

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



Documents

Document Sharing Hub

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**.

The **IAEA Nuclear Energy Series** comprises informational publications to encourage and assist research on, and the development and practical application of, nuclear energy for peaceful purposes. It includes reports and guides on the status of and advances in technology, and on experience, good practices and practical examples in the areas of nuclear power, the nuclear fuel cycle, radioactive waste management and decommissioning.

VOLCANIC HAZARDS IN SITE EVALUATION FOR NUCLEAR INSTALLATIONS



Documents
Document Sharing Hub

The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN	GHANA	NIGERIA
ALBANIA	GREECE	NORWAY
ALGERIA	GUATEMALA	OMAN
ANGOLA	HAITI	PAKISTAN
ARGENTINA	HOLY SEE	PALAU
ARMENIA	HONDURAS	PANAMA
AUSTRALIA	HUNGARY	PAPUA NEW GUINEA
AUSTRIA	ICELAND	PARAGUAY
AZERBAIJAN	INDIA	PERU
BAHRAIN	INDONESIA	PHILIPPINES
BANGLADESH	IRAN, ISLAMIC REPUBLIC OF	POLAND
BELARUS	IRAQ	PORTUGAL
BELGIUM	IRELAND	QATAR
BELIZE	ISRAEL	REPUBLIC OF MOLDOVA
BENIN	ITALY	ROMANIA
BOLIVIA	JAMAICA	RUSSIAN FEDERATION
BOSNIA AND HERZEGOVINA	JAPAN	RWANDA
BOTSWANA	JORDAN	SAUDI ARABIA
BRAZIL	KAZAKHSTAN	SENEGAL
BULGARIA	KENYA	SERBIA
BURKINA FASO	KOREA, REPUBLIC OF	SEYCHELLES
BURUNDI	KUWAIT	SIERRA LEONE
CAMBODIA	KYRGYZSTAN	SINGAPORE
CAMEROON	LAO PEOPLE'S DEMOCRATIC REPUBLIC	SLOVAKIA
CANADA	LATVIA	SLOVENIA
CENTRAL AFRICAN REPUBLIC	LEBANON	SOUTH AFRICA
CHAD	LESOTHO	SPAIN
CHILE	LIBERIA	SRI LANKA
CHINA	LIBYA	SUDAN
COLOMBIA	LIECHTENSTEIN	SWEDEN
CONGO	LITHUANIA	SWITZERLAND
COSTA RICA	LUXEMBOURG	SYRIAN ARAB REPUBLIC
CÔTE D'IVOIRE	MADAGASCAR	TAJIKISTAN
CROATIA	MALAWI	THAILAND
CUBA	MALAYSIA	THE FORMER YUGOSLAV REPUBLIC OF MACEDONIA
CYPRUS	MALI	TUNISIA
CZECH REPUBLIC	MALTA	TURKEY
DEMOCRATIC REPUBLIC OF THE CONGO	MARSHALL ISLANDS	UGANDA
DENMARK	MAURITANIA	UKRAINE
DOMINICA	MAURITIUS	UNITED ARAB EMIRATES
DOMINICAN REPUBLIC	MEXICO	UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
ECUADOR	MONACO	UNITED REPUBLIC OF TANZANIA
EGYPT	MONGOLIA	UNITED STATES OF AMERICA
EL SALVADOR	MONTENEGRO	URUGUAY
ERITREA	MOROCCO	UZBEKISTAN
ESTONIA	MOZAMBIQUE	VENEZUELA
ETHIOPIA	MYANMAR	VIETNAM
FINLAND	NAMIBIA	YEMEN
FRANCE	NEPAL	ZAMBIA
GABON	NETHERLANDS	ZIMBABWE
GEORGIA	NEW ZEALAND	
GERMANY	NICARAGUA	
	NIGER	

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

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2012

COPYRIGHT NOTICE

All IAEA scientific and technical publications are protected by the terms of the Universal Copyright Convention as adopted in 1952 (Berne) and as revised in 1972 (Paris). The copyright has since been extended by the World Intellectual Property Organization (Geneva) to include electronic and virtual intellectual property. Permission to use whole or parts of texts contained in IAEA publications in printed or electronic form must be obtained and is usually subject to royalty agreements. Proposals for non-commercial reproductions and translations are welcomed and considered on a case-by-case basis. Enquiries should be addressed to the IAEA Publishing Section at:

Marketing and Sales Unit, Publishing Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
fax: +43 1 2600 29302
tel.: +43 1 2600 22417
email: sales.publications@iaea.org
<http://www.iaea.org/books>

© IAEA, 2012

Printed by the IAEA in Austria
October 2012
STI/PUB/1552

IAEA Library Cataloguing in Publication Data

Volcanic hazards in site evaluation for nuclear installations : specific safety guide. — Vienna : International Atomic Energy Agency, 2012.
p. ; 24 cm. — (IAEA safety standards series, ISSN 1020-525X ; no. SSG-21)
STI/PUB/1552
ISBN 978-92-0-128110-4
Includes bibliographical references.

