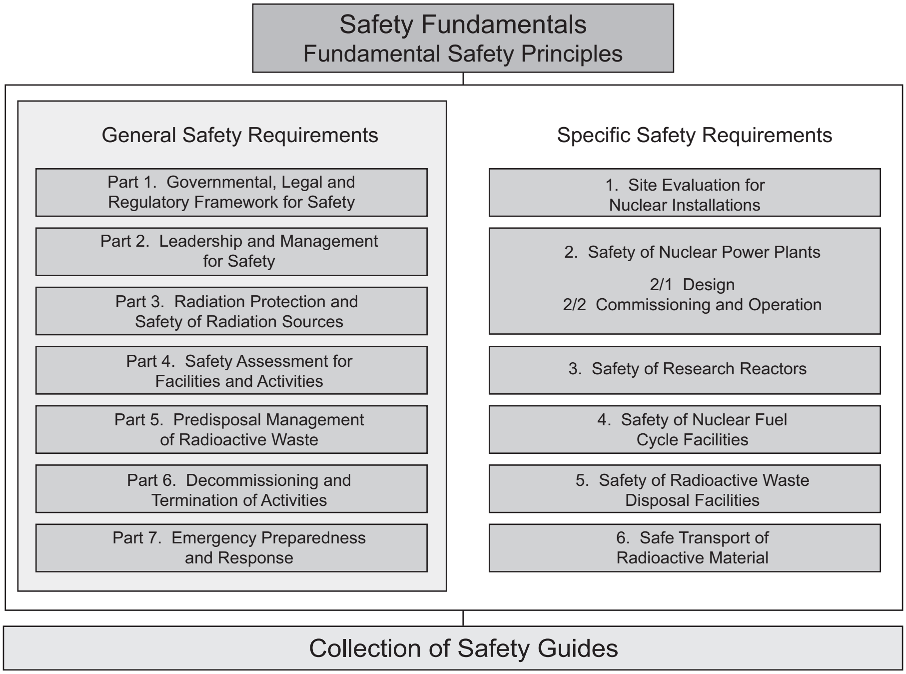

FIG. 1. The long term structure of the IAEA Safety Standards Series.

Guides present international good practices, and increasingly they reflect best practices, to help users striving to achieve high levels of safety. The recommendations provided in Safety Guides are expressed as 'should' statements.

APPLICATION OF THE IAEA SAFETY STANDARDS

The principal users of safety standards in IAEA Member States are regulatory bodies and other relevant national authorities. The IAEA safety standards are also used by co-sponsoring organizations and by many organizations that design, construct and operate nuclear facilities, as well as organizations involved in the use of radiation and radioactive sources.

The IAEA safety standards are applicable, as relevant, throughout the entire lifetime of all facilities and activities — existing and new — utilized for peaceful purposes and to protective actions to reduce existing radiation risks. They can be used by States as a reference for their national regulations in respect of facilities and activities.

The IAEA's Statute makes the safety standards binding on the IAEA in relation to its own operations and also on States in relation to IAEA assisted operations.

The IAEA safety standards also form the basis for the IAEA's safety review services, and they are used by the IAEA in support of competence building, including the development of educational curricula and training courses.

International conventions contain requirements similar to those in the IAEA safety standards and make them binding on contracting parties. The IAEA safety standards, supplemented by international conventions, industry standards and detailed national requirements, establish a consistent basis for protecting people and the environment. There will also be some special aspects of safety that need to be assessed at the national level. For example, many of the IAEA safety standards, in particular those addressing aspects of safety in planning or design, are intended to apply primarily to new facilities and activities. The requirements established in the IAEA safety standards might not be fully met at some existing facilities that were built to earlier standards. The way in which IAEA safety standards are to be applied to such facilities is a decision for individual States.

The scientific considerations underlying the IAEA safety standards provide an objective basis for decisions concerning safety; however, decision makers must also make informed judgements and must determine how best to balance the benefits of an action or an activity against the associated radiation risks and any other detrimental impacts to which it gives rise.

DEVELOPMENT PROCESS FOR THE IAEA SAFETY STANDARDS

The preparation and review of the safety standards involves the IAEA Secretariat and four safety standards committees, for nuclear safety (NUSSC), radiation safety (RASSC), the safety of radioactive waste (WASSC) and the safe transport of radioactive material (TRANSSC), and a Commission on Safety Standards (CSS) which oversees the IAEA safety standards programme (see Fig. 2).

All IAEA Member States may nominate experts for the safety standards committees and may provide comments on draft standards. The membership of the Commission on Safety Standards is appointed by the Director General and includes senior governmental officials having responsibility for establishing national standards.

A management system has been established for the processes of planning, developing, reviewing, revising and establishing the IAEA safety standards. It articulates the mandate of the IAEA, the vision for the future application of the

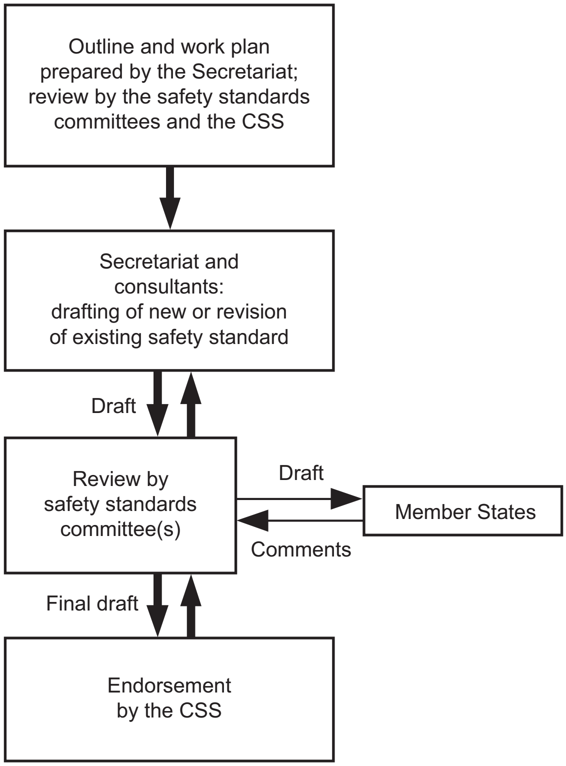

FIG. 2. The process for developing a new safety standard or revising an existing standard.

safety standards, policies and strategies, and corresponding functions and responsibilities.

INTERACTION WITH OTHER INTERNATIONAL ORGANIZATIONS

The findings of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and the recommendations of international expert bodies, notably the International Commission on Radiological Protection (ICRP), are taken into account in developing the IAEA safety standards. Some safety standards are developed in cooperation with other bodies in the United Nations system or other specialized agencies, including the Food and Agriculture Organization of the United Nations, the United Nations Environment Programme, the International Labour Organization, the OECD Nuclear Energy Agency, the Pan American Health Organization and the World Health Organization.

INTERPRETATION OF THE TEXT

Safety related terms are to be understood as defined in the IAEA Safety Glossary (see http://www-ns.iaea.org/standards/safety-glossary.htm). Otherwise, words are used with the spellings and meanings assigned to them in the latest edition of The Concise Oxford Dictionary. For Safety Guides, the English version of the text is the authoritative version.

The background and context of each standard in the IAEA Safety Standards Series and its objective, scope and structure are explained in Section 1, Introduction, of each publication.

Material for which there is no appropriate place in the body text (e.g. material that is subsidiary to or separate from the body text, is included in support of statements in the body text, or describes methods of calculation, procedures or limits and conditions) may be presented in appendices or annexes.

An appendix, if included, is considered to form an integral part of the safety standard. Material in an appendix has the same status as the body text, and the IAEA assumes authorship of it. Annexes and footnotes to the main text, if included, are used to provide practical examples or additional information or explanation. Annexes and footnotes are not integral parts of the main text. Annex material published by the IAEA is not necessarily issued under its authorship; material under other authorship may be presented in annexes to the safety standards. Extraneous material presented in annexes is excerpted and adapted as necessary to be generally useful.

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 established in the Safety Requirements publication on Site Evaluation for Nuclear Installations [1] in relation to volcanic hazards. Thus, this Safety Guide complements the other Safety Guides that deal with the protection of nuclear installations against external natural events and human induced events by means of site selection and site evaluation assessments, and the incorporation of appropriate design features and site protective measures, if necessary [2–6].

1.2. The Safety Requirements publication on 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" (para. 2.17 of Ref. [1]). In this regard, volcanism is explicitly mentioned in para. 3.52 of Ref. [1], which states that "Historical data concerning phenomena that have the 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 assessed". Therefore, volcanism is required to be considered during the site selection and site evaluation stages of a nuclear installation. Consequently, this Safety Guide provides a basis for meeting that requirement — as other IAEA Safety Guides do for other natural and human induced external events — through the comprehensive consideration of all potential volcanic hazards. Such consideration should not be interpreted as a way of promoting the location of nuclear installations in regions of hazardous volcanic activity.

1.3. The present Safety Guide upgrades and supersedes Provisional Safety Standards Series No. 1, Volcanoes and Associated Topics in Relation to Nuclear Power Plant Siting, published in 1997. This was the first guidance provided by the IAEA on this subject and it was published at a time when development was still ongoing at both national and international levels. Since that time, many aspects of volcanological science have been developed further. At the same time, there is growing interest in the nuclear community about the construction of additional nuclear power plants at existing sites that had not been comprehensively assessed in terms of volcanic hazards at the time of site selection. For new nuclear installations, more regions in the world are now being surveyed and assessed. In particular, some States 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. IAEA Provisional Safety Standards Series No. 1 was a unique reference about this subject and has been used by both the scientific and the nuclear communities to improve volcanic hazard assessment. 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 significant depths within the Earth over prolonged periods of time. Volcanic activity is caused by deep geological phenomena that determine the local rate of magma generation. The recommendations provided in this Safety Guide reflect the current status of development of the science of volcanology, which has undergone a transformation over the past thirty years. In this time, volcanology has evolved from an essentially descriptive science into a quantitative science that relies on observations of volcanic systems that were not previously possible and the use of 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 against this type of external hazard.

1.5. Engineering or operational solutions are generally available to mitigate some of the effects of external events by the incorporation of certain design features and/or operational procedures. 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 fulfils Principle 8 of the Fundamental Safety Principles [7] on the request to proceed with adequate site selection as a means of providing defence in depth, firstly for providing the basis for screening out those sites that are found to be unsuitable in 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 the assessment of volcanic hazards at a nuclear installation site, so as to enable the identification and comprehensive characterization of all potentially hazardous phenomena that may be associated with future volcanic events. These volcanic phenomena may affect the suitability of the selected site and some of them may determine corresponding design basis parameters for the installation.

1.7. This Safety Guide is intended for use by regulatory bodies responsible for establishing regulatory requirements, for designers of nuclear installations and for operating organizations directly responsible for the assessment of volcanic hazards at a nuclear installation site.

1.8. This Safety Guide is not intended to deal with response analysis and capacity evaluation of volcanic hazards at 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 in the site selection and evaluation process for 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.

1.10. Siting is the process of selecting, using adequate criteria, a suitable site for an installation [8]. The selection of a suitable site is one of the elements of the concept of defence in depth used for preventing accidents, as set out in Principle 8 of the Fundamental Safety Principles [7].

1.11. The siting process for a nuclear installation generally consists of an initial stage of the investigation, the site survey, which aims to cover a large region and identify potential sites and to select and rank one or more candidate sites. This is followed by an evaluation phase of those candidate sites, with the aim of finally selecting the site on which the nuclear installation will be located. Once the site is selected, the siting process is thus finished.

1.12. Site evaluation is a process that extends from (i) the last stage of the siting process (i.e. the phase of evaluation of the candidate sites in order to select the preferred site(s)), to (ii) the assessment of the selected site to confirm its suitability and to derive the site related design bases for the installation, to (iii) the confirmation and completion of the assessment during the pre-operational stage of the installation (i.e. during the design, construction, assembly and commissioning stages) and finally to (iv) the operational stage of the installation (see paras 1.8 and 1.14 of Ref. [1]). Thus, site evaluation continues throughout the entire lifetime of the installation to take into account the changes in site characteristics, availability of data and information, operational records, regulatory approaches, evaluation methodologies and safety standards.

1.13. The volcanic hazards treated in this Safety Guide are obviously considered external events, that is, natural or human induced events that originate external to both the site and the process of the installation, and over which the operating organization may have very little or no control. Such events are unconnected with the operation of a facility or conduct of an activity, but they could have an effect on the safety of the facility or activity. It is also to be noted that the concept of ‘external to the installation’ is intended to include more than the external zone (see Ref. [8]), 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 also be necessary when performing a probabilistic safety assessment (PSA) of the installation and considering the full scope of external events as initiating events.

1.14. This Safety Guide discusses the volcanic processes that may have adverse effects on the performance of safety systems at a nuclear installation 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 suitability and on the derivation of design basis parameters.

1.15. Volcanic phenomena may affect site suitability and the design of a nuclear installation. Hazards from volcanoes can exist over a broad scale of time and distance. These hazards are not uniformly distributed worldwide. Approximately 25% of Member States have potentially active volcanoes and the hazards posed by them can readily extend across international boundaries. Some hazards can even be present at inactive volcanoes, for example, the potential for collapse of a volcano edifice generating a tsunami long after volcanic activity has ceased.

1.16. For the purposes of this Safety Guide, a volcanic hazard is considered to be any phenomenon related to volcanism that may affect site suitability or the design of a nuclear installation. Volcanism is the natural process resulting from magma ascending through the Earth and erupting, or nearly erupting, at the Earth’s surface and producing phenomena that may have far reaching and long term effects. Volcanic hazards are complex and varied. Some phenomena, such as the opening of a new volcanic vent, may create a hazard (or hazards) that represents an exclusion condition and, therefore, precludes the particular nuclear installation site from further consideration during site selection. The potential for such disruptive phenomena in the site vicinity needs to be considered early in the site selection and evaluation processes in order to assess whether site suitability can be confirmed or not. In general, the site vicinity is defined as the area extending a few kilometres from the site area, with account taken of the topography of the site, and defined in agreement with the regulatory body. 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 suitability 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 needs to be applied 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 the evaluation of volcanic hazards.

1.17. The potential for so-called mud volcanoes to form near a 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 (Appendix, para. I.14). 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. [6].

1.18. This Safety Guide addresses an extended range of nuclear installations as defined in Ref. [8]: 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 installation in accordance with the potential radiological consequences of their failure due to volcanic hazards. The recommended direction of grading is to start with attributes relating to nuclear power plants and, if possible, to grade down to installations with which lesser radiological consequences are associated[1]. Therefore, if no grading is performed, the

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

recommendations relating to nuclear power plants are applicable to other nuclear installations.

