

IAEA Safety Standards

for protecting people and the environment

Deterministic Safety Analysis for Nuclear Power Plants

Specific Safety Guide

No. SSG-2



IAEA

International Atomic Energy Agency



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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

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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.

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DETERMINISTIC SAFETY ANALYSIS FOR NUCLEAR POWER PLANTS

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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".

This publication has been superseded by SSG-2 (Rev. 1).

IAEA SAFETY STANDARDS SERIES No. SSG-2

DETERMINISTIC SAFETY ANALYSIS FOR NUCLEAR POWER PLANTS

SPECIFIC SAFETY GUIDE

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2009

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FOREWORD

The IAEA's Statute authorizes the Agency to establish safety standards to protect health and minimize danger to life and property — standards which the IAEA must use in its own operations, and which a State can apply by means of its regulatory provisions for nuclear and radiation safety. A comprehensive body of safety standards under regular review, together with the IAEA's assistance in their application, has become a key element in a global safety regime.

In the mid-1990s, a major overhaul of the IAEA's safety standards programme was initiated, with a revised oversight committee structure and a systematic approach to updating the entire corpus of standards. The new standards that have resulted are of a high calibre and reflect best practices in Member States. With the assistance of the Commission on Safety Standards, the IAEA is working to promote the global acceptance and use of its safety standards.

Safety standards are only effective, however, if they are properly applied in practice. The IAEA's safety services — which range in scope from engineering safety, operational safety, and radiation, transport and waste safety to regulatory matters and safety culture in organizations — assist Member States in applying the standards and appraise their effectiveness. These safety services enable valuable insights to be shared and I continue to urge all Member States to make use of them.

Regulating nuclear and radiation safety is a national responsibility, and many Member States have decided to adopt the IAEA's safety standards for use in their national regulations. For the contracting 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 designers, manufacturers and operators around the world to enhance nuclear and radiation safety in power generation, medicine, industry, agriculture, research and education.

The IAEA takes seriously the enduring challenge for users and regulators everywhere: that of ensuring a high level of safety in the use of nuclear materials and radiation sources around the world. Their continuing utilization for the benefit of humankind must be managed in a safe manner, and the IAEA safety standards are designed to facilitate the achievement of that goal.

This publication has been superseded by SSG-2 (Rev. 1).

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. The safety requirements use 'shall' statements together with statements of

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

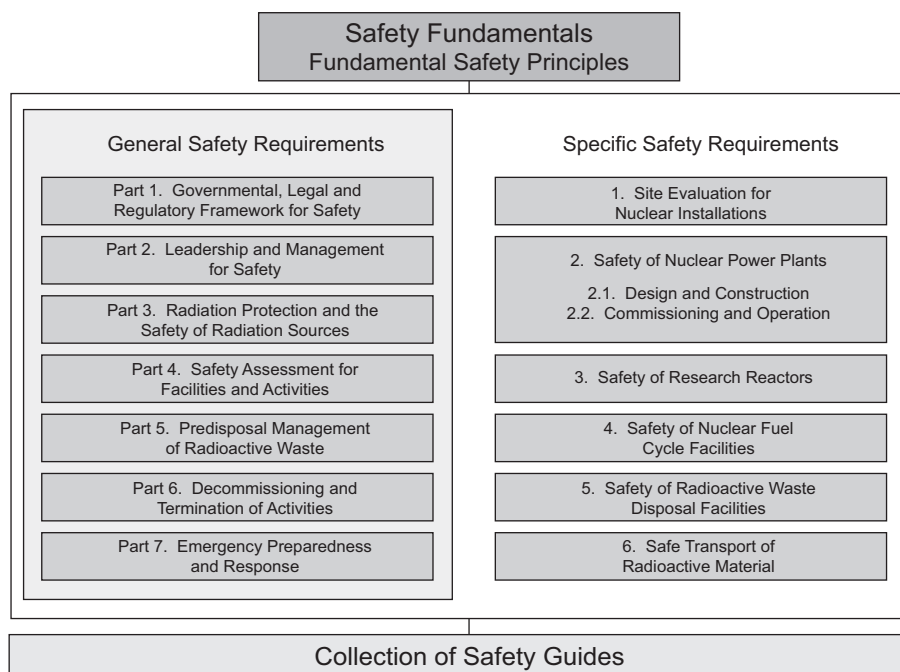


FIG. 1. The long term structure of the IAEA Safety Standards Series.

associated conditions to be met. 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 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).

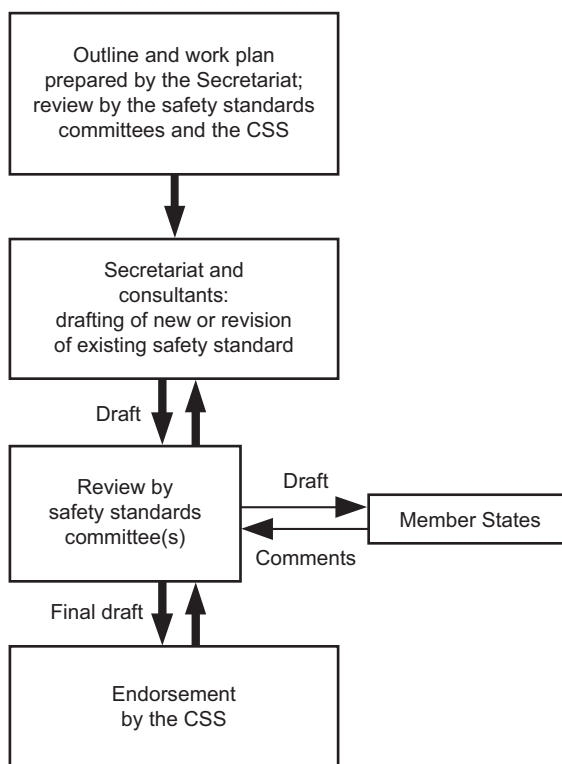


FIG. 2. The process for developing a new safety standard or revising an existing standard.

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 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.

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1. INTRODUCTION

BACKGROUND

1.1. This Safety Guide provides recommendations and guidance on the use of deterministic safety analysis and its application to nuclear power plants in compliance with the IAEA's Safety Requirements publications on Safety of Nuclear Power Plants: Design [1] and Safety Assessment for Facilities and Activities [2].

1.2. Current developments for ensuring the stable, safe and competitive operation of nuclear reactors are closely related to the advances that are being made in safety analysis. Deterministic safety analyses for anticipated operational occurrences, design basis accidents (DBAs) and beyond design basis accidents (BDBAs), as defined in Ref. [1] and in the IAEA Safety Glossary [3], are essential instruments for confirming the adequacy of safety provisions.

1.3. Initially, rigorous conservative approaches to anticipated operational occurrences and design basis accidents were used in deterministic safety analyses. Licensing calculations used conservative codes with conservative input data, mostly owing to the difficulty of modelling complicated physical phenomena with limited computer capacity and a lack of adequate data. As more experimental data have become available, and with advances in code development, for loss of coolant accidents (LOCAs) in particular, the practice in many States has moved towards a more realistic approach together with an evaluation of uncertainties. This is termed a best estimate approach.

1.4. There are three ways of analysing anticipated operational occurrences and design basis accidents to demonstrate that the safety requirements, which are currently used to support applications for licensing, are met:

- (1) Use of conservative computer codes with conservative initial and boundary conditions (conservative analysis).
- (2) Use of best estimate computer codes combined with conservative initial and boundary conditions (combined analysis).

- (3) Use of best estimate computer codes with conservative and/or realistic input data but coupled with an evaluation of the uncertainties in the calculation results, with account taken of both the uncertainties in the input data and the uncertainties associated with the models in the best estimate computer code (best estimate analysis). The result, which reflects conservative choice but has a quantified level of uncertainty, is used in the safety evaluation.

1.5. For beyond design basis accidents, best estimate calculations are used in several States, together with an evaluation of the uncertainties associated with the relevant phenomena. However, in determining what measures should be taken to mitigate the consequences of beyond design basis accidents, an uncertainty analysis is not usually performed.

1.6. The use of best estimate analysis together with an evaluation of the uncertainties is increasing for the following reasons:

- (a) The use of conservative assumptions may sometimes lead to the prediction of an incorrect progression of events or unrealistic timescales, or it may exclude some important physical phenomena. The sequences of events that constitute the accident scenario, which are important in assessing the safety of the plant, may thus be overlooked.
- (b) In addition, the use of a conservative approach often does not show the margins to the acceptance criteria that apply in reality, which could be taken into account to improve operational flexibility.
- (c) A best estimate approach provides more realistic information about the physical behaviour of the plant, assists in identifying the most relevant safety parameters and allows more realistic comparison with acceptance criteria.

1.7. For accident scenarios with large margins to the acceptance criteria, it is appropriate for simplicity, and therefore economy, to use a conservative analysis (with no evaluation of uncertainties). For scenarios in which the margin is smaller, a best estimate analysis is necessary to quantify the conservatism.

1.8. For anticipated operational occurrences, the use of a best estimate approach together with an evaluation of the uncertainties may avoid the selection of unnecessarily restrictive limits and set points, and may provide a more precise evaluation of actual margins relating to the limits and set points. In turn, this may provide additional operational flexibility and reduce unnecessary reactor scrams or actuations of the protection systems.

1.9. Changes that require the plant to be modified, such as power uprating and achieving a higher burnup, longer fuel cycles and life extension, necessitate comprehensive analysis to demonstrate compliance with acceptance criteria. Special care has to be taken when a combination of changes is planned.