1. Nuclear facilities — Location. 2. Volcanic hazard analysis. 3. Nuclear facilities — Safety measures — Standards. I. International Atomic Energy Agency. II. Series.

IAEAL

12-00755

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.



Documents

Document Sharing Hub

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 measures¹ 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

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

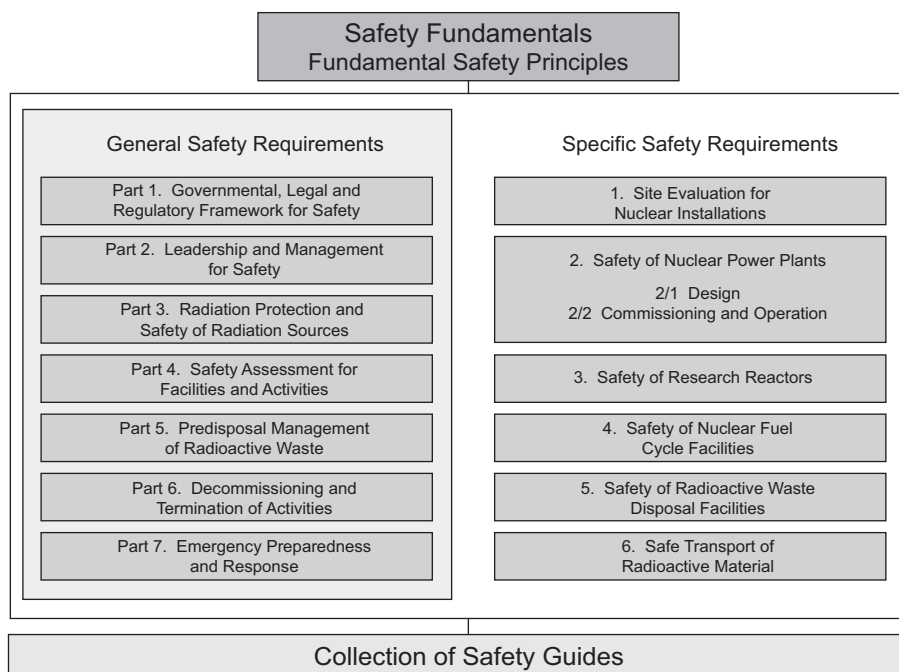


FIG. 1. The long term structure of the IAEA Safety Standards Series.

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

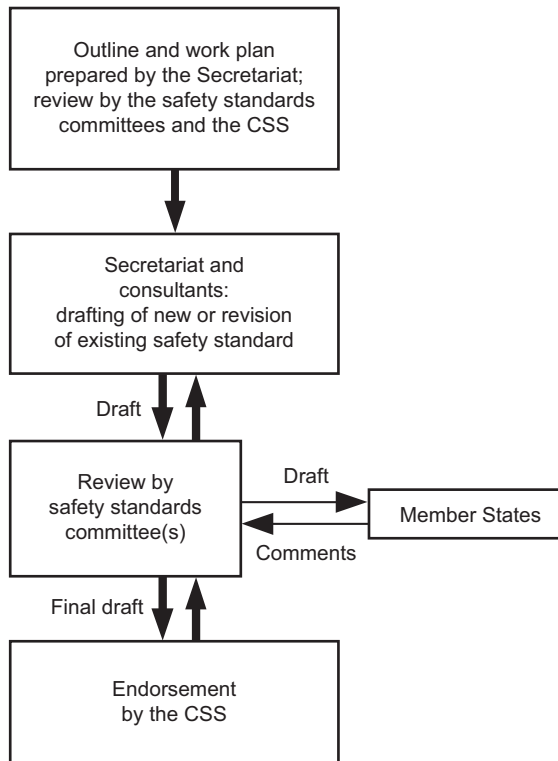


FIG. 2. The process for developing a new safety standard or revising an existing standard.