1.19. For the purpose of this Safety Guide, existing nuclear installations are those installations that are: (i) at the operational stage (including long term operation and extended temporary shutdown periods), or (ii) 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 nuclear installation, it is considered to be at the operational stage in which a high level of operational safety is required to be maintained [11]. 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

1.20. In this Safety Guide, the description of the phenomena associated with volcanism and the collection of the necessary data and information are set out separately from the criteria for hazard assessment. Thus, Section 2 and the Appendix provide 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 provides general recommendations and outlines the general procedure to be followed in the site selection and site evaluation stages. Sections 4–6 provide detailed guidance for nuclear power plants. Section 4 provides recommendations on the acquisition and development of the database for the hazard assessment. Sections 5 and 6 provide recommendations 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 I provides examples of the complex series of events that accompany different types of volcanic eruption, while Annex II gives information on worldwide available sources of data on the subject. Finally, although it is recognized that complete consensus has not been reached within the scientific community on the use and meaning of some terms, definitions of volcanological terms are provided, applicable only to usages adopted in this Safety Guide.

2. OVERVIEW OF VOLCANIC HAZARD ASSESSMENT

NATURE OF VOLCANIC PHENOMENA AND VOLCANIC HAZARDS

2.1. Volcanic events can present significant hazards for nuclear installations. Volcanic hazards arise from phenomena that have a broad range 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 a volcanic eruption. This section provides an overview of the nature and types of volcanic phenomena and the volcanic hazards resulting from a volcanic event, as well as a general description of the methodologies and criteria used for hazard assessment in relation to such phenomena.

2.2. Phenomena associated with volcanic events that may pose a potential hazard to a site are summarized in Table 1, with a clear indication of those phenomena whose characteristics should be considered to preclude selection of a candidate site at the site selection stage and those phenomena that may be accommodated by measures for design and operation. A decision on the suitability of the site is taken in accordance with the potential that phenomena listed as 'Yes' in the third column of Table 1, which generally constitute an exclusionary condition during the site selection stages, will occur within the site area or in the site vicinity.

2.3. If the results of the assessment show that a potential exists for those phenomena listed as 'Yes' in the third column of Table 1 to occur at the site area or in the site vicinity and for them to affect the safety of the nuclear power plant, and that no practical engineering solutions are available, the site should be deemed unsuitable.

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 an exclusion condition at site selection stage?	Can effects be mitigated by measures for design[2] and operation?
1. Tephra fallout	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	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. Volcanic debris flows, lahars and 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

TABLE 1. VOLCANIC PHENOMENA AND ASSOCIATED CHARACTERISTICS THAT COULD AFFECT NUCLEAR INSTALLATIONS, WITH IMPLICATIONS FOR SITE SELECTION AND EVALUATION AND DESIGN (cont.)

Phenomena	Potentially adverse characteristics for nuclear installations	Considered an exclusion condition at site selection stage?	Can effects be mitigated by measures for design[2] and operation?
9. Tsunamis, seiches, crater lake failure and 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 related hazards	Continuous tremor, multiple shocks, usually earthquake magnitude $M < 5$	No	Yes
13. Hydrothermal systems and groundwater anomalies	Thermal water, corrosive water, water contamination, inundation or upwelling, hydrothermal 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 a nuclear installation. The design and operation column indicates the general practicality of mitigating the potential hazard associated with particular phenomena, by either facility design or operational planning. A ‘Yes’ in both columns indicates that, in principle, this phenomenon constitutes a site exclusion criterion, although for some cases a design basis may be achievable.

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

2.4. As stated above, the potential occurrence of a phenomenon that represents an exclusion condition (e.g. pyroclastic density current, lava flow, new vent) having direct effects on a site or in the site vicinity precludes the site from further consideration. Some phenomena (e.g. lahars and floods, tsunamis and hydrothermal systems) are considered exclusion conditions if they have direct effects on the site, or if they occur directly at the site or in the site vicinity. However, in some special cases and circumstances, such phenomena that occur in the region of the site and which have some effects on the site may be accommodated by means of appropriate design, protective measures and operational measures. In the latter case, adequate design bases may need to be formulated. Factors affecting the site suitability or design bases are further explained in Section 6 and in the Appendix.

2.5. If the site is deemed suitable, the corresponding design basis should be derived for those phenomena that can occur at the site and that can affect the safety of the nuclear power plant.

2.6. Volcanic events are infrequent, relative to most other natural events that can affect the safety and performance of a nuclear installation. Some volcanoes have erupted after lying dormant for thousands of years, or even longer. As a general guide, volcanoes that have erupted during the past 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 II), and these volcanoes are formally referred to as Holocene volcanoes, i.e. volcanoes that have erupted during the past 10 000 years (named after the Holocene period). Holocene volcanoes may erupt after long periods of inactivity. Some volcanoes have reactivated after periods of inactivity longer than 10 000 years. Many individual volcanoes have not been studied in sufficient detail to know for certain whether they erupted during the Holocene or not. Therefore, consideration of volcanic hazards is not to be limited to known Holocene volcanoes.

2.7. Volcanic activity within a geographical region can persist for longer timescales than those associated with individual volcanoes. Many volcanic arcs exhibit recurring volcanic activity for longer than 10 Ma [3], although individual volcanoes within the arc itself may themselves remain active for only around 1 Ma. As such distributed volcanic activity can persist for many millions of years, regions that have experienced volcanic activity during the past 10 Ma are considered to have the potential for future activity. A straightforward estimate of

[3] Ma: million years.

a regional volcanic recurrence rate of less than 1 event in 10 Ma would imply a current annual probability of future volcanic activity of less than 10^{-7}. In hazard assessment of external events for nuclear installations (see para. 4.3 of Ref. [2]), a limiting value of the annual probability of occurrence of events with potential radiological consequences is termed the screening probability level, for which, in some Member States, a value of 10^{-7} is ascribed. Initiating events with an annual probability of occurrence lower than this screening probability level should not be given further consideration, regardless of their consequences. Therefore, during the initial screening stage, an annual probability of occurrence of 10^{-7} is a reasonable basis on which to evaluate whether a volcano could generate any type of volcanic activity in the future, given that hazardous effects at the site due to an eruption will be even less likely.

2.8. Episodes of eruptive volcanic activity at individual volcanoes can persist 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 missiles of limited range, to high energy events that bury the countryside under tens of metres of hot ash. Thus, a variety of volcanic phenomena can occur on substantially different scales 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.

2.9. Non-eruptive phenomena at volcanoes may also represent hazards for nuclear installations. Volcanoes are commonly unstable landforms. Even after long periods of repose, portions of a volcano 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 relating to fault movement may also cause collapse of the volcanic edifice. These examples demonstrate the need for the volcanic hazard assessment for a nuclear installation to consider the influence of extreme weather and hydrological and tectonic processes on the likelihood and characteristics of future volcanic events.

2.10. 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. Specific impacts of volcanic phenomena depend on a range of conditions, such as composition of the erupted products, temperature, water content and related factors. The occurrence of some volcanic phenomena may change the likelihood of occurrence of other phenomena. A volcanic hazard assessment uses a systematic approach to evaluate credible, interrelated phenomena and to ensure that all relevant hazards are integrated into the analysis.

GEOLOGICAL RECORD AND DATA UNCERTAINTY

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

2.12. The geological 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 the characteristics of the 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 geological record and also to assess potential changes in volcanic hazards over time.

2.13. The frequency and timing of past events is incompletely understood and uncertain for most volcanoes. For example, the timing 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.

2.14. 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 timing 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 occurrence of hazardous phenomena. Detailed hazard assessments, if warranted, may need to consider the likelihood of occurrence and associated uncertainties for volcanic phenomena that may reach the site concerned.

ALTERNATIVE CONCEPTUAL MODELS OF VOLCANISM

2.15. 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 the development of conceptual models to interpret the geological record in terms of volcanic processes. Such conceptual models can encompass the origin of magma, the tectonic setting of volcanoes, the rates and volumes of ejecta produced during 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 geological record could be assumed to persist in the future. Alternatively, a potential site may be located in an area where the tectonic setting has changed through time such that the geological record of past volcanic activity might be a poor representation of potential future volcanism. For example, the characteristics of individual volcanoes in a volcanic arc could change over a relatively short period, owing to changes in the orientation or magnitude of the crustal stress field. Therefore, a conceptual model of the tectonic setting for volcanism assists in the determination of the extent to which past events appropriately represent future events.

2.16. A clear and proper understanding of the processes that affect volcanism, as represented by the conceptual model, makes best use of available geological data and guides the collection of additional data. Updates to conceptual models are carried out 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.

2.17. Volcanic hazard assessments usually consider alternative conceptual models. These models are consistent with available data and current scientific understanding and are evaluated with due regard to the influence of their effects on hazard estimation. For example, volcanic systems may vary from primarily effusive systems with low energy eruptions to higher energy explosive eruptions. Use of a conceptual model for volcanic activity at a volcano that only has the products of low energy eruptions preserved in the geological record may lead to estimation of hazards for this volcanic activity alone. In contrast, an alternative conceptual model using information from analogous volcanic systems would include hazards associated with higher energy explosive eruptions.

2.18. The hazard assessment is usually clearly documented where alternative conceptual models could result in significant differences in the estimation of hazards. If alternative models result in significant differences in the estimation of hazards, then these alternative models are propagated through the hazard assessment.

VOLCANO CAPABILITY

2.19. The concept of a 'capable' volcano or volcanic field is introduced in this Safety Guide to denote those volcano(es) and/or volcanic field(s) that are potentially capable of producing hazardous phenomena that may affect the site of a nuclear installation. A capable volcano or volcanic field is one that: (i) has a credible likelihood of experiencing future activity during the lifetime of the installation and (ii) has the potential to produce phenomena that may affect the site of the installation. Following the identification of one or more capable volcanoes and/or volcanic fields, a comprehensive and site specific volcanic hazard assessment is developed. 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 the occurrence of future volcanic eruptions. This distinction is made because: (i) there is often considerable uncertainty about the timing of the most recent volcanic activity at volcanoes that have no documentation of historical eruptions and (ii) there are multiple deterministic or probabilistic 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

2.20. Both deterministic and probabilistic methods are currently used to assess volcanic hazards. Deterministic methods assess volcanic hazards using one or a few postulated worst case scenarios. Thus, they use thresholds to screen specific phenomena from further consideration. Such thresholds are often based on empirical evidence, such as the maximum volume or maximum lateral extent of pyroclastic flows. These methods, however, do not consider the full range of data and model uncertainty in the analysis. Probabilistic methods consider all potential hazard scenarios for a site and incorporate the uncertainties associated with each scenario into the final hazard calculation. Such analyses usually consider a range of potential frequencies, intensities and characteristics for each event. Both deterministic and probabilistic methods of hazard assessment rely on empirical observations and a theoretical understanding of volcanic processes. Volcano capability and the site specific volcanic hazard are evaluated using, to the extent possible, both deterministic and probabilistic methods because they are complementary.

2.21. In both deterministic and probabilistic approaches, the magnitude and spatial extent of volcanic phenomena are evaluated using geological data gathered in the site region and in a manner consistent with conceptual models of volcanic processes. These geological data can be supplemented with information from analogous volcanoes and from numerical simulation of volcanic phenomena. If the likelihood of occurrence of a phenomenon needs to be used to assess volcano capability or site specific volcanic hazards, relative and absolute age determinations can be used to estimate recurrence rates of volcanic events. In either a probabilistic or deterministic approach, analysis of uncertainties due to the available data and due to model assumptions is an integral part of the hazard assessment, as discussed in detail in Section 6, which deals with specific volcanic phenomena.

2.22. If differences in alternative models cannot be explained or resolved by means of additional investigations within a reasonable time frame, the final hazard evaluation should consider all such alternative models. The volcanic hazard assessment needs to quantify all uncertainties represented in alternative conceptual models, supported by the preparation of clear and traceable documentation recording the method(s) used to propagate each uncertainty through the hazard assessment process. Examples of methods used to include and propagate uncertainties include logic trees and bounding analyses based on individual models. It is important to recognize that any assessment approach, whether deterministic or probabilistic, will involve intrinsic uncertainties that will need to be taken into consideration.

3. GENERAL RECOMMENDATIONS

INTRODUCTION

3.1. This section provides general recommendations on the procedure for evaluating the volcanic hazards for the potential site of a nuclear installation. The outcome of a volcanic hazard assessment should be a transparent and traceable record of decisions made about site suitability and the determination of the design basis. Indeed, the recommended approach focuses only on volcanic phenomena that represent potential hazards to the site. This approach recognizes the need for increasing levels of detail in information in accordance with increasing levels of hazard at the site. This approach also recognizes that, for sites located far from potentially active volcanoes, only a limited subset of potential hazards should be considered, for example, only distant tephra fallout and/or volcanogenic tsunamis. The full range of potential hazards should be considered for sites located closer to potentially active volcanoes.

3.2. The general goal for the volcanic hazard assessment is to determine the capability of a volcanic source, defined as a volcano and/or volcanic field for the purpose of this Safety Guide, to produce potentially hazardous phenomena that may reach the site and affect the safety of the nuclear installation. Thus, a comprehensive volcanic hazard model for the site should be established, if deemed necessary. This goal should be accomplished throughout the implementation of an approach based on four stages, as follows and as presented in Fig. 1:

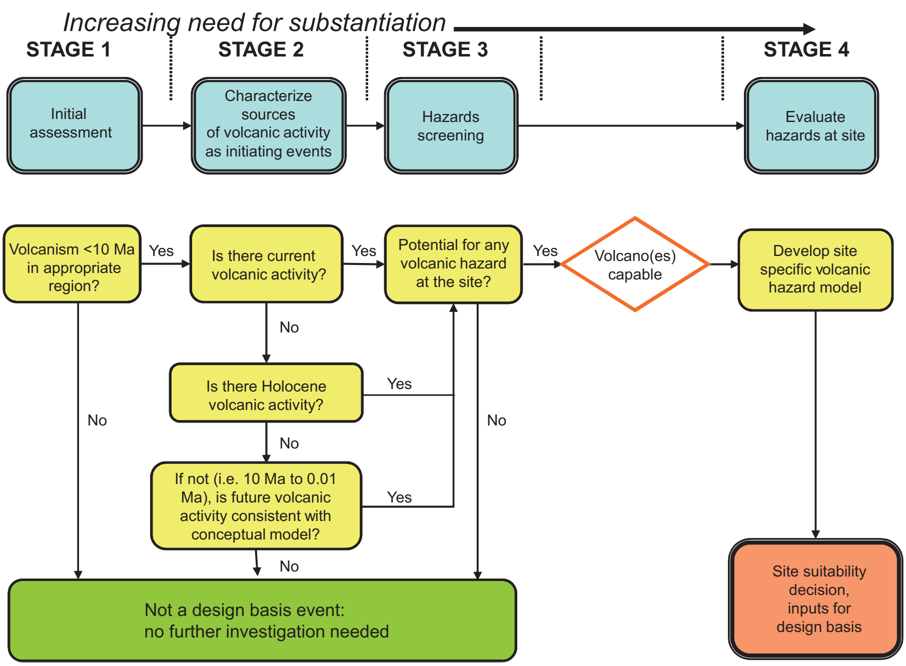

FIG. 1. Methodological approach to volcanic hazard assessment.

(i) Stage 1: First, an initial assessment should be carried out to define a geographical region around the site that encompasses all sources of volcanic activity that may have occurred during the past 10 Ma.
(ii) Stage 2: Second, once these sources of volcanic activity have been identified, they should be evaluated to establish the possibility of their erupting or producing another volcanic event in the future.
(iii) Stage 3: Third, the possibility of future volcanic events creating hazardous phenomena that may adversely affect the site of the nuclear installation should be evaluated. Volcanoes that do not have the potential to produce hazardous phenomena at the site should be screened out from further consideration.
(iv) Stage 4: Finally, if a capable volcanic source is identified, a site specific volcanic hazard assessment should be conducted. This assessment should include each of the specific phenomena that may affect the site and should consider potential causal relationships among these phenomena.

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, it should be determined whether sufficient information is available to evaluate adequately the volcanic hazards at the site. In some cases, the information available 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, to determine site suitability and/or to derive the related design basis events.

3.4. In the first stage of the siting process, i.e. during the site survey, relevant data should be collected from available sources of information (publications, technical reports and related material) in order to identify volcanic phenomena with the potential for hazardous effects at the identified candidate site(s). In this regard, Annex II 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 should focus on two primary considerations:

(1) Definition of an appropriate geographical region around the identified candidate site(s) that encompasses all potential sources of volcanic hazards;
(2) Collection of evidence of volcanic activity occurring within that region during the past 10 Ma.

The geographical region will depend on the nature and type of volcanic phenomena listed in Table 1, which span orders of magnitude in scale, varying from tens of kilometres for some phenomena, which are the most important regarding the selection of the site and the safety of the installation, to thousands of kilometres for other phenomena, such as tephra fallout and tsunami. This stage should include a detailed review of available sources of information for the geographical region around the site. This detailed review would typically use geological maps, results from previous geological investigations and other information as discussed in Section 4. At this stage, the geographical region around the site(s) for which the hazard assessment will be performed is defined.[4]

3.6. The outcome of stage 1 should be a determination of the presence and distribution of volcanic sources younger than 10 Ma in the geographical region around the identified candidate site(s). If volcanic sources younger than 10 Ma are not present in the geographical region, no further investigations are necessary.

Stage 2: Characterization of potential sources of future volcanic activity

3.7. If the outcome of the initial assessment in stage 1 indicates that volcanic sources younger than 10 Ma are present in the geographical region, then a conceptual model for volcanic processes in the region should be developed. This conceptual model, or set of alternative conceptual models, should include analysis of the tectonic setting of volcanism, frequency of eruptive activity and similar information about geological trends. Volcanoes that are consistent with the conceptual model for volcanic processes, and all volcanoes registering 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 out from further consideration. Such justification may be supported using a hierarchical analysis, as described in paras 5.5–5.15.

[4] In the following paragraphs, the term ‘geographical region’ refers to the region around the site(s) for which the volcanic hazard assessment is performed.

Stage 3: Screening of volcanic hazards

3.8. In cases where the potential for future volcanic activity in the site region cannot be ruled out, the potential should be evaluated for hazardous phenomena to affect the site in the event that an eruption or other volcanic event occurs. This evaluation should be performed for each of the phenomena associated with each potentially active volcanic source (i.e. a volcano or a volcanic field) in the geographical region around the site, as defined in stage 1. Deterministic and/or probabilistic methods should be used to evaluate the potential for hazardous volcanic phenomena to reach the site. All potentially active volcanic sources in the geographical region do not necessarily produce all the volcanic phenomena listed in Table 1. Volcanoes that do not have the potential for producing hazardous volcanic phenomena at the site should be screened out from further consideration in the hazard assessment.

Stage 4: Hazard assessment of capable volcanoes

3.9. Volcanic sources identified in stage 3 as being volcanic sources that may possibly erupt in the future and which may produce potentially hazardous volcanic phenomena at the site are considered capable volcanic sources (see para. 2.16). Consequently, a site specific volcanic hazard assessment should be conducted for all capable volcanic sources in a comprehensive manner, covering all the volcanic phenomena listed in Table 1. The outcome of this assessment forms the technical basis for decisions about:

(a) The suitability of the site;
(b) The derivation of the design basis for those phenomena whose effects can be mitigated by measures for design and operation if the site is deemed as otherwise suitable.

Additional considerations

3.10. If volcanoes within the geographical region are sources of credible hazards at the site, then the characteristics of these capable volcanoes are required to be monitored over the lifetime of the installation [1]. In this case, a monitoring programme for early warning in the operational stage should be prepared and implemented before commissioning, in coordination with specialized agencies in the State for early warning of natural hazards. Normally, emergency planning requirements for an installation will include such a monitoring programme and such 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:

(a) The character of each individual volcanic source within the appropriate geographical region;
(b) The wider volcanological, geological and tectonic contexts of such volcanic sources;
(c) 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 collected or acquired and compiled in a database.

4.2. The database should incorporate all the information that is necessary to support decisions at each stage of the volcanic hazard assessment. The structure of the database should be sufficiently flexible as to accommodate increasing levels of detail in information, completeness and integration as the analysis progresses through advancing stages of complexity. Initially, the database may be based on, or may 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 of and levels of detail in the information necessary for the assessment of volcanic hazards in accordance with the need for substantiation as the assessment progresses.

4.3. In addition to serving as an information resource, the database should also provide a structure for documenting the handling of data during the volcanic hazard assessment. This will serve to record the evidence and interpretations on which scientific decisions are based, as well as providing a basis for quality assurance of the data used for the assessment. For instance, all data used to formulate screening criteria and the consequent decisions should be contained in the database. Any data considered in the assessment but rejected as irrelevant or inaccurate for assessing the hazards or otherwise not used should also be retained in the database and identified as such, and justification should be provided as to why these rejected data are not considered in the assessment. To achieve consistency in the presentation of information, data should, whenever possible, be compiled in a geographical information system with adequate information concerning the source of the data. All data should be stored in a manner that facilitates comparison and integration.

INFORMATION NECESSARY FOR THE INITIAL ASSESSMENT (STAGE 1)

4.4. For the initial assessment (see Fig. 1), available geological knowledge should be used to determine whether any volcanic activity occurred in the past 10 Ma in an appropriate geographical region surrounding the site. If it is judged that the available geological information on the region is insufficient for this purpose, additional data should be sought, such as those described in paras 4.6–4.8, to provide an adequate basis for initial assessment.

4.5. The geographical region for the assessment does not have predetermined, uniform dimensions, but should be determined on the basis of the types of potentially hazardous phenomena resulting from volcanic activity younger than 10 Ma and which may have an impact on the safety of the nuclear power plant. The most important volcanic phenomena for the site selection and safety of the nuclear power plant are those that extend for short distances from the volcano. The region considered for such potential hazards might extend for only tens of kilometres from the site. For tephra fallout and other atmospheric hazards relating to volcanoes, the geographical region should extend for hundreds to thousands of kilometres from the site, with due consideration given to regional wind field patterns.[5] Assessment of potential tsunamis induced by volcanic phenomena should consider, in an appropriate manner, an entire ocean basin for some coastal sites (see Ref. [5]). The geographical region to be investigated should be defined at the beginning of the volcanic hazard assessment.

4.6. A hierarchy of geological maps and volcanological data is necessary for the initial assessment. At this stage, available geological maps may be adequate if they provide data at various scales. For example, a 1:500 000 scale map may serve for the full area of study, while 1:50 000 scale maps may be used for the

[5] As an example of the extension of the area affected by a volcanic eruption, a tephra fallout deposit of decimetric thickness off the Atlantic coast of South America from an unknown volcano located in the far Andean region, probably 1000 km distant, has been reported.

region close to the site. Geological maps of volcanoes at a scale of 1:50 000 or larger will normally be necessary for the initial assessment. Available satellite images and aerial photographs may also be useful for this purpose. Data should also be retrieved from 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 by means of a geographical information system, which should be developed throughout the various stages of the volcanic hazard assessment, as recommended in para 4.3.

4.7. Volcanism should be characterized in terms of the types of volcano and potential volcanic eruption concerned (see Annex I). At this initial stage, it will be helpful to consider volcanic activity also 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 bathymetric data or drill core logs or descriptions, may be important in identifying potential volcanic sources and deposits during the initial assessment. This detailed characterization provides the groundwork for determination of the appropriate geographical region for volcanic hazard assessment. This characterization should be supported by data of an appropriate resolution.

4.8. Determinations of the age of volcanic products associated with the volcanic sources provide fundamental information for the initial assessment stage. Such age determinations may include historical information, stratigraphic relationships, radiometric dating and morphological considerations. The level of detail in the information should be critically assessed to ensure that all relevant volcanic sources have been identified and have age determinations of suitable quality. For many cases, the available information may not be sufficient for a robust appraisal at this stage of a site evaluation. In such circumstances, additional geochronological, geological and volcanological data should be established or acquired, and compiled. For instance, further sampling may be necessary in order to ascertain the age of volcanic products in the geographical region.

INFORMATION NECESSARY FOR HAZARD SCREENING AND SITE SPECIFIC HAZARD ASSESSMENT (STAGES 2–4)

4.9. If the findings of the initial assessment indicate the occurrence of volcanism younger than 10 Ma, the next step should be to examine and, if necessary, gather more detailed information on the timing and the 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, data sources and any other related information that can be helpful in assessing the strength of evidence and the reliability of the data in relation to establishing the robustness of the hazard assessment. Particular attention should be paid to documenting sources of uncertainty that arise from incomplete knowledge (i.e. epistemic uncertainties), as well as uncertainties that arise from data variability (i.e. aleatory uncertainties).

4.11. As volcanoes often have complex geological histories, additional information may be necessary in order to ensure a comprehensive hazard assessment. First and foremost, any information that is specific to a volcanic source found in the geographical region should be included in the database. Additionally, it needs to be recognized that the geological record of volcanic activity for a given specific source could be incomplete. For such cases, rates of activity at analogous volcanoes may be useful in supplementing information collected in the geographical region of the site in order to evaluate the potential for future eruptions. Similarly, the spatial distributions of volcanic products found at analogous volcanoes may be useful in helping to define ‘screening distance values’, i.e. the maximum distance value for a particular type of volcanic phenomenon and source beyond which the effects of the phenomenon may be ignored. Whenever such analogous information is utilized in the hazard assessment, it too should be included in the database.

Geological and volcanological data

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

(a) The types (morphology) and spatial distribution of volcanic sources and geological controls on the distribution of these volcanic sources (such as their relationship to tectonic features);
(b) The number and timings of eruptions at each source;
(c) The repose intervals between eruptions and the durations of eruptive episodes at each source, where it is possible to determine these;
(d) The current topography of each possible source of volcanic activity and its relationship to the topography of the site (such information may be included 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 the spatial migration of volcanic sources or temporal evolution of geochemistry, and changes in the volume of eruptive products.

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

(a) The location of the volcanic sources (e.g. latitude, longitude, elevation) and the dates and durations of eruptions;
(b) A description of the types of eruptive product, including their areal extent, volume and composition;
(c) The areal extent and characterization (e.g. magnitude, intensity, peak ground acceleration and time history, if available) of associated seismic activity, ground deformation and other geophysical and hydrological activity or anomalies;
(d) A 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 geological 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, typically, the stratigraphy of pyroclastic units is complex and incomplete. Assessment of the completeness of the geological record should be attempted, even if all volcanic deposits cannot be mapped. The ages of volcanic deposits should be expressed numerically and should be correlated to provide a complete description of the history of the 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 of the potential sources identified. Deposits younger than 10 Ma in the geographical region of interest should be identified and evaluated to provide the following information:

(a) The type and distribution of deposits and an identification of the likely source or sources;
(b) The ages and volcanological and petrological characteristics of the associated eruptions and their products.

4.16. The viability and usefulness of this type of information is highly dependent on the age of the deposits and the completeness of the geological record. Wherever possible, complete volcanological information should be collected. In order to compile complete volcanological information, it may be necessary to drill 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 and geochemically, and, if appropriate, radiometric age determinations may be made using these samples.

4.17. If volcanic deposits are identified, additional information should be provided for each distinguishable tephra fallout 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. The following information should be collected about each individual tephra fallout deposit:

(a) Isopach and isopleth maps showing the extent, thickness, volume, particle sizes and dispersion axis of the deposit;
(b) The equivalent static load (wet and dry) of the deposit;
(c) Derived eruption parameters, such as eruption column height (if not directly observed), mass eruption rate and eruption duration.

4.18. 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) Thickness, volume, density, areal distribution, probable velocities and temperatures of emplacement and estimates of maximum dynamic pressure achieved during flow, if possible and if necessary;
(b) Data on topographic features that influenced the direction and kinetic energy of flows driven by gravity or directed by 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 the vent of a pyroclastic flow involving column collapse).

4.19. 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 and the thickness and volume of the deposit;
(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 on topographic features that influenced the flow path from the source, velocity and distribution of the flow and the relationship of the deposit to current topography.

Geophysical and geochemical survey data

4.20. 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 a specific volcano and the prospects for future eruptive phenomena;
(c) To take advantage of new emerging or improved technologies or techniques to strengthen available information (i.e. the volcanological database) about a specific volcano;
(d) To comply with safety requirements for monitoring [1].

4.21. The type and extent of geophysical and geochemical surveys to be carried out should be determined on the basis of information requirements for the volcanic hazard assessment. In the case of the selection of a site for a new nuclear power plant, surveys should be considered at the earliest stage of the process. In addition to surface measurements, geophysical and geochemical data retrieved from 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 contribute to the site evaluation process and should be included in the database.

4.22. In the following paragraphs, brief reviews of some of the various recognized ways of surveying volcanoes for the evaluation of volcanic activity are provided. Specialist advice should be obtained for the design, implementation and analysis of these techniques. Close cooperation should be sought with institutions that operate existing monitoring systems, such as those national programmes with responsibilities and competences for forecasting volcanic eruptions and mitigating the consequences of any disaster. Survey planning and design should consider the possibility that data collection activities might evolve into a monitoring programme for operating nuclear power plants [1].

Volcano-seismic signals

4.23. 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. Volcanic unrest with the potential for eruptive activity can be discerned by certain patterns and types of volcano-seismic signal generated within or near the volcano. Dedicated seismic monitoring is necessary to detect these signals.

4.24. A well-designed, installed and operated seismographic network for volcano monitoring will record all types of volcano-seismic signal (e.g. tremors, as well as transient events) and its technical capabilities 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 volcanic systems.

Ground deformation

4.25. Ground deformation and changes in volcanic topography may reflect surface instability or underground movement of magma, groundwater and gas. Reactivation of old landslides usually reflects unstable ground conditions or ground deformation. Typically, techniques for determining ground deformation provide measurements of variations in elevation, angles and distances between points in a network at established times. These measurements can be acquired by various techniques on the ground or by remote sensing. As ground deformation may be extremely subtle, or may be obscured by confounding effects, ground deformation monitoring networks need to be deployed at an early stage in site evaluation.

Geomagnetism and geoelectricity

4.26. Measurements of geomagnetic and geoelectrical parameters may be useful for understanding underground structure and the position of magmatic bodies or groundwater systems and for detecting changes in them. The results of these measurements can enhance the understanding of volcanic structures and the large scale geophysical and geological properties of the volcanic edifice, such as zones of hydrothermal alteration.

Gravity

4.27. Measurements of gravity are made over volcanic terrain to provide useful information about rock properties, such as porosity and mass density, and about geological structure, such as the distribution of faults in volcano edifices. When detailed measurements of temporal variations in 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

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

Geothermal anomalies and geothermal fluids

4.29. Changes in the temperature, composition and location of thermal anomalies relating to fumaroles, vents, crater lakes, hot and cold springs, soils and snow and ice fields are often good indicators of variations in volcanic activity. Therefore, the implementation of a programme of inspection, monitoring or repeated measurements on the ground or by remote sensing will allow all this information to be obtained.

Groundwater circulation

4.30. Significant changes in groundwater conditions can be induced by volcanic activity, sometimes acting over large distances. In this regard, the monitoring of fluctuations in water level and discharge rate and changes in the chemical composition, temperature, conductivity and dissolved gas content of hot or cold springs and crater lakes provides useful information. In addition, other, more specialized, techniques such as bathymetric measurements and acoustic monitoring of crater lakes may be appropriate.

Other phenomenological observations

4.31. Detailed and regular visual observations and inspections provide the most fundamental primary data for assessing the state of activity of a volcano. Sometimes, the earliest signs of unrest can be detected by basic observations, such as anomalous sounds, earthquakes and ground vibrations sensible to humans, temperature variations and fluctuations in the activity of fumaroles and hot springs, 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, for instance, may be warranted.

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

4.33. 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 useful for the identification of potentially unstable slopes on volcanoes that could result in landslides and debris avalanches, such as digital elevation models, topographic maps and drainage patterns.

4.34. For satisfactory interpretation, volcano monitoring data should be integrated with complementary meteorological data. These may be obtained by cooperation with surveillance functions undertaken for other purposes at the nuclear power plant, as well as from regional, national or international weather services.

4.35. Water courses that could become involved with the transport of volcanic products towards, or the accumulation of sediment near, the site should be characterized and measurement programmes should be instituted. Real time early warning monitoring systems may be warranted in certain circumstances.

Monitoring for unrest and eruptions

4.36. Since the identified capable volcanic sources should be subject to a monitoring programme (see para. 3.9), monitoring data on unrest and eruptions should be recorded in the database. Many of the methods discussed in this section, such as volcano-seismic signals, 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 the potential for further hazardous phenomena. Such data gathering and documentation relating to unrest and eruptions should, whenever possible, be coordinated with institutions that have responsibilities and competence in national volcano monitoring programmes.

Emerging techniques

4.37. New and improved techniques for volcano monitoring and for geophysical and geochemical surveying of volcanic systems will continue to emerge. In terms of supporting a site specific volcanic hazard assessment or determining volcano capability, the fundamental criterion as to whether any new monitoring or surveying technique can be accepted for use in a volcanic hazard assessment already under way is that the new test or technique provides substantive data or evidence in context and that it is well recognized by the scientific community. If these conditions are satisfied, data from such techniques may be incorporated in the database, although, in the event of controversy, preference should be given to data obtained using well-established ‘state of the art’ techniques. Use should also be made of data arising from work undertaken for other purposes (e.g. for the assessment of other types of hazard at the site, to meet operational safety requirements or as part of national or regional hazard mitigation programmes).

5. SCREENING OF VOLCANIC HAZARDS

5.1. Stages 1–3 of the volcanic hazard assessment (see Fig. 1) provide steps that lead to the identification of capable volcanoes. This should be accomplished using a hierarchy of screening decisions based on the potential for 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 (as mentioned in para. 3.5): (i) definition of an appropriate geographical region for the initial assessment of volcanic hazards and (ii) collection of evidence of volcanic activity occurring within that region during the past 10 Ma. Stage 1 includes a detailed review of all available sources of information in order to determine an appropriate geographical region around the site. This detailed review should typically include geological maps, results from previous geological investigations and other information as discussed in Section 4. Criteria for defining the geographical region for the assessment are 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 possible 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 geographical region should be justified, to ensure that potentially hazardous volcanoes have been duly considered in the assessment.

5.4. The initial assessment in stage 1 should evaluate the evidence for the occurrence of volcanic activity within the past 10 Ma. As described in para. 2.7, 10 Ma encompasses the timescales of regional volcanic activity in many volcanic arcs and intraplate volcanic settings. In addition, if modern radiometric age determinations are available, these are generally decisive for distinguishing igneous rocks that are older than or much younger than 10 Ma, thereby minimizing the potential for ambiguity in the available data. Thus, if a lack of volcanism in the past 10 Ma is demonstrated, this implies that annual probabilities of future eruptions are less than 10^{-7} per year and, therefore, no further investigations for the purpose of volcanic hazard assessment would be necessary.

STAGE 2: CHARACTERIZATION OF POTENTIAL SOURCES OF FUTURE VOLCANIC ACTIVITY

5.5. If the outcome of the initial assessment in stage 1 indicates that volcanic sources younger than 10 Ma are present in the geographical region, then these volcanic sources should be further characterized by additional investigations to be performed in stage 2.

5.6. If the outcome of stage 2 confirms 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 historical volcanic eruptions, ongoing volcanic unrest, an active hydrothermal system (e.g. the presence of fumaroles) and related phenomena.

5.7. Evidence of an eruption during the past 10 000 years (i.e. the Holocene) is a widely accepted indicator that future eruptions are credible. As the Holocene is often a readily recognized geological boundary, national and international databases usually differentiate between volcanoes that have been active in the Holocene and older volcanoes. Information for determining whether 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 volcanic products may be difficult to determine. In such circumstances, additional criteria may be used to judge a volcano as Holocene, including: (i) volcanic products overlying the most recent Pleistocene glacial debris, (ii) youthful volcanic landforms in areas where erosion would be expected to be pronounced after many thousands of years and (iii) vegetation patterns that would be far more developed if the volcanic substrates were more than a few thousand (or hundred) years old.

5.9. Specialists may disagree over the evidence for Holocene volcanism and there may be significant uncertainty about the most reliable age estimate of the most recent eruption. In such cases, the volcanoes should be classified as

Holocene(?).[6] From a safety perspective, future eruptions should be considered credible for all Holocene volcanoes, including those with an uncertain record of eruption in the Holocene, and the analysis should proceed to stage 3.

5.10. If there is no evidence of current or Holocene activity, more detailed consideration should be given to assessing the timing of older activity in the region. Evidence of an eruption in the past 2 Ma generally indicates that future volcanic activity remains possible. Furthermore, for some volcanic systems such as distributed volcanic fields or infrequently active calderas, activity during approximately the past 5 Ma may also indicate some potential for future activity. To ensure adequate evaluation, the geological data should be assessed to determine whether any of the volcanic sources in the region as old as 10 Ma have the potential for future eruption.

5.11. At this step, a probabilistic analysis of the potential for future volcanic events can be used. Such events may be volcanic eruptions, or non-eruptive activity such as slope failure resulting from a previous eruption. Probabilistic methods may include frequency based approaches based on the recurrence of past volcanic eruptions, such as 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. 2.7, 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. the occurrence of an eruption) at or below 10^{-7} could be considered a reasonable criterion for initial screening. As there is some small likelihood that a hazardous phenomenon could 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. However, the acceptable limit value of the annual probability of occurrence of a specific hazardous volcanic phenomenon should be established by the regulatory body.

5.13. Deterministic approaches may also be used. For example, analogous volcanoes can be investigated to determine the maximum period of time elapsing between episodes of eruptive activity and to use this hiatus in activity as a

[6] Consistent with established volcanological terminology, a volcano of questionable Holocene age is indicated by Holocene(?).

threshold value. For a volcano with an ongoing period of quiescence, the possibility of a return to activity could be assessed by comparison with this threshold value. Such a deterministic analysis should include discussion of the volcanic processes that drive volcanic activity and an explanation of why the volcanoes are truly analogous in terms of these processes should be provided.

5.14. An additional deterministic approach might invoke time–volume or petrological trends in the volcanic system. For example, a time–volume relationship may indicate an obvious waning trend and demonstrable cessation of volcanic activity in the early Pleistocene or older periods. In such situations, it could be argued that renewed volcanism is very unlikely. In cases where a resolution based on these criteria is not achieved, it should be assumed simply that future eruptions are likely for any volcano younger than 10 Ma.

5.15. It may be found that future volcanic activity in the geographical region is considered less likely than the established acceptable limit value of the annual probability of occurrence, as mentioned in para 5.12. If sufficient information is available to support this conclusion, no further analysis is necessary and volcanic hazards do not need further investigation for this site. Conversely, a lack of sufficient evidence, or a finding that future volcanic events in the region of interest appear to be possible, may warrant additional analyses and the hazard assessment should proceed to stage 3.

STAGE 3: SCREENING OF VOLCANIC HAZARDS

5.16. In cases where the 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 analysed. This analysis should be performed for each of the phenomena associated with volcanic activity listed in Table 1. In some cases, specific hazardous phenomena may be screened from further consideration if there is negligible likelihood of these phenomena reaching the site. In decisions on screening, consideration should be given to whether such phenomena might result from secondary processes or scenarios that comprise complex sequences of volcanic events (see Annex I).

5.17. A deterministic approach to assessing hazards at this stage can be based on screening distance values for each specific volcanic phenomenon. 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, with account taken of the characteristics of the source volcano and the nature of the 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 on the basis of data gathered at analogous volcanoes or where the topography would prevent 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 is located beyond the screening distance for a specific volcanic phenomenon, then no further analysis is necessary for that phenomenon. However, if future volcanic activity appears to be possible and if the site is located 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 phenomenon may have a different screening distance value.

5.19. A complementary approach to assessing hazards at this stage is to estimate the conditional probability of a specific volcanic phenomenon reaching the site, given an eruption at the volcanic source. 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 geological record incompletely preserves past activity from volcanoes and because past volcanic activity may not have encompassed the full range of potential phenomena resulting from a future volcanic event.

5.20. Estimation of the conditional probability of 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 necessary and volcanic hazards do not represent credible design basis events for the site. If use of the conditional probability alone is insufficient to support screening, volcano capability should be considered.

5.21. As indicated in para. 2.7, in some States a value for the annual probability of 10^{-7} is used in the hazard assessment of 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 on which to base screening decisions in a similar way to that recommended in stage 2 (see para. 5.12). The annual probability may be calculated, for example, by multiplying the probability of occurrence 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 the probabilities of occurrence of the initiating event by the conditional probability is also an appropriate basis for identification of a capable volcano or volcanic field. For those phenomena associated with exclusion criteria for a site, as indicated in Table 1, the acceptable limit value of the annual probability of occurrence of 10^{-7} may be adopted but, in any case, the acceptable limit value should be established in agreement with the regulatory body. Finally, a site specific volcanic hazard assessment (stage 4) should be conducted for phenomena originating from capable volcanoes.

5.22. 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 geological 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 geological record, there may be more certainty in estimating the probability of large magnitude eruptions on the basis of the geological record of past activity. The conceptual model of the volcano, encompassing the nature and evolution of volcanic processes, should be reflected in the estimate of the probability of the occurrence of such large magnitude volcanic events. Nevertheless, when estimating the full range of uncertainty in the record of past events, care should be taken to avoid placing undue emphasis on large events that are well preserved in the geological record.

5.23. Many volcanic phenomena involve coupling between different processes, so that deterministic and probabilistic approaches should not consider individual processes only in isolation but rather 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 I).

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 within the geographical region. This guidance should be used in conducting the assessment of specific volcanic hazards at the site of a nuclear power plant in stage 4 of the volcanic hazard assessment (Fig. 1).

6.2. The volcanic phenomena listed in Section 2 and described in the Appendix are screened in stages 1–3 of the hazard assessment process. Volcanic phenomena that were not screened out as a result of stages 1–3 require further consideration in the site specific volcanic hazard assessment to determine the frequency, nature and magnitude of potential hazards. The assessment should provide sufficient information to determine whether a design basis or other practicable solution for this volcanic hazard can be established. If a design basis or other practicable solution (e.g. site protective measures) for this volcanic hazard cannot be established, the site should be deemed unsuitable.

6.3. As in screening decisions taken in stages 2 and 3, a combination of deterministic and probabilistic approaches may be necessary to assess volcanic hazards in stage 4. In deterministic methods, threshold values are defined on the basis of empirical observations of past volcanic activity, analogous information from other volcanoes and/or numerical simulation of volcanic processes. Decisions on site suitability and on the determination of the design basis are based upon whether these thresholds are exceeded or not. Probabilistic methods may also use a range of empirical observations, analogous information from other volcanoes and/or numerical simulation to develop a probability distribution for the likelihood that a hazardous phenomenon will exceed a specified magnitude. Decisions on site suitability and on the determination of the design basis are derived from the analysis of these probability distributions. In either method, both the potential for volcanic events to occur and their potential impacts on the nuclear power plant 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, to the extent possible, with the design basis characteristics of other external events. It may be possible to demonstrate that the design basis derived for other external events encompasses that derived for some volcanic hazards. For example, physical loads resulting from tephra fallout may be enveloped by physical loads derived for other external events.

6.5. Recommendations are provided in the following paragraphs on volcanic phenomena that should be considered in the site specific volcanic hazard assessment. Relevant volcanological information for each of these phenomena is provided in the Appendix.

TEPHRA FALLOUT

6.6. Tephra fallout is the most widespread hazardous volcanic phenomenon. Even minimal tephra accumulation has the potential to disrupt normal operations at a nuclear power plant. Hazards associated with tephra fallout include: static load on structures; particle impact; blockage of, and abrasion within, water circulation systems; mechanical and chemical effects on ventilation systems, electrical systems and instrumentation and control systems; and particle loading in the atmosphere surrounding the nuclear power plant. Water can significantly increase the static load of a tephra deposit. Tephra particles commonly have adsorbed acid leachates (e.g. SO_4^{2-}, F^-, Cl^-) on their surfaces and so can cause chemical corrosion as well as pollution of water supplies.

6.7. The hazard assessment for tephra fallout for each capable volcano should consider:

(a) Potential sources of tephra;
(b) Magnitudes of potential tephra producing volcanic eruptions and the physical characteristics of these eruptions;
(c) Frequency of tephra producing eruptions;
(d) Meteorological conditions between source regions and the site that will affect transport and deposition of tephra;
(e) Secondary effects of tephra eruptions, such as the increased likelihood of lahars and the potential for pollution and chemical corrosion, which may have adverse effects on the safe operation of a nuclear power plant.

Deterministic assessment

6.8. A deterministic approach should develop a threshold value for the maximum credible thickness for tephra fallout deposits at the site. For example, actual deposits from eruptions of analogous volcanoes could be used to define the maximum thickness of deposits at the site for a capable volcano. Particle size characteristics (i.e. grain size distribution and maximum clast size) could be estimated from these deposits. Analogous 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, for specific eruption and meteorological conditions. The uncertainties in the various 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 or other applicable simulation techniques of tephra fallout from each capable volcano should be conducted, with account taken of variation in eruption volume, eruption column height, total grain size distribution and wind velocity distribution in the region as a function of altitude and related parameters. Such models lead to a frequency distribution of tephra accumulation, commonly presented as an annual frequency of exceedance curve for the hazard (or ‘hazard curve’). Uncertainty in the resulting hazard curves should be expressed by confidence bounds, and the basis for the selection of the reported confidence levels should be documented.

Factors to consider in site selection, site evaluation and development of the design basis

6.10. As indicated in Table 1, the effects of tephra fallout are not considered part of the exclusion criteria for the site, since these effects can be mitigated by appropriate measures for design and operation. For either deterministic or probabilistic assessments, the results of assessment 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 the static loads that are defined as part of the design basis for the nuclear power plant, the contribution for each capable volcano should be integrated into a single, site specific maximum credible value or single hazard curve for tephra fallout. This information may also be used to assess particle size distribution and the potential for remobilization of tephra deposits, which could create particle loads in the atmosphere or debris flows and lahars. Tephra fallout 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 eruptions that form lava domes and thick lava flows. The impacts of pyroclastic density currents are very severe for obstacles in their flow paths as these flows move at high velocities, and are commonly at high temperatures (e.g. more than 300°C). In addition, they are destructive, owing to the momentum of the massive terrain enveloping mixture of hot lava blocks, ash and volcanic gas. Deposits 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, they should be considered an exclusion criterion for the site (see Table 1).

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

6.13. The hazard assessment for pyroclastic density currents for each capable volcano should consider:

(a) The potential sources of explosive volcanic events and lava domes and flows that may collapse;
(b) The magnitudes of potential volcanic eruptions and the physical characteristics of eruptions that result in pyroclastic density currents;
(c) The frequency of explosive volcanic eruptions or dome collapse events that lead to different types of pyroclastic density current;
(d) The topography between source regions and the site that can affect the flow path and the extent of pyroclastic density currents;
(e) The secondary effects of deposition from pyroclastic density currents, such as the 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 should establish threshold values on the basis of the potential maximum travel distance (runout). Screening distance values for these phenomena can be determined on the basis of the volume and nature of pyroclastic density current deposits exposed within the geographical region of concern or by referring to flow events identified at analogous volcanoes. Potential runout can also be estimated by using numerical models. The uncertainties in the various 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, the screening distance value for pyroclastic surges will generally be greater than that for pyroclastic flows.

Probabilistic assessment

6.16. The probability of occurrence of pyroclastic density currents should be calculated as a conditional probability of an eruption of a given intensity, multiplied by conditional probability distributions for:

(a) Occurrence of pyroclastic density currents;
(b) Runouts of these phenomena;
(c) Directivity effects.

The value for conditional probability of pyroclastic density currents should be representative of the physical properties of the magma, 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 be used to refine the estimate. Uncertainty in the resulting hazard curves should be expressed by confidence bounds and the basis for selection of the reported confidence levels should be documented.

Factors to consider in site selection, site evaluation and development of the design basis

6.17. As indicated in Table 1, the effects from pyroclastic density currents should be considered one of the exclusion criteria for the site, since these effects cannot be mitigated by appropriate measures for design and operation. For either deterministic or probabilistic assessments, several additional factors should be considered in making judgements on site suitability in relation to hazards posed by pyroclastic density currents. Both threshold values and probability estimates relating to most pyroclastic density currents could be evaluated using the energy cone model, which is an empirical model commonly used to estimate potential runout distances. More sophisticated numerical models of pyroclastic density currents coupled with Monte Carlo simulations or other applicable simulation techniques can generate probabilistic assessments of runout and the corresponding 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 assessments. 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 over which lava flows move are also factors in controlling the length of lava flows. Lava flows have a direct impact owing to their dynamic and static loads and their high temperature (up to 1200°C). The effects of lava flows usually exceed many common design bases and they should be considered an exclusion criterion for the site (see Table 1).

6.19. Evaluation of the hazard associated with lava flows for each capable volcano should consider:

(a) The potential magnitude (e.g. mass discharge rate, areal extent, velocity, thickness) of lava flows;
(b) The frequency of future effusive volcanic eruptions;
(c) The eruptive scenario (e.g. individual lava flows, lava tubes, flow fields);
(d) 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, the hazard assessment for lava flows should determine threshold values on the basis of the maximum credible length, areal extent, thickness, temperature and potential speed of lava flows that could reach the nuclear power plant. This can be achieved using data from other volcanoes from the geographical region, from analogous volcanoes and from empirical or numerical models of lava flow emplacement. Some empirical models of lava flow emplacement rely on correlations between lava flow length and effusion rate, whereas others are volume limited. Topography along the path and at the site of the nuclear power plant should be considered. A screening distance value can thus be defined for lava flows beyond which lava incursion is not considered a credible event. The uncertainties in the various parameters should be properly taken into account.

Probabilistic assessment

6.21. A probabilistic approach should also address the location of vents and the potential formation of new volcanic vents. The probabilistic approach should entail numerical modelling of lava flows and should proceed with numerical simulations for each capable volcano, with account taken of a range of values for parameters that control flow length and thickness, using stochastic methods. In numerical simulation, vent location, topography, discharge rate, viscosity of the flow and duration of the eruption are key parameters that control the modelled lava flow emplacement. Probabilistic assessments use models of lava flows coupled with Monte Carlo simulations and other applicable simulation techniques. Empirical observations from the capable volcano and analogous volcanoes can be used to refine the probabilistic analysis. Lava flow hazard curves should then be determined and combined to express the annual frequency of exceedance of different levels of lava flow incursion and lava thickness at the nuclear power plant. Uncertainty in the resulting hazard curves should be expressed by confidence bounds, and the basis for the selection of the reported confidence intervals should be documented.

Factors to consider in site selection, site evaluation and development of the design basis

6.22. As indicated in Table 1, the effects of lava flows should be considered one of the exclusion criteria for the site, since these effects cannot be mitigated by appropriate measures for design and operation. For either deterministic or probabilistic assessments, several additional factors should be considered in making judgements on site suitability in relation to lava flow hazards. Probabilistic or deterministic approaches should result in estimates of the potential for any lava flow to reach the nuclear power plant, and its likely thickness, as well as its thermal properties. This assessment should consider the effects of phenomena associated with lava flows, such as generation of floods following interaction with ice and snowfields, 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 cubic kilometres), 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 [6]. The impact of volcanic debris avalanches is predominantly mechanical, owing 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 usually be considered rejection criteria for the site.

6.24. The hazard assessment for debris avalanches, landslides and slope failures for each capable volcano should consider:

(a) The identification of potential source regions of these events, including areas of potential instability;
(b) The potential magnitude (i.e. volume, areal extent, thickness) of these events;
(c) The frequency of such events;
(d) The potential flow paths;
(e) The influence of volcanic activity on changes in such factors as groundwater levels, surface water conditions, static and dynamic loadings and others that may contribute to these events.

Modifications of the flow properties along the path, as well as the topography from the source region to the nuclear power plant, should also be considered, noting that topography may be altered during the eruption thereby altering the flow paths significantly.

Deterministic assessment

6.25. A deterministic approach should determine threshold values for the maximum credible volume, the runout distance and the thickness of avalanche deposits at the site using information collected from actual deposits on analogous volcanoes and from 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 considered to be credible events. The uncertainties in the various parameters should be properly taken into account.

Probabilistic assessment

6.26. A probabilistic approach should extend the numerical modelling of these flows and should proceed with numerical simulations, using stochastic methods, for each capable volcano, with account taken of a range of values for those parameters that control the geometry of the source region, flow length, velocity, volume and thickness. Probabilistic methods can be refined by using 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 and the basis for the selection of the reported confidence intervals should be documented.

Factors to consider in site selection, site evaluation and development of the design basis

6.27. As indicated in Table 1, the effects of debris avalanches, landslides and slope failures should be considered one of the exclusion criteria for the site, since these effects cannot be mitigated by means of appropriate measures for design and operation if they occur in the site vicinity or if they affect the site directly. For either deterministic or probabilistic assessments, several additional factors should be considered in making judgements on site suitability in relation to debris avalanches, landslides and slope failures. The results of probabilistic or deterministic approaches should include estimates of the potential for incursion at the site, as well as flow thickness and velocity. The hazard assessment should consider other indirect phenomena associated with debris avalanches, landslides and slope failures, such tephra fallout, 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 warning times available after the onset of the flow, the high flow velocities and discharge rates, the 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, owing to the mass of material involved and its velocity and therefore its erosive power. The occurrence and the effects of debris flows and lahars can persist for periods ranging from months to decades following volcanic eruptions, as volcanic products such as pyroclastic density current and tephra fallout deposits are remobilized over time. Deposits of debris flows and lahars may reach significant thicknesses (e.g. tens of metres). Given the wide range of volumes, and hence consequences for a site, the effects of debris flows, lahars and floods should usually be considered exclusion criteria for the site. However, in some cases their effects can be accommodated by site and plant layout and design considerations, as well as by on-site protective measures. Floods associated with volcanic events should be treated in a manner consistent with that for floods of non-volcanic origin [5].

6.29. The hazard assessment for lahars, debris flows and floods of volcanic origin for each capable volcano should consider:

(a) The identification of potential source regions for volcanic debris and for water, including snowcaps and glaciers;
(b) The potential magnitude and characteristics of the flow;
(c) The potential for modification of the flow properties along the path, the sources of water and the topography between the source region and the nuclear power plant;
(d) The frequency of such events in the past;
(e) The meteorological data at the source region and along the potential path of such flows.

Deterministic assessment

6.30. A deterministic approach should establish threshold values for 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 considered to be credible events. Floods of volcanic origin should be evaluated in a manner consistent with that described in Ref. [5]. The uncertainties in the various parameters should be properly taken into account.

Probabilistic assessment

6.31. A probabilistic approach should entail the numerical modelling of these flows and should proceed with numerical simulations, using stochastic methods, for each capable volcano, with account taken of a range of values for parameters that control flow geometry and discharge rate. These models can be refined by means of 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 annual frequency of exceedance values for flow incursion at the site and discharge rates. Uncertainty in the resulting hazard curves should be expressed by confidence bounds and the basis for the selection of the reported confidence intervals should be documented.

Factors to consider in site selection, site evaluation and development of the design basis

6.32. As indicated in Table 1, the effects from volcanic debris flows, lahars and floods should be considered, in principle, one of the exclusion criteria for the site. However, since their effects may be accommodated by site and plant layout, design, operation or site protective measures, the appropriate design basis should be determined. For either deterministic or probabilistic assessments, several additional factors should be considered in deriving the design basis and in making judgements on site suitability in relation to debris flows, lahars and associated floods. The probabilistic or deterministic approaches should result in estimates of their potential to reach the nuclear power plant as well as their likely flow geometry and discharge rates. Indirect event sequences such as tephra fallout from capable volcanic sources on a neighbouring snow clad mountain that could act as a source for debris flows, floods generated by eruption under ice or snow, and the sudden release of water and debris from breakage of volcanic dams in craters or valleys filled with volcanic debris should also be considered.

OPENING OF NEW VENTS

6.33. The opening of new vents is a geological phenomenon that can produce significant flow, tephra fallout, volcano generated missile and ground deformation hazards for a nuclear power plant. 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, the hazard assessment of each capable volcano or volcanic field should consider volcanic phenomena produced as a result of, and during, a volcanic eruption, such as tephra fallout, lava flows, lava domes and pyroclastic flows, that may originate from new vents as well as from existing vents. Opening of new vents at the site vicinity should be considered an exclusion criterion for the site (see Table 1).

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 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 considered to be a credible event. Additional information, such as significant changes in the tectonic setting 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 uncertainties in the various parameters should be properly taken into account.

Probabilistic assessment

6.36. Modern analyses of volcanic hazards associated with new vent formation normally involve a probabilistic approach. A probabilistic hazard assessment should estimate a spatial probability density function which describes 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, the 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 and the basis for the selection of the reported confidence intervals should be documented.

Factors to consider in site selection, site evaluation and development of the design basis

6.37. As indicated in Table 1, the effects from the opening of new vents should be considered one of the exclusion criteria for the site, since these effects cannot be mitigated by appropriate measures for design and operation if they occur in the site vicinity or if they affect the site directly. For either deterministic or probabilistic assessments, several additional factors should be considered in making judgements on site suitability in relation 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. per year) and within a specific area (e.g. the site vicinity). The potential for new vent formation should be considered in the hazard assessment for other volcanic phenomena, such as lava flows, volcano generated missiles, tephra fallout and surges. In the event of the 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 volcano generated missiles that may fall on a nuclear power plant can be very high. At the vent, particles have velocities in the range of 50–300 m/s and the distance travelled is a function of their size and aerodynamic drag, which can be reduced behind the shock waves produced by large eruptions. These factors mean that even large, dense particles (e.g. 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 can disrupt normal operations at a nuclear power plant and could result in damage to structures at the plant. These hazardous volcanic phenomena should usually be considered an exclusion criterion for the site, although in some cases their effects can be accommodated in the design of protective measures.

Deterministic assessment

6.39. A deterministic approach should determine the threshold values for the maximum distance and maximum size that volcano generated missiles can attain using information on the maximum distance and maximum size of missiles produced in previous explosive eruptions from analogous volcanoes. Missile transport models could also be used to determine a screening distance value as a function of exit speed, density of particles, exit angle and wind field parameters. The analysis should consider the effect of topographic barriers between the nuclear power plant and the vent and the possibility of missiles from secondary vents. The uncertainties in the various 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, with account taken of variation in explosion pressure, density of particles, exit angle and related parameters. Such models produce a frequency distribution of particle accumulation, commonly presented as a hazard curve. Uncertainty in the resulting hazard curves should be expressed by confidence bounds, and the basis for the selection of the reported confidence intervals should be documented.

Factors to consider in site selection, site evaluation and development of the design basis

6.41. As indicated in Table 1, the effects from volcano generated missiles should be considered, in principle, one of the exclusion criteria for the site. However, in some cases, their effects may be accommodated by means of site and plant layout, design, operation and site protective measures. For either deterministic or probabilistic assessments, several additional factors should be considered in deriving design basis data and in making judgements on site suitability in relation to volcano generated missiles. Probabilistic and deterministic approaches may be combined in the analysis. Results of this combined analysis could be expressed, for example, as the probability of potential impacts beyond a specified screening distance. The potential for volcano generated missiles should be considered as part of the hazard assessment of the opening of new vents and as impacts relating to tephra fallout. As missile fragments are commonly hot, their potential to initiate fires in or around the nuclear power plant should be considered. Results of the analysis should be consistent with those for similar external hazards, such as missiles generated by human induced events or extreme meteorological phenomena (see Refs [2, 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 also diffuse through soils and along fracture systems on, and adjacent to, volcanoes. Extensive lava flows are also a significant source of volcanic gases. The adverse effects of volcanic gases include asphyxiation, toxicity and corrosion, often associated with the condensation of acids from volcanic gases, dry deposition and heavy acid loading. The effects of volcanic gases on mechanical systems and personnel should be accommodated by appropriate measures for design and operation and should be taken account of in derivation of the design basis.

6.43. Estimation of hazards due to volcanic gases relies on accurate estimation of the potential flux of such gases in volcanic systems and on the accuracy of 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 an offset distance between potential volcanic gas sources and the site by using information gathered from analogous volcanoes or gas concentration measurements at the capable volcano. Alternatively, assuming that degassing from a capable volcano will occur, 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 uncertainties in the various 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 may 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, and the basis for the selection of the reported confidence intervals should be documented.

Factors to consider in site selection, site evaluation and development of the design basis

6.46. As indicated in Table 1, the effects from volcanic gases are not considered one of the exclusion criteria for the site, since these effects can be mitigated by appropriate measures for design and operation. For either deterministic or probabilistic assessments, several additional factors should be considered in deriving the design basis and in making judgements on site suitability in relation to volcanic gases. Results of this analysis are generally expressed in terms of the expected atmospheric concentration of volcanic gases and the expected dry deposition in the site vicinity. This analysis should consider the 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 can also displace large volumes of water, from both slope collapse and the release of volcanic gases, and should be considered in the site specific hazard assessment. For coastal sites, or sites located near large bodies of water, such as lakes and reservoirs, tsunami and seiche hazards should normally be considered in the site assessment (see Ref. [5]). Nevertheless, specialist knowledge is necessary to evaluate fully 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 power plants. Therefore, tsunami and seiche hazards are required to be considered in both site evaluation and design.

6.48. Currently, tsunami and seiche hazards are evaluated using deterministic numerical models, which should consider the locations of potential sources, the volume and rate of mass flow, the source and characteristics of water displacement and the resulting propagation of waves on the basis of location specific bathymetry data [5]. 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 are commonly associated with frequent lightning and are occasionally associated with strong downburst winds. Such atmospheric phenomena should be considered when the design basis for a nuclear power plant is being derived.

6.50. As explosive volcanic eruptions may lead to rare atmospheric phenomena, as described in Ref. [5], consideration should be given in the hazard assessment to the use of a deterministic approach to model the maximum hazard for each atmospheric phenomenon associated with a potential volcanic eruption.

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

6.52. Volcanically induced lightning has the same hazardous characteristics as lightning from other meteorological phenomena but is a frequent phenomenon 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 use of the screening criteria used in hazard assessments of rare atmospheric phenomena [5] with consideration given to the fact 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 increased potential for landslides, debris flow or related phenomena and volcanic gas flow. Ground deformation also accompanies the opening of new volcanic vents. The magnitude of ground deformation varies considerably, from millimetre scale vertical and horizontal displacements at great distances from the volcano (e.g. >10 km) to metres of displacement near some volcanic centres (e.g. opening of a new vent or a ‘restless’ caldera). Thus, the most significant potential deformation in the site locations is associated with the opening of new vents. Therefore, volcano deformation associated with distant capable volcanoes can be within the design basis of the nuclear power plant. 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 should be considered an exclusion criterion for the site.

6.54. The potential magnitude of ground deformation should be estimated in terms of displacement and the results of this should be superimposed onto 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 from models of ground deformation that consider the movement and pressurization of magma bodies of various geometries and possessing various rock mechanical properties. The uncertainties in the various parameters should be properly taken into account.

Probabilistic assessment

6.56. A 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 geometries for intrusion. As in deterministic approaches, models of ground deformation should consider the movement and pressurization of magma bodies of various geometries and having various rock mechanical properties. The probabilistic analysis may be refined by using information from analogous volcanoes where ground deformation has been observed.

Factors to consider in site selection, site evaluation and development of the design basis

6.57. As indicated in Table 1, the effects of ground deformation should be considered one of the exclusion criteria for the site since these effects cannot be mitigated by appropriate measures for design and operation if they occur in the site vicinity or if they affect the site directly. For either deterministic or probabilistic assessments, results of this analysis should include estimation of the potential for ground displacement to occur at the site as a result of volcanic activity, including the opening of new vents. The most significant aspect of the ground deformation analysis, however, should involve coupling this analysis with analysis of the potential for other volcanic phenomena. In particular, the potential for ground deformation in landslide and volcanic debris avalanche source regions should be assessed, as ground deformation in these zones may greatly change the potential volume of such flows (i.e. landslides and debris avalanches) and consequently their potential for reaching the site of the nuclear power plant. Volcanic activity or subsurface intrusions of magma may change groundwater flow patterns or cause fluctuations in the depth of the water table. The potential hazards associated with such changes should also be considered in the assessment of flood hazards [5].

VOLCANIC EARTHQUAKES AND RELATED HAZARDS

6.58. Volcanic earthquakes and related hazards normally occur as a result of stress and strain changes associated with the rise of magma towards 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 hazard assessment for tectonic earthquakes (i.e. seismic earthquakes), a deterministic method for assessing volcano-seismic ground motion should determine the combination of magnitude of the volcano-seismic event, depth of focus and distance from the site that 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 interpreted as a capable fault that may produce surface displacements (see Section 8 of Ref. [4]).) Suitable relationships for volcano-tectonic earthquakes should be derived for alternative parameterizations of ground motion, such as peak ground acceleration, duration of shaking or spectral content. (Specific ground motion characteristics of volcano-tectonic earthquakes may differ from those considered in Ref. [4], but the same principles should be applied.) The uncertainties in the various parameters should be properly taken into account.

Probabilistic assessment

6.60. A probabilistic assessment of the volcano-seismic hazard at a site should follow principles similar to 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:

(a) Construction and parameterization of a volcano-seismic source model, including uncertainty in source locations;
(b) Evaluation of event magnitude–frequency distributions for all such sources, together with uncertainties;
(c) Estimation of the attenuation of seismic ground motion for the site region and its stochastic variability.

With these steps, the results of the probabilistic computation of the ground motion hazard should be expressed in terms of the annual frequency of exceedance of different levels of relevant ground motion parameters (e.g. peak ground acceleration, appropriate range of response, spectral acceleration) for both horizontal and vertical motions.

Factors to consider in site selection, site evaluation and development of the design basis

6.61. As indicated in Table 1, the effects produced by volcanic earthquakes are not considered one of the exclusion criteria for the site since these effects can be mitigated by appropriate measures for design and operation. In many cases, a site close to a capable volcano will also lie in a region of significant seismic hazards from tectonic faults and fault zones and it may be possible to demonstrate that the volcano-seismic hazards at the site are significantly lower than those associated with other sources of seismic activity. 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 an increased potential for slope failure and may alter loads on structures (e.g. in tandem with tephra fallout loading). Such effects should be considered and assessed for their potential influence on the design basis and site evaluation.

HYDROTHERMAL SYSTEMS AND GROUNDWATER ANOMALIES

6.63. Hydrothermal systems can generate steam explosions that eject rock fragments to a distance of several kilometres and can create craters hundreds of metres in diameter and result in the formation of new vents. Hydrothermal systems can also alter rock to clays and other minerals, which lead to generally unstable ground that can be highly susceptible to landslides. These factors make it questionable whether a design basis can be derived for a nuclear power plant located in an active hydrothermal system. Thus, the occurrence of a hydrothermal system and the potential for such a system to develop should be considered an exclusion criterion for the site, although in some cases their effects can be accommodated by employing protective measures at the site. Active hydrothermal systems and groundwater perturbations due to volcanic events at capable volcanic sources can create conditions that result in lahars, ground subsidence and slope instability.

6.64. Factors that should be considered in evaluating the development and possible impacts of hydrothermal systems include:

(a) The lateral extent and nature of active hydrothermal systems associated with capable volcanoes;
(b) The patterns of groundwater circulation that may give rise to hydrothermal systems;
(c) The distribution of features, such as faults, that may influence the location and development of hydrothermal systems.

Deterministic assessment

6.65. A deterministic assessment should 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 the nature of hydrothermal systems at each capable volcano, the lateral extent of hydrothermal systems at analogous volcanoes, and the hydrogeology of the site and the surrounding area. The uncertainties in the various parameters should be properly taken into account.

Probabilistic assessment

6.66. A probabilistic assessment should consider numerical models for the development of hydrothermal systems in specific geological settings, given changes in volcanic activity at each capable volcano, and in conjunction with the opening of new vents. Such probabilistic models can be refined by data from analogous volcanoes. The output from the probabilistic model should be the likelihood of a hydrothermal system developing at the site, given a range of input parameters relating to the thermal state of the volcano and the properties controlling flow and transport in the hydrological system.

Factors to consider in site selection, site evaluation and development of the design basis

6.67. As indicated in Table 1, the effects of the development of volcanic hydrothermal systems should be considered, in principle, as one of the exclusion criteria for the site. However, in some cases, since their effects may be accommodated in the site and plant layout, or in design, operational or site protective measures, the appropriate design basis should be determined. Currently, it is difficult to determine the likelihood of steam explosions occurring at specific locations within most hydrothermal systems. Hazards associated with specific phenomena, such as the development of fumaroles or the opening of new vents during steam explosions, are less important to consider explicitly than the development and lateral extent of the hydrothermal system itself. The effects of groundwater anomalies on the potential for lahars, debris flows, ground subsidence and slope instability should be assessed as part of the analysis of these phenomena.

A COMPREHENSIVE MODEL OF VOLCANIC HAZARDS

6.68. A comprehensive and site specific volcanic hazard model should be developed to inform decisions about site suitability and the design basis for the nuclear power plant. In reaching these decisions, the potential for future volcanism and assessment of its potential effects should be considered from the perspective of the potential impact on the safety of the nuclear power plant, including plant availability for operation.

6.69. A comprehensive and site specific model of the volcanic hazards involves a large number of complex interacting phenomena. Development of such models will require assistance from volcanological experts, preferably through a formal process designed to consider all expert judgement in relation to volcanic hazards 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.

6.70. Volcanic events can give rise to multiple hazardous phenomena (e.g. tephra loading and seismic loading). A volcanic hazard may be the cause of other hazards in the region (e.g. a volcano generated earthquake can cause a landslide that may affect dams or local river courses). In combination, these hazards can exacerbate the risk to a nuclear power plant, even though the individual risk stemming from each hazard may be relatively minor. A comprehensive model of volcanic hazards should, therefore, take account of the combined effects of volcanic phenomena.

6.71. 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 with many external hazards, volcanic activity may persist for longer periods of time and may affect larger areas around the nuclear power plant. For example, debris flows may persist in a region for years following explosive volcanic eruptions. Although such debris flows may not damage a nuclear power plant directly, they may render normal operation of the power plant impossible owing to extensive or devastating impacts on the population and infrastructure of the surrounding region.

7. NUCLEAR INSTALLATIONS OTHER THAN NUCLEAR 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 in Ref. [8]: 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 performed in accordance with this grading.

7.3. Prior to categorizing an installation for the purpose of adopting a graded approach, a conservative screening process should be applied in which it is assumed that the entire radioactive inventory of the installation is released by an accident initiated by a volcanic event. Provided that the potential result of such a radioactive release were that no unacceptable consequences would be likely for workers or for the public (i.e. provided that doses to workers or to the public due to the release of that radioactive inventory would be below the authorized dose limits established by the regulatory body), or for the environment, and provided that no other specific requirements are 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 the conservative screening process show that the potential consequences of such releases would be 'significant', a volcanic hazard assessment and a safety evaluation of the nuclear installation should be carried out, in accordance with the steps indicated in paras 7.5–7.14.

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

(a) The amount, type and status of the radioactive inventory at the site (e.g. whether solid or fluid, processed or only stored);
(b) The intrinsic hazard associated with the physical processes (e.g. criticality) and the chemical processes that take place at the installation, if applicable;
(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 in fuel processing and storage facilities it may be distributed throughout the installation);
(f) The changing nature of the configuration and layout of installations designed for experimental work (such activities have an associated intrinsic unpredictability);
(g) The need for active safety systems and/or operator actions for the prevention of accidents and for mitigation of the consequences of accidents;
(h) The characteristics of engineered safety features for the prevention of accidents and for mitigation of the consequences of accidents (e.g. the containment and containment systems);

(i) The characteristics of the processes or the engineering features that might show a cliff edge effect[7] in the event of an accident;
(j) The characteristics of the site relevant to the consequences of the dispersion of radioactive material to the atmosphere and to the hydrosphere (e.g. size, demographics of the region);
(k) The potential for on-site and off-site contamination resulting from the volcanic event.

7.6. Volcanic hazards 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 below the surface. 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 emission of volcanic gases, ground deformation, generation of volcanic earthquakes and circulation of geothermal fluids, are of principal concern for the volcanic hazard assessment of subsurface installations. Analyses of volcanic hazards for subsurface installations may need to consider the transport and release of radioactive material to 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 used by the regulatory body, some or all of the factors mentioned should be considered. For example, fuel damage, radioactive release or dose 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 for the installation, which should be the primary source of information, if available;

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[7] A cliff edge effect in a nuclear installation is an instance of severely abnormal system behaviour caused by an abrupt transition from one system status to another following a small deviation in a system parameter, and thus a sudden large variation in system conditions in response to a small variation in an input.

(b) The results of a comprehensive volcanic hazard assessment (stages 1–4), if one has been performed;
(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 release 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 within the installation itself, to radiological consequences confined to 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 installation may be defined on the basis of national practice and criteria, as indicated in para. 7.10. 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 standards and codes for nuclear power plants should be applied.
(c) There is often at least one intermediate category of hazardous installation, 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 hazards may be estimated from national volcanic hazard maps or similar volcano-specific hazard assessments.
(b) For installations in the highest hazard category, methodologies for volcanic hazard assessment, as described in earlier sections of this Safety Guide, should be used (i.e. recommendations applicable to nuclear power plants).

(c) For installations categorized in the intermediate hazard category, the volcanic hazard assessment is typically performed using methods similar to those 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 installations in the intermediate hazards category, simplified methods may be appropriate in cases where the database and the methods recommended in this Safety Guide are found to be excessively complex, time consuming and demanding in terms of effort for the nuclear installation in question. Such analyses may be based on national or similar regional databases of volcanic eruptions (see Annex II), and simplifying assumptions may be used to assess the potential for specific volcanic phenomena to affect the site.

7.13. Unless otherwise required by national regulations, the evaluation of volcanic hazards for nuclear installations in the lowest hazard category should be based on existing volcanic hazard maps applicable for the site, including appropriate factors for the rates and nature of volcanism and the topography of the site region. In cases where no such volcanic hazard maps exist, then such hazard maps should be prepared and applied to the site, in accordance with national standards for volcanic hazard assessments.

7.14. Application of the recommendations relating to the monitoring of capable volcanoes in the geographical region of interest (see paras 3.9 and 4.36) should be commensurate with the category of the installation as defined in para. 7.11.

8. MONITORING AND PREPARATION FOR RESPONSE

8.1. As stated in para. 5.1 of Ref. [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, are required to be monitored over the lifetime of the nuclear installation. As capable volcanoes represent natural induced hazards, if a nuclear installation is constructed that has an associated capable volcano which may generate phenomena hazardous to the installation, as considered for design or site protective measures, that volcano should be monitored over the lifetime of the nuclear installation. Thus, if a volcano monitoring programme is not in place at the site suitability stage, such a programme should be developed prior to the start of construction of the installation and should be maintained and kept up to date throughout 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 responsible for the observation and monitoring of volcanoes. It may be the case that capable volcanoes are not currently monitored or that their monitoring is given comparatively low priority by national and international volcano observatories tasked with the volcano monitoring activities and the mitigation of volcanic hazards on a national scale. Therefore, all interested parties (e.g. operating organizations, regulatory bodies and other government organizations) should work with such 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, it may be necessary to establish such an observatory as part of the required monitoring programme.

8.3. Some of the data collection activities performed during the site characterization stage (Section 4) may involve assessment of the current state of activity of volcanoes that might be capable. As the personnel who performed these assessments may be from volcano observatories and the instrumentation necessary to monitor capable volcanoes may be in place at this stage, a monitoring programme should be developed that uses these personnel and this infrastructure to the greatest extent practicable. 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 take into account how results or alerts from the volcano monitoring programme will be used in emergency response. A detailed procedure should be prepared for the response 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 eruption, which allows for the development and use of graded levels of alert. Most volcano observatories around the world establish levels of alert on the basis of 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 proper response to information on alerts that is provided in periods of volcanic activity.

9. MANAGEMENT SYSTEM FOR VOLCANIC HAZARD ASSESSMENT

9.1. An adequate management system that includes a quality assurance programme [9, 10] should be established and implemented to cover all activities relating 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 the 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 past rates of volcanic activity), methods used for the volcanic hazard assessment (e.g. numerical models), and quantification and documentation. The peer review panel should have the multidisciplinary expertise necessary 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: (i) participatory peer review and (ii) late stage and follow-up 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. A late stage and follow-up peer review is carried out towards the end of the study. Conducting a participatory peer review will reduce the likelihood of rejection of the study at a later stage.

Appendix

DESCRIPTION OF TYPES OF VOLCANIC PHENOMENA

I.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 the volcanological terms used in the following paragraphs is provided in the list of definitions.

Tephra fallout

I.2. The fall and deposition of pyroclastic material such as ash, pumice and scoria occur after these particles are lifted by an explosive eruption to altitudes of several kilometres 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 the total mass released in an explosive volcanic eruption commonly exceeds 10^{11} kg (approximately 10^8 m^3 of tephra). On falling, pyroclasts normally reach a constant velocity (so-called terminal velocity), which is determined by the size, shape and density of the falling particles, 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. The 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 the 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 type volcanic eruptions also generate tephra fallout. Tephra fallout is common for all types of volcanic eruption, but the most voluminous fallout is normally associated with caldera-forming eruptions and composite volcanoes.

Pyroclastic flows, surges and blasts

I.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 the 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 10–100 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 and 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 a few millimetres to tens of metres. These flows carry projectiles that may inflict significant damage on some structures.

I.4. Pyroclastic surges and blasts are dilute gas–solid suspensions that flow over the ground surface at high velocities and are less influenced by topography than pyroclastic flows. Estimated densities of pyroclastic surges range from 1 kg/m^3 to 6 kg/m^3. There are three types of pyroclastic surge: (i) base surge, (ii) ash cloud surge and (iii) ground surge. A base surge is usually formed when the volcano initially starts to erupt from the base of the eruption column as it collapses. It usually does not travel further than 10 kilometres from its source. A ground surge usually forms at the base of a pyroclastic flow. An ash cloud surge forms when the eruption column is neither buoying material upward by convection nor collapsing. Such deposits can be formed before, after and during the formation of pyroclastic flows. Base surges typically contain water and/or steam and have temperatures at or below the boiling point of water.[8] Base surges can extend up to 10 km from the vent. Ground surges are generated by many of the same processes that form pyroclastic flows and often precede pyroclastic flows. Ground surges have many of the characteristics of pyroclastic flows but are more dilute and of lower volume and, in general, leave thinner deposits. Base surges originate from hydromagmatic explosions in which interaction occurs between shallow groundwater or surface water and magma. A volcanic blast is a laterally directed pressure wave 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 poisoning and asphyxiation. Pyroclastic flows, surges and blasts are capable of travelling over bodies of water for tens of kilometres. In some cases, the entry of dense pyroclastic flows into water may generate tsunamis.

[8] http://www.geo.mtu.edu/volcanoes/hazards/primer/images/volc-images/basesurge.jpg

I.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 volcano, including monogenetic tuff rings and scoria cones, may be the locus of such activity.

Lava flows and domes

I.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 temperature of lava can range from 1200°C to around 800°C or less. Lava 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.

I.7. Depending on its nature, a lava flow can create its own topography by vertical expansion, enabling the lava flow 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 explosions from trapped CO_2 and CH_4 gases. 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).

I.8. The extrusion of viscous lavas can last from 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 flow. This material is emplaced at the base and on the volcano where it can be remobilized (i.e. lahars) many years to decades after cessation of the eruption. Repeated, frequent magma intrusions, such as those that feed long lived lava flows, also promote the development of hydrothermal systems that can be active for years to decades, or even centuries. The dynamics of the hydrothermal system will govern, in part, the processes of magma ascent and the eruptive style and will contribute, in turn, to slope instability of altered parts of the edifice.

Debris avalanches, landslides and slope failures

I.9. 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 high velocity fluidized flows accelerated downslope by gravity (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 failure, 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, the entry of debris avalanches and landslides into water bodies may generate tsunamis.

I.10. As noted above, debris avalanches, landslides and slope failures are common on steep topography. Nevertheless, very large debris avalanches (100–1000 km^3) 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

I.11. Volcanic debris flows and lahars are mixtures of volcanic rock fragments ranging in diameter from 10^{-6} m to 10^{2} m, 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 can become 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 of up to 10^5 m^3/s for jökulhlaups. 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 cubic kilometres for jökulhlaups and debris flows and lahars transformed from debris avalanches). Debris flows may surmount topographic barriers, especially near the base of volcano edifices.

I.12. 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 the entry of these flows into existing bodies of water.

I.13. Debris flows and related phenomena are common on composite volcanoes, sometimes occurring many years after volcanic eruptions have ceased. Such flows are much less common on other types of volcano, except in unusual circumstances. For example, rivers have been known to become dammed at topographic restrictions, causing flooding, following pyroclastic eruptions from monogenetic volcanoes. Flooding of nearby lowlands is also common after explosive eruptions if material from the volcano reduces the channel capacity of rivers in these areas.

Opening of new vents

I.14. A new vent forms when magma ascends through the Earth's crust along a new pathway, leading to an eruption of lava at a new location. New volcanoes can form at locations tens of kilometres away from the 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 falls and voluminous lava flows. Occurrence of a non-volcanic phenomenon such as a so-called mud volcano may also be considered 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 in 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 fluidization of the rock formation. The gases, which may contain significant quantities of methane, may be flammable on contact with the air. Eruptions of mud volcanoes have persisted for years and have resulted in long and voluminous flows of mud. Soil fluidization and mudflows associated with mud volcanoes may constitute a potential hazard relevant to surface stability (see Ref. [6]). Mud volcano phenomena are not addressed specifically in this Safety Guide and the criteria set out in this Safety Guide for determining volcano capability and the related volcanic hazards should not be applied. Nevertheless, some of the methods used in current practice for evaluating the probability of opening of new volcanic vents and for characterizing mudflows on volcanoes may be applicable to mud volcano hazard assessment.

Volcano generated missiles

I.15. 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 further than expected, owing to the decrease in the influence of drag forces. When their size is sufficiently small, the friction of air decelerates them enough to affect their trajectory. Typically, volcano generated missiles larger than 1 m in diameter are not significantly affected by drag forces.

I.16. 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 and shield volcanoes, and of 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

I.17. 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 and 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 a volcano not undergoing eruption may be of the order a few tonnes per day to a few thousand tonnes per day and can be transported by the 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. As CO_2 is heavier than air, dense flows of CO_2 gas may follow drainage systems and collect in topographical depressions, displacing air and posing a danger of asphyxiation. The interaction of volcanic gases with water in the atmosphere also results in acid rain and possibly pollution of surface water.

I.18. 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 land 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

I.19. Volcanogenic tsunamis and seiches may be generated when voluminous (e.g. from 10^6 m^3 to in excess of 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.

I.20. As 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 phenomena may result in basin-wide tsunamis. In addition, even moderate eruptions at island volcanoes have generated tsunamis, although generally it is large, explosive eruptions that initiate these effects in extreme cases.

Atmospheric phenomena

I.21. 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 the topography. They are accompanied by ejection of bombs and blocks, as discussed in para. I.15, but the radius of the shock wave effects may be greater than that of the projected material.

I.22. Lightning often accompanies many types of volcanic eruption and may involve hundreds of ground strikes. In some cases, lightning and high static charges occur up to several kilometres from the erupting volcano.

I.23. 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 extending beyond the lava flows themselves.

I.24. Although such atmospheric phenomena may occur during any volcanic eruption, they are most commonly associated with large explosive eruptions.

Ground deformation

I.25. Some of the largest amplitude natural ground deformations ever observed have occurred on volcanoes. Prior to a volcanic eruption, ground deformation can involve rapid uplift of several metres or more. More generally, ground displacements of millimetres to centimetres may occur over broad areas in response to magma 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 in the surface. Ground deformation in calderas may result in significant vertical movements over large areas on different timescales. Large scale ground deformation is common to virtually all types of volcano.

Volcanic earthquakes and seismic events

I.26. Volcanic earthquakes and seismic events normally occur as a result of stress releases associated with the rise of magma towards the surface. There are two principal forms of volcano-seismic activity which could give rise to potentially hazardous ground motions at a site. 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 at the volcanic centre, whereas volcano-tectonic earthquakes can occur 10 km or more from the centre. Volcanic tremors are best characterized by their limited frequency content and long duration. They are due to resonance phenomena involving systems of large dimensions (i.e. hundreds of metres to a few kilometres) and hence involve frequencies of a few Hertz, and are associated with fluid motion.

I.27. Generally, 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 those of 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]).

I.28. Volcanic earthquakes accompany every type of volcanic eruption and are generated by all types of volcano.

Hydrothermal systems and groundwater anomalies

I.29. Extensive hydrothermal systems are sometimes 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 produce steam explosions that are capable of ejecting rock fragments over distances of several kilometres and of forming explosion craters hundreds of metres in diameter. The interaction of rising magma with groundwater may cause a phreatic or phreatomagmatic eruption. Volcanic activity or igneous intrusions, such as dykes, may change groundwater 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 can generate lahars that are attributed to the disturbance of the hydrothermal or groundwater system by volcanic intrusions. Magma intrusions can also 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 as a result of the development of hydrothermal systems. Changes in the hydrogeology of the site due to volcanic activity may also result in changes of the hydraulic pressure in soil-bearing layers and water aquifer layers. Development of hydrothermal systems and groundwater anomalies are most common at calderas and may be associated with all types of volcano.

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Annex I

VOLCANIC HAZARD SCENARIOS

I–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 the uncertainty associated with it, means that volcanic events are varied and complex and are 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

I–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 fallout. 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 and appropriate consideration needs to be given to a broad range of potentially hazardous explosive and effusive phenomena. The geological record at many composite volcanoes shows that abrupt changes in composition or eruptive character are common and that eruptive centres can suddenly emerge kilometres distant from the central (summit) vent.

I–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 gases, all of which may be detected by monitoring activities. Potentially precursory unrest can last as little 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.

I–4. An 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, followed later by the sudden emergence of explosive activity from the summit vent. In other examples, large explosions herald the onset of the eruption. Pyroclastic flows and tephra fallout can characterize days of sustained activity, followed by cessation of the eruption or a prolonged period of lava dome 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. to the order of cubic kilometres) edifice collapse. Although not all phenomena will necessarily occur during an eruption of a composite volcano, the potential for multiple phenomena to occur during a single eruption is extremely high for such a volcano.

I–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 summary, 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

I–6. An effusive eruption of fluid lava will generally begin with the formation of eruptive fractures associated with locally experienced 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 rapid 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 only be a short time in which to implement safety measures at a nearby nuclear installation in the event of an effusive eruption.

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

I–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 the formation of lava tubes through which lava can flow with little thermal loss and thus can reach areas relatively far from the vent. The sudden breakage of lava tubes or of secondary lava pools formed along the flow, or lateral lava flow fronts (i.e. levées), can generate additional rapidly moving flows with different characteristics and moving in different directions from the main flow.

I–9. Effusive volcanoes can have styles of eruptive behaviour that persist for long periods of time and then suddenly change to a different style (e.g. crater centred 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 from 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.

I–10. Thus, a nuclear installation located near a volcano experiencing such effusive activity would face hazardous phenomena in the event of incursion of the site by lava flows, opening of new vents, tephra fallout, gas emissions or connected seismic activity. Some of these phenomena are considered to be beyond the design basis of nuclear installations and therefore have to be avoided through the site selection and evaluation process. Therefore, it is critical to evaluate the capability of a volcanic system to produce 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

I–11. Not all volcanism occurs from the central vents of existing composite or shield volcanoes. In many circumstances, volcanism is distributed over the close volcanic region and renewed volcanic activity results in the formation of new vents. On large volcanoes, such as Mount Fuji, Japan, or Mount Etna, Italy, 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 around the volcano. In other areas, volcanism builds volcanic fields, sometimes consisting of hundreds of individual vents, distributed over hundreds or thousands of square kilometres, where each vent opened separately as an individual batch of magma ascended to the surface.

I–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 metre in width and perhaps kilometres in length, ascending through the Earth's crust at a rate of the order of 1 m/s. The first sign of this activity would likely be a series of low magnitude earthquakes in the area. Hundreds to thousands of earthquakes per day have been observed to be associated with magma ascent of this nature. If seismic network observations are sufficiently precise, these earthquake hypocentres might be observed to rise gradually 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 cools within the Earth, without forming a new vent.

I–13. 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 10 m 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 localizes into one or several new vents. Mass flow of magma from these vents increases rapidly with time, creating a fire fountain of incandescent rock rising hundreds of metres into the air and raining 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 1 km in diameter. In some circumstances, buoyant volcanic plumes develop that carry tephra to heights of several kilometres or even tens of kilometres above the new vent. Scoria cones grow quickly as a result of this type of volcanic activity, commonly achieving heights of more than 100 m 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. New vents may form at any time along the original fracture. Such eruptions have been observed to persist for less than one month, while 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.

I–14. 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 II

WORLDWIDE SOURCES OF INFORMATION

II–1. The 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 are necessary. Internationally, the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI, Ref. [II–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 assessment for nuclear installations include the World Organization of Volcano Observatories (WOVO, Ref. [II–2]), the Cities and Volcanoes Commission [II–1] and the Commission on Statistics in Volcanology [II–3]. The IAVCEI and these IAVCEI Commissions provide essential information concerning the state of the art in volcanic hazard assessment, access to specific information about volcanism by region and access to specific techniques necessary to assess volcanic hazards quantitatively. Several databases exist that may be of great utility in volcanic hazard assessment, especially in the initial assessment (stage 1).

II–2. The Smithsonian's Global Volcanism Program (GVP) is dedicated to gathering and verifying data on Holocene volcanic activity worldwide [II–4, II–5] (see Fig. II–1). While insufficient alone for performing initial assessments of nuclear installations, the GVP database is an excellent resource that can support these assessments. A database of historical volcanic unrest worldwide is also under construction by WOVO.

II–3. Many States have national databases for Holocene volcanism (e.g. Russian Federation [II–6], United States of America [II–7]). The Geological Survey of Japan maintains a detailed database on active [II–8] and Quaternary volcanoes [II–9] in 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.

II–4. An important source of information on updated criteria and methodologies for volcanic hazard assessment for nuclear power plants is available in Ref. [II–10].

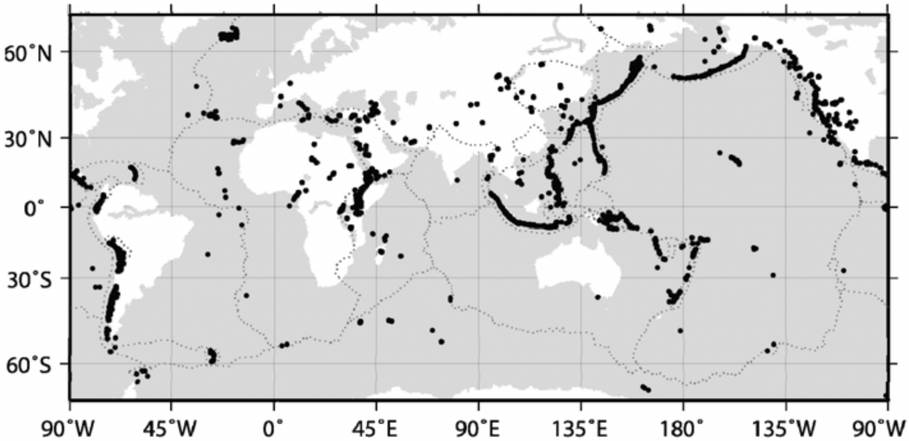

FIG. II–1. Map showing the global distribution of subareal and submarine volcanoes, active during the past 10 000 years, including major plate boundaries (dotted lines). Data courtesy of the GVP [II–5].

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DEFINITIONS OF VOLCANOLOGICAL TERMS

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

ash. A fragment of volcanic rock that is less than 2 mm 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). See also tephra, pyroclast.

basalt. A type of dark coloured volcanic rock that often forms lava flows and low lying volcanoes. Basalt composition has less than 52 wt% SiO_2, 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 magma, basaltic magma does erupt explosively, especially if interaction with groundwater or seawater occurs. Basalt is generally erupted at temperatures of 1100–1250°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 the data. The principle can be used in volcanology as a method to help constrain the results and uncertainty estimates of statistical and numerical modelling, taking advantage of as much data and other relevant information as are 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 an estimate of probability of occurrence 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) and which is capable of causing widespread devastation. See also pyroclastic surge.

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

block and ash flow. A type of pyroclastic flow that is generally concentrated in particles including blocks of dense lava (decimetres to metres 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) greater than 64 mm in mean diameter ejected during a volcanic explosion and which is sufficiently hot as to undergo ductile deformation during transport. See also 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 and (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 capable volcano or volcanic field is defined in this Safety Guide as one that has a credible likelihood of undergoing future activity and producing hazardous phenomena, including non-eruptive phenomena, during the lifetime of the nuclear installation and which may potentially affect the site. As discussed in Sections 3 and 5, hierarchical criteria for determining whether 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 geographical region, (ii) Holocene volcanic activity for any volcano within the geographical region and (iii) some evidence of potential for activity, such as recurrence rates of volcanism greater than 10^{-7} per year, and the potential to produce hazardous phenomena that may affect the site vicinity.

cinder cone. Also termed scoria cone, this is 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, which have fallen back after a moderate explosion. Often, they are surrounded by lava flows from the same vent. Cinder cones commonly grow rapidly and quickly attain their maximum size. They occur in groups, often on the flanks of large composite volcanoes and shield volcanoes. Examples of cinder cones include Paricutín, 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. Also termed stratovolcano, this is 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 the summit to form a caldera or the sliding of an entire flank of the volcano to form a large debris avalanche. Episodes of eruption followed by years or centuries (or even longer) of inactivity can recur at composite volcanoes over hundreds of thousands of years. Examples of composite volcanoes include Mount Vesuvius, Italy, and Mount St. Helens, United States of America.

conduit. The pathway along which magma reaches the surface at a volcano. Conduit geometries vary from tabular dykes to near cylindrical subvertical 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 style of volcanic eruption 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 contain 63–68 wt% SiO_2. Owing to their high SiO_2 content, dacitic magmas can have high viscosity and erupt explosively, generating such eruptive phenomena as pyroclastic flows. Generally, dacitic magmas erupt at temperatures of 800–1000°C.

debris avalanche. A large mass (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 high speeds (200 km/h). Debris avalanches often excavate a significant part of the hydrothermally altered portions of a volcanic edifice. Debris avalanches contain a mixture of small fragments of millimetre size to large blocks hundreds of metres in size that move as coherent entities, deforming with flow and eventually fragmenting into smaller particles. They can contain significant quantities of water or mix with inflowing water bodies to transform into more mobile mudflows. Edifice collapse can generate large explosive depressurization of the shallow depth magma–hydrothermal system. See also 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 flow path. They can form from water saturated landslide blocks, or when water from heavy rain, rapid snowmelt or 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 years after an eruption. Debris flows exhibit significant yield strength and usually contain more than 60% sediment by volume. See also hyperconcentrated flow and lahar.

degassing. 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 fragment the magma 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 as a result of an extrusion of lava. Domes are frequently, but not exclusively, composed of andesitic or rhyolitic magma. Domes usually form when the magma is very viscous or extrudes slowly, thereby accumulating 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, Montserrat, the 1991–1995 eruption of Mount Unzen, Japan, and the 1994 and 2006 eruptions of Mount Merapi, 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 geological structures. Dykes that 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. See also explosive eruption and extrusive flow.

elutriation. A process in which finer volcanic ash particles are separated from coarser ones 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 non-magmatic (phreatic) if they involve only recycled rock fragments. Eruptions can occur over widely varying timescales (seconds to years). See also phreatic eruption, phreatomagmatic eruption, plinian eruption, strombolian eruption, Hawaiian-style eruption, 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 forms during most explosive activity is referred to as an eruption column, or strong plume, and includes a momentum dominated region and a buoyancy dominated region. Eruption clouds may rapidly spread laterally under gravity, 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 gases 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. Pyroclastic flows, falls and volcano generated missiles are characteristic of explosive eruptions. See also phreatic eruption.

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 having sufficient force to propel fragments of magma hundreds of metres above the vent. Fire fountain eruptions often feed lava flows and are characteristic of Hawaiian-style 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 temperature to magmatic temperatures. A solfatara denotes a fumarole that emits sulphurous gases (SO_2, H_2S). A mofette denotes a fumarole that emits mainly CO_2 at temperatures below the boiling point of water.

geological record. Also termed the stratigraphic record, this is the sequence of rock layers in a vertical section of the Earth. The oldest layers occur at the base of the section, with successively younger layers occurring higher in the sequence. Geologists use the stratigraphic record to assign relative ages to deposits. Volcanic stratigraphy is often complex, with deposits characterized by having relatively limited lateral extent, exhibiting rapid facies changes and having undergone multiple episodes of erosion and refilling of valleys.

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

Holocene. The most recent epoch of the geological Quaternary period, defined as the interval from 10 000 years before present to the present.

Holocene volcano. A volcano or volcanic field that has erupted within the past 10 000 years (the Holocene). 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 investigation, the exact age of the most recent volcanic products may be difficult to determine. In such circumstances, additional evidence may be used to judge a volcano as Holocene, following the methods used by the Smithsonian Institution[1]. Such evidence includes: (i) volcanic products overlying latest Pleistocene glacial debris, (ii) youthful volcanic landforms in areas where erosion would be expected to be pronounced after many thousands of years, (iii) vegetation patterns that would have been far richer if the volcanic substrates were more than a few thousand (or hundred) years old and (iv) 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 to proceed with the hazard assessment.

hot spot. A location at the Earth's surface that has experienced volcanism as a result of a thermal or compositional perturbation or plume in the Earth's

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[1] See SIMKIN, T., SIEBERT, L., Volcanoes of the World, 2nd Ed., Geoscience Press (1994).

mantle. Many hot spots are located in intraplate tectonic settings, far from the tectonic plate boundaries that often host volcanism.

hyperconcentrated flow. A flowing mixture of sediment and water, with intermediate characteristics and sediment concentration with respect to muddy stream flow and debris flow. Hyperconcentrated flow has no appreciable yield strength and typically contains 20–60 vol% sediment.

igneous. Term used to describe characteristics pertaining to rocks that have formed from magma. Extruded igneous (volcanic) rocks are typically divided into four basic types according to their SiO_2 content: basalt, andesite, dacite and rhyolite.

ignimbrite. Also termed ash flow tuff, this is 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 flow.

lapilli. A type of pyroclast (i.e. fragment of volcanic rock) greater than 2 mm and less than 64 mm in mean diameter. Lapilli are sometimes formed in eruption columns by the accretion of ash sized particles, termed accretionary lapilli. See also tephra.

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

magma. A mixture of molten rock (800–1200°C) which can also contain suspended crystals, dissolved gases and sometimes gas bubbles. Magma forms by the melting of 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 magma (e.g. basalt) allows gas to separate more efficiently, limiting the explosivity of the eruption, while cooler, more viscous magma (e.g. andesite, dacite and rhyolite) is 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 over time.

mantle. A solid layer of the Earth, approximately 2300 km thick, that is located between the crust and the core. Basaltic magma forms from the partial melting of mantle rocks.

monogenetic volcano. A volcano resulting 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. See also volcanic field.

mudflow. A general term for a flow of water and earth material possessing a high degree of fluidity in its movement. See also 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 being erupted at the surface. Phreatic eruptions are usually steam explosions that occur when hot water is suddenly depressurized, but may occasionally be non-explosive expulsions 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. See also phreatomagmatic eruption, debris flow and lahar.

phreatomagmatic eruption. A type of explosive eruption that involves subsurface interaction of magma and water and 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. See also eruption and phreatic eruption.

plinian eruption. An explosive pyroclastic eruption characterized by a sustained eruption column that generally rises to altitiudes of 10–50 km. Plinian eruptions may produce thick tephra fallout over areas of 500–5000 km^2 and/or pyroclastic flows and surges that travel tens of kilometres from the volcano. The 1991 eruption of Mount Pinatubo, Philippines, is a recent plinian eruption.

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

polygenetic volcano. A volcano built up from multiple eruptions, some of which follow long periods of inactivity. As many polygenetic volcanoes can remain active for 10 000–1 000 000 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. A light coloured, extremely vesicular (typically 60–80% volume void fraction) pyroclastic rock that is formed in explosive eruptions and which floats on water. Pumice often forms from rhyolitic or dacitic magma and occasionally from andesitic magma. It resembles solidified foam as 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 solidifies quickly to glass, trapping the vesicles.

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

pyroclastic density current. A generic term for a mixture of volcanic gas, pyroclasts and rocks that flows 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 downslope. 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 are typically greater than 50 km/h and sometimes exceed 100 km/h.

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

repose interval. The time elapsing between successive volcanic eruptions at the same volcano. Ideally, the repose interval would be the time elapsing from the end of one volcanic eruption to the beginning of the next. However, eruption duration can rarely be determined. Therefore, the repose interval is the best estimate of the time elapsing 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 in excess of 68 wt% SiO_2, which gives it a high viscosity and traps gases in the magma. Thus, rhyolite eruptions are often explosive and form pyroclastic deposits, although lavas and domes can occur. Rhyolite is generally erupted at temperatures of 700–850°C. Obsidian is a volcanic glass of rhyolitic composition.

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. See also fire fountain.

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

sill. A sheet-like igneous intrusion, often horizontal or subhorizontal, that is concordant with pre-existing geological structures. See also dyke.

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 is often released in coalesced slugs rather than in a continuous jet. Strombolian eruptions are commonly discrete events, punctuated by intervals of relative quiescence lasting from a few seconds to several hours. Strombolian eruptions, usually basaltic to andesitic in composition, form weak eruption columns that rarely exceed 5 km in 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.

thermokarst. Process of creating a complex and variegated land surface by melting of permafrost ice and subsequent movement of soils.

vent. An opening in the Earth's crust where volcanic products (e.g. lava, solid rock, gas, liquid water) is erupted. Vents may be either circular structures (i.e. craters) 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 pressures and temperatures. The most common volatile in magma is water, followed by CO_2 and SO_2. 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 heat gases emanating from the Earth and their interaction with nearby crustal rocks or groundwater. Volcanic activity includes seismicity, fumarolic activity, high rates of heat flow, emission of ground gases, thermal springs, deformation, ground cracks, pressurization of aquifers and ash venting. The term includes volcanic unrest and volcanic eruption.

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, tremors, 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 used for forecasting the onset of an eruption and for assessing the potential for volcanic eruption. Increasing seismicity, continuous tremor, shift in hypocentres towards the surface with time and the occurrence of shallow long period (or low frequency) events imply a high possibility that the onset of eruption is very close. Tremors can also 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 (also termed volcano group). Any spatial cluster of volcanoes. Volcanic fields range in size from a few volcanoes to over 1000 volcanoes. Volcanic fields may consist of monogenetic volcanoes (e.g. the Cima volcanic field, USA), or both polygenetic and monogenetic volcanoes (e.g. the Kluchevskoy volcano group, Russian Federation).

volcanic hazard. A volcanic process or phenomenon that can have an adverse effect on people or infrastructure. In the more restricted context of risk assessment, it is the probability of occurrence, within a specific period of time in a given area, of a potentially damaging volcanic event of a given intensity value (e.g. thickness of tephra fallout).

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 baseline level of activity known for this volcano or for other similar volcanoes outside periods of eruptive activity. Volcanic unrest can be precursory and can culminate in an eruption, although 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 lava, solid rock and associated gases 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. The VEI varies from VEI 0 (non-explosive eruption, less than 10^4 m^3 tephra ejected) to VEI 8 (largest explosive volcanic eruption identified in the geological record, more than 10^{12} m^3 tephra ejected). A unit of increasing explosivity on the VEI scale generally 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 for a forthcoming eruption, forecast the onset of eruption, understand an ongoing eruption and evaluate the potential volcanic hazards arising from an eruption. Instruments such as seismometers, global positioning system 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 in monitoring temporal thermal, topographical and geological changes in volcanoes.

vulcanian eruption. A type of volcanic eruption characterized by discrete explosions, which produces 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. Andesitic and dacitic magmas are most often associated with vulcanian eruptions. Examples of recent vulcanian eruptions include Sakurajima volcano, Japan, Soufrière Hills volcano, Montserrat, and Colima volcano, Mexico.

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