1.10. This Safety Guide addresses both conservative and best estimate approaches to deterministic safety analysis, and provides recommendations and guidance on the use of deterministic safety analysis and its applications.

OBJECTIVE

1.11. The objective of this Safety Guide is to provide recommendations and guidance on deterministic safety analysis for designers, operators, regulators and technical support organizations. It also provides recommendations on the use of deterministic safety analysis in:

- (a) Demonstrating or assessing compliance with regulatory requirements;
- (b) Identifying possible enhancements of safety and reliability;
- (c) Obtaining increased operational flexibility within safety limits for nuclear power plants.

The recommendations are based on current good practices at nuclear power plants around the world and derive mainly from experience in performing transient analyses and accident analyses for nuclear power plants.

SCOPE

1.12. This Safety Guide applies to nuclear power plants. It addresses safety analyses that are required to be performed to demonstrate that barriers to the release of radioactive material will prevent an uncontrolled release to the environment for all plant states (Ref. [1], paras 5.71, 5.72). It therefore addresses the ways in which deterministic methods are used to verify that the defence in depth concept has been properly implemented. This includes demonstrating that the fission process is controlled within the design limit, that the reactor core can be cooled and that the heat generated can be removed to heat sinks of sufficient size.

1.13. The Safety Guide also addresses applications of deterministic safety analysis for the development and validation of emergency operating procedures and the determination of safety margins for modifications to nuclear power plants. Furthermore, it addresses the analysis of transients that have occurred in operating plants and analysis in support of accident management and planning for emergency preparedness and response.

1.14. The Safety Guide focuses on thermohydraulic, neutronic and source term analysis. Other types of analysis, such as structural mechanical analysis or analysis of electrical transients, are important aspects of demonstrating the safety of a plant; however, they are outside the scope of this Safety Guide. Information on other types of analysis can be found in specific engineering guides.

1.15. Safety analyses play an important role throughout the lifetime of a nuclear power plant. The stages of and occasions in a plant's lifetime in which the use of safety analyses is relevant include:

- (a) Design;
- (b) Commissioning;
- (c) Operation and shutdown;
- (d) Modification of design or operation;
- (e) Periodic safety review;
- (f) Life extension, in States where licences are issued for a limited duration.

STRUCTURE

1.16. Section 2 addresses the plant states and the classification of conditions that should be considered. Deterministic safety analysis and acceptance criteria are described in Section 3, and conservative deterministic safety analysis is explained in Section 4. Best estimate plus uncertainty analysis is discussed in Section 5. The quality of the analysis of computer codes and their verification and validation are described in Section 6. The relationship of deterministic safety analysis to engineering aspects of safety and to probabilistic safety analysis is presented in Section 7. The application of deterministic safety analysis is described in Section 8. Source term evaluation for operational states of and accident conditions for nuclear reactors is described in Section 9.

2. GROUPING OF INITIATING EVENTS AND ASSOCIATED TRANSIENTS RELATING TO PLANT STATES

2.1. Plant states for nuclear power plants are specified in Ref. [1], as shown in Table 1. The plant states are divided into operational states and accident conditions. Operational states include normal operation as well as anticipated operational occurrences. Accident conditions include conditions within design basis accidents and conditions beyond design basis accidents. Beyond design basis accident conditions include severe accident conditions, which are characterized as states with significant core degradation in which, for example, core components start to melt.

2.2. For the plant states listed in Table 1, as specified in Ref. [1], normal operation is defined as operation within specified operational limits and conditions. An anticipated operational occurrence is an operational process deviating from normal operation which is expected to occur at least once during the operating lifetime of a facility but which, in view of appropriate design provisions, does not cause any significant damage to items important to safety or lead to accident conditions (it may result in a reactor scram, however). Design basis accidents are accident conditions against which a facility is designed according to established design criteria, and for which the damage to the fuel and the release of radioactive material are kept within authorized limits (see Ref. [3]).

TABLE 1. PLANT STATES [1, 3]

Operational states		Accident conditions			
Normal operation	Anticipated operational occurrences	Within design basis accidents		Beyond design basis accidents	
		a	Design basis accidents	b	Severe accidents
		Accident management			

^a *Accident conditions* that are not *design basis accidents* as explicitly considered but which are encompassed by them.

^b *Beyond design basis accidents* without significant core degradation.

2.3. For all plant states, a comprehensive listing of postulated initiating events (PIEs) should be prepared for ensuring that the analysis of the behaviour of the plant is complete. An initiating event is an event that leads to anticipated operational occurrences or accident conditions. This includes operator errors and equipment failures (both within and external to the facility), human induced or natural events, and internal or external hazards that, directly or indirectly, challenge one or more of the systems required to maintain the safety of the plant.

2.4. Postulated initiating events and the consequential transients should be specified to ensure that all possible scenarios are being addressed. When performing deterministic safety analyses for anticipated operational occurrences, design basis accidents and beyond design basis accidents, all postulated initiating events and associated transients should be grouped into categories. There are different sets of criteria for grouping initiating events and transients into categories, and each set of criteria will result in a different event list. One approach is to group events according to the principal effects that could result in the degradation of safety systems.

2.5. Anticipated operational occurrences typically include loss of normal power, turbine trip, failure of control equipment and loss of power to the main coolant pump.

2.6. The categories of postulated initiating events for design basis accidents typically include the following transients:

- (a) Increase or decrease of the removal of heat from the reactor coolant system;
- (b) Increase or decrease of the flow rate for the reactor coolant system;
- (c) Anomalies in reactivity and power distribution;
- (d) Increase or decrease of the reactor coolant inventory;
- (e) Release of radioactive material from a subsystem or component.

2.7. Computational analysis of all possible design basis accident scenarios may not be practicable. A reasonable number of limiting cases, which are referred to as bounding or enveloping scenarios, should be selected from each category of events. These bounding or enveloping scenarios should be chosen so that they present the greatest possible challenge to the relevant acceptance criteria and are limiting for the performance parameters of safety related equipment. In addition to design basis accidents, anticipated transients without scram (ATWS) have traditionally been analysed for light water reactors. It is

becoming increasingly common for the analysis of other beyond design basis accidents to be required.

2.8. A different grouping of initiating events and transients is more useful when calculating potential releases of radioactive material to the environment. In particular, accidents in which major barriers such as the containment may be ineffective should be identified, and it should be ensured that analyses are performed for these transients. Examples of such cases include steam generator tube ruptures as postulated initiating events or consequential events, loss of coolant accidents in the auxiliary building and faults that occur when the containment is open during shutdown.

2.9. There are two alternative approaches to grouping postulated initiating events and their associated transients. Currently, the most common approach is to group initiating events and their associated transients according to the expected frequency of the initiating events, as indicated in Table 2. The second approach is to group according to the frequency of the accident scenarios. One way of quantifying the frequency of each accident scenario is to perform a probabilistic safety analysis. Probabilistic safety analysis identifies not only the sequences that lead to core degradation, but also the more frequent sequences that do not lead to plant damage or that lead to limited damage.

2.10. Beyond design basis accidents, including severe accidents, are typically treated separately in deterministic safety analyses, although some initiating events may be the same as for design basis accidents. The results help to determine the necessary measures to prevent severe accidents and to mitigate their radiological consequences if they do occur.

3. DETERMINISTIC SAFETY ANALYSIS AND ACCEPTANCE CRITERIA

DETERMINISTIC SAFETY ANALYSIS

3.1. Safety analyses are analytical evaluations of physical phenomena occurring at nuclear power plants, made for the purpose of demonstrating that safety requirements, such as the requirement for ensuring the integrity of barriers against the release of radioactive material and various other acceptance criteria,

TABLE 2. POSSIBLE SUBDIVISION OF POSTULATED INITIATING EVENTS

Occurrence (1/reactor year)	Characteristics	Plant state	Terminology	Acceptance criteria
10^{-2} –1 (expected over the lifetime of the plant)	Expected	Anticipated operational occurrences	Anticipated transients, transients, frequent faults, incidents of moderate frequency, upset conditions, abnormal conditions	No additional fuel damage
10^{-4} – 10^{-2} (chance greater than 1% over the lifetime of the plant)	Possible	Design basis accidents	Infrequent incidents, infrequent faults, limiting faults, emergency conditions	No radiological impact at all, or no radiological impact outside the exclusion area
10^{-6} – 10^{-4} (chance less than 1% over the lifetime of the plant)	Unlikely	Beyond design basis accidents	Faulted conditions	Radiological consequences outside the exclusion area within limits
$<10^{-6}$ (very unlikely to occur)	Remote	Severe accidents	Faulted conditions	Emergency response needed

are met for all postulated initiating events that could occur over a broad range of operational states, including different levels of availability of the safety systems. There are two basic types of safety analysis: deterministic safety analysis and probabilistic safety analysis.

3.2. Deterministic safety analyses for a nuclear power plant predict the response to postulated initiating events. A specific set of rules and acceptance criteria is applied. Typically, these should focus on neutronic, thermohydraulic, radiological, thermomechanical and structural aspects, which are often analysed with different computational tools. The computations are usually carried out for predetermined operating modes and operational states, and the events include anticipated transients, postulated accidents, selected beyond design basis accidents and severe accidents with core degradation. The results of computations are spatial and time dependences of various physical variables (e.g. neutron flux; thermal power of the