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	1
	Background (1.1–1.5)	1
	Objective (1.6–1.8)	2
	Scope (1.9–1.19)	3
	Structure (1.20)	6
2.	OVERVIEW OF VOLCANIC HAZARD ASSESSMENT	7
	Nature of volcanic phenomena and volcanic hazards (2.1–2.10)	7
	Geological record and data uncertainty (2.11–2.14)	12
	Alternative conceptual models of volcanism (2.15–2.18)	13
	Volcano capability (2.19)	14
	Deterministic and probabilistic approaches (2.20–2.22)	14
3.	GENERAL RECOMMENDATIONS	15
	Introduction (3.1–3.4)	15
	General procedure (3.5–3.10)	17
4.	NECESSARY INFORMATION AND INVESTIGATIONS (DATABASE)	20
	Overview (4.1–4.3)	20
	Information necessary for the initial assessment (Stage 1) (4.4–4.8)	21
	Information necessary for hazard screening and site specific hazard assessment (Stages 2–4) (4.9–4.37)	23
5.	SCREENING OF VOLCANIC HAZARDS (5.1)	31
	Stage 1: Initial assessment (5.2–5.4)	31
	Stage 2: Characterization of potential sources of future volcanic activity (5.5–5.15)	32
	Stage 3: Screening of volcanic hazards (5.16–5.23)	34

6.	SITE SPECIFIC VOLCANIC HAZARD ASSESSMENT (6.1–6.5) . . .	37
	Tephra fallout (6.6–6.10)	38
	Pyroclastic density currents: Pyroclastic flows, surges and blasts (6.11–6.17)	39
	Lava flows (6.18–6.22)	42
	Debris avalanches, landslides and slope failures (6.23–6.27)	43
	Volcanic debris flows, lahars and floods (6.28–6.32)	45
	Opening of new vents (6.33–6.37)	47
	Volcano generated missiles (6.38–6.41)	49
	Volcanic gases (6.42–6.46)	50
	Tsunamis and seiches (6.47–6.48)	52
	Atmospheric phenomena (6.49–6.52)	52
	Ground deformation (6.53–6.57)	53
	Volcanic earthquakes and related hazards (6.58–6.62)	55
	Hydrothermal systems and groundwater anomalies (6.63–6.67)	57
	A comprehensive model of volcanic hazards (6.68–6.71)	58
7.	NUCLEAR INSTALLATIONS OTHER THAN NUCLEAR POWER PLANTS (7.1–7.14)	59
8.	MONITORING AND PREPARATION FOR RESPONSE (8.1–8.4)	63
9.	MANAGEMENT SYSTEM FOR VOLCANIC HAZARD ASSESSMENT (9.1–9.4)	65
	APPENDIX: DESCRIPTION OF TYPES OF VOLCANIC PHENOMENA	67
	REFERENCES	77
	ANNEX I: VOLCANIC HAZARD SCENARIOS	79
	ANNEX II: WORLDWIDE SOURCES OF INFORMATION	84
	DEFINITIONS OF VOLCANOLOGICAL TERMS	87
	CONTRIBUTORS TO DRAFTING AND REVIEW	101
	BODIES FOR THE ENDORSEMENT OF IAEA SAFETY STANDARDS	103

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 associated¹. 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 Ma³, 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:

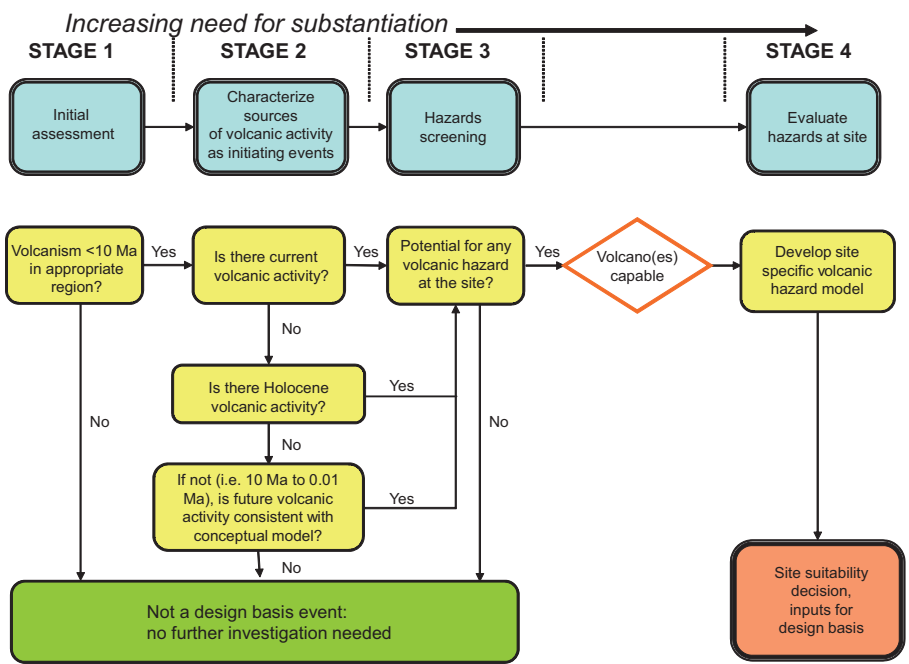


FIG. 1. Methodological approach to volcanic hazard assessment.

- (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 tsunamis. 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: