

IAEA Safety Standards

for protecting people and the environment

Criticality Safety in the Handling of Fissile Material

Specific Safety Guide

No. SSG-27



IAEA

International Atomic Energy Agency



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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 on 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: Vienna International Centre, 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 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.

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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.

CRITICALITY SAFETY IN THE HANDLING OF FISSILE MATERIAL



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

IAEA SAFETY STANDARDS SERIES No. SSG-27

CRITICALITY SAFETY IN THE HANDLING OF FISSILE MATERIAL

SPECIFIC SAFETY GUIDE

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2014

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FOREWORD

by Yukiya Amano
Director General

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

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

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

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

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

NOTE BY THE SECRETARIAT

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

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

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

THE IAEA SAFETY STANDARDS

BACKGROUND

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

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

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

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

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

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

THE IAEA SAFETY STANDARDS

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

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

Safety measures and security 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.

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

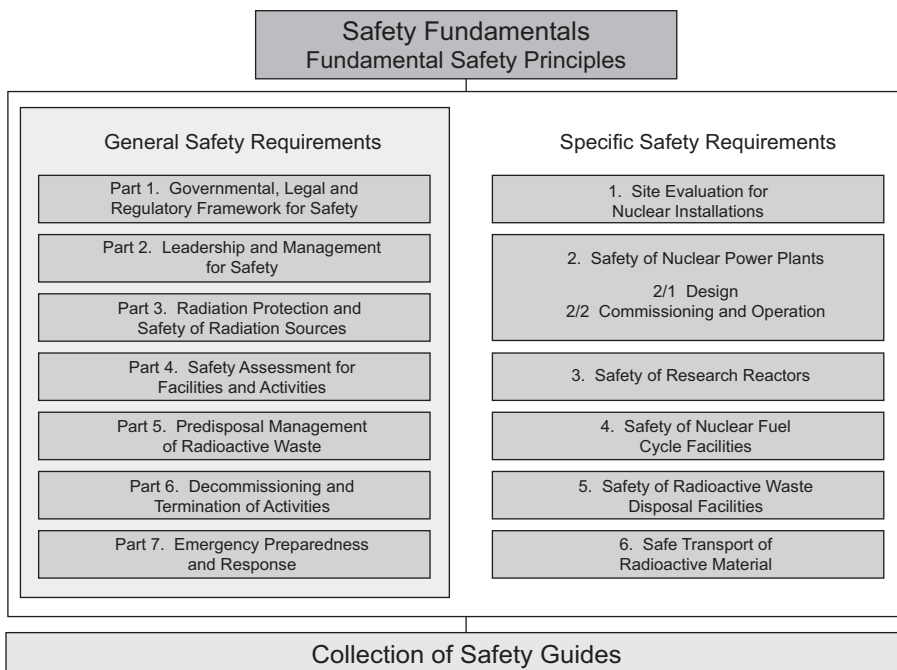


FIG. 1. The long term structure of the IAEA Safety Standards Series.

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).

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

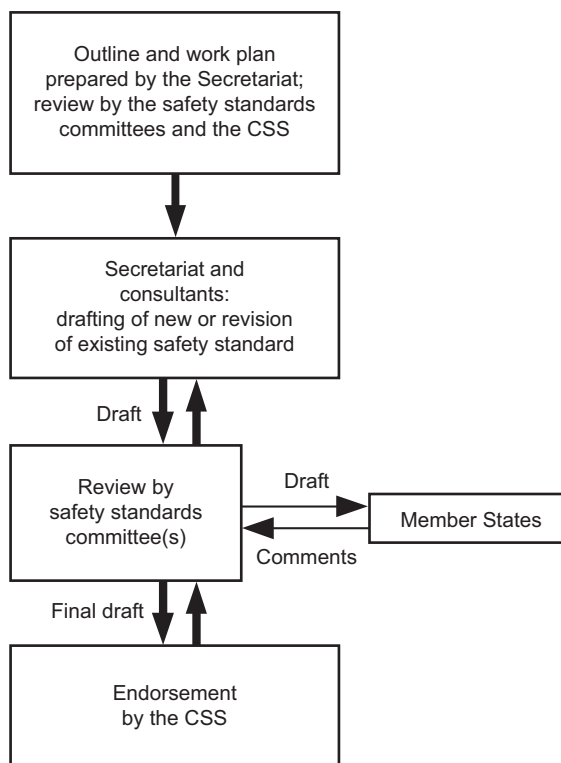


FIG. 2. The process for developing a new safety standard or revising an existing standard.

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. Nuclear criticality can theoretically be achieved under certain conditions by most fissionable nuclides belonging to the actinide elements. Some of these nuclides are also fissile¹, meaning that they can sustain a critical chain reaction in a thermalized ('slow') neutron energy flux. This Safety Guide thus addresses criticality safety for fissile material² and also covers mixtures of fissile and other fissionable nuclides.

1.2. Nuclear facilities and activities containing fissile material or in which fissile material is handled are required to be managed in such a way as to ensure criticality safety in normal operation, anticipated operational occurrences, and during and after design basis accidents (or the equivalent) [1]. This requirement applies to large commercial facilities, such as nuclear facilities that deal with the supply of fresh fuel, with the management of spent fuel and with radioactive waste containing fissile nuclides, including the handling, processing, use, storage and disposal of such waste. This requirement also applies to research and development facilities and activities that use fissile material, and to the transport of packages containing fissile material.

1.3. The subcriticality of a system depends on many parameters relating to the fissile material, including its mass, concentration, geometry, volume, enrichment and density. Subcriticality is also affected by the presence of other materials such as moderators, absorbers and reflectors. Subcriticality can be ensured through the control of an individual parameter or a combination of parameters, for example, by limiting mass or by limiting both mass and moderation. Such parameters can be controlled by engineered and/or administrative measures.

¹ Fissile nuclides are nuclides, in particular ²³³U, ²³⁵U, ²³⁹Pu and ²⁴¹Pu, that are able to support a self-sustaining nuclear chain reaction with neutrons of all energies, but predominantly with slow neutrons.

² Fissile material refers to a material containing any of the fissile nuclides in sufficient proportion to enable a self-sustained nuclear chain reaction with slow (thermal) neutrons.

OBJECTIVE

1.4. The objective of this Safety Guide is to provide guidance and recommendations on how to meet the relevant requirements for ensuring subcriticality when dealing with fissile material and for planning the response to criticality accidents. The guidance and recommendations are applicable to both regulatory bodies and operating organizations. This Safety Guide presents guidance and recommendations on how to meet the requirements relating to criticality safety established in the following IAEA Safety Requirements publications: Safety of Nuclear Fuel Cycle Facilities [1], Safety Assessment for Facilities and Activities [2], The Management System for Facilities and Activities [3], Predisposal Management of Radioactive Waste [4], Decommissioning of Facilities Using Radioactive Material [5], Regulations for the Safe Transport of Radioactive Material (the Transport Regulations) [6], Disposal of Radioactive Waste [7] and Preparedness and Response for a Nuclear or Radiological Emergency [8]. Terms used in nuclear safety are defined in the IAEA Safety Glossary [9].

SCOPE

1.5. The objectives of criticality safety are to prevent a self-sustained nuclear chain reaction and to minimize the consequences of this if it were to occur. This Safety Guide makes recommendations on how to ensure subcriticality in systems involving fissile material during normal operation, anticipated operational occurrences, and, in the case of accident conditions, in design basis accidents, from initial design, through commissioning, through operation, and through decommissioning and disposal. It covers all types of facilities and activities that have or use fissile material, except those that are designed to be intentionally critical, for example a reactor core in a nuclear reactor, or a critical assembly. In cases where criticality safety is specifically addressed by regulations, for example, transport which is performed in accordance with the Transport Regulations [6], this Safety Guide supplements but does not replace the specific transport guidance provided in the Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material [10]. This Safety Guide does not cover activities at defence related facilities. The recommendations of this Safety Guide may be applied to operations that are intended to remain subcritical in nuclear power plants, for example, the storage and handling of fresh fuel and spent fuel. The recommendations of this Safety Guide encompass: approaches to and criteria for ensuring subcriticality; conducting criticality safety assessments,

including the use of data; specifying safety measures to ensure subcriticality; and the planned response to criticality accidents.

STRUCTURE

1.6. Section 2 provides an introduction to the processes that affect criticality safety and provides guidance for criticality specialists. It also provides an introduction to the management system that should be in place, safety criteria and safety margins, and criteria for determining exemptions to certain criticality safety measures. Section 3 provides guidance on the safety measures necessary for ensuring subcriticality, especially the importance of implementing adequate safety measures, the factors affecting these safety measures, and the roles and responsibilities of those involved in implementing the safety measures. Section 4 provides guidance on conducting criticality safety assessments, the role of deterministic and probabilistic approaches, and the process by which the criticality safety assessment should be carried out. Section 5 provides recommendations on criticality safety practices in the various areas of conversion and enrichment, fuel fabrication, spent fuel operations prior to reprocessing or disposal, reprocessing, waste management (i.e. processing, storage and disposal) and decommissioning, transport of fissile material, and research and development laboratories. Section 6 provides guidance on planning the response to a criticality accident and the basic responsibilities of those involved. In addition, it provides guidance on criticality detection and alarm systems. The Annex provides a bibliography of sources of useful background information on criticality safety, covering methodology for criticality safety assessment, handbooks, computational methods, training and education, and operational experience.

2. APPROACH TO ENSURING CRITICALITY SAFETY

GENERAL

2.1. Safety measures, both engineered measures and administrative measures (i.e. based on actions of operating personnel), should be identified, implemented, maintained and periodically reviewed to ensure that all activities are conducted within specified operational limits and conditions that ensure subcriticality (i.e. within a defined safety limit, see para. 2.5).

2.2. Criticality safety is generally achieved through the control of a limited set of macroscopic parameters such as mass, concentration, moderation, geometry, isotopic composition, enrichment, density, reflection, interaction and neutron absorption. A description of the neutron multiplication of a system on the basis of values of these parameters alone is incomplete, and a full description would require the use of microscopic parameters such as neutron fission cross-sections, capture cross-sections and scattering cross-sections for the system. For this reason, and because of the large number of variables upon which neutron multiplication depends, there are many examples of apparently ‘anomalous’ behaviour in fissile systems in which the effective neutron multiplication factor³ (k_{eff}) changes in ways that seem counterintuitive.

2.3. An awareness of the anomalies known to date will contribute to ensuring criticality safety. A detailed description of many of the most important anomalies that have been observed in criticality safety is provided in Ref. [11].

SAFETY CRITERIA AND SAFETY MARGINS

2.4. Safety limits should be derived on the basis of one of two types of criteria:

- Safety criteria based on the value of k_{eff} for the system under analysis;
- Safety criteria based on the critical value⁴ of one or more control parameters, such as mass, volume, concentration, geometry, moderation, reflection, interaction, isotopic composition and density, and with account taken of neutron production, leakage, scattering and absorption.

2.5. Safety margins should be applied to determine the safety limits. Subcriticality implies a value of k_{eff} of less than unity and/or a control parameter value ‘below’ its critical value. In this context, ‘below’ is used in the sense that the control parameter remains on the safe side of the critical value.

2.6. In applying safety margins to k_{eff} (relative to 1) and/or to a control parameter (relative to the critical value), consideration should be given to uncertainty in

³ The effective neutron multiplication factor is the ratio of the total number of neutrons produced by a fission chain reaction to the total number of neutrons lost by absorption and leakage. The system is: (a) critical if $k_{\text{eff}} = 1$; (b) subcritical if $k_{\text{eff}} < 1$; and (c) supercritical if $k_{\text{eff}} > 1$.

⁴ The critical value is that value of a control parameter that would result in the system no longer being reliably known to be subcritical.

the calculation of k_{eff} (in the first case) or the critical value (in the second case), including the possibility of any code bias, and to sensitivity with respect to changes in a control parameter. The relationship between k_{eff} and other parameters may be significantly non-linear.

2.7. In determining operational limits and conditions for the facility or activity, sufficient and appropriate safety measures should be put in place to detect and intercept deviations from normal operation before any safety limit is exceeded. Uncertainties in measurement, instruments and sensor delay should also be considered. Alternatively, design features should be put in place to effectively prevent criticality being achieved. This should also be demonstrated in the criticality safety assessment. Operational limits and conditions are often expressed in terms of process parameters, for example, fissile mass and moderator content, concentration, acidity, liquid flow rates and temperature.

EXEMPTIONS

2.8. In some facilities or activities, the amount of fissile material may be so low or the isotopic composition may be such that a full criticality safety assessment would not be justified. Exemption criteria should be developed, reviewed by management and agreed with the regulatory body, as appropriate. A useful starting point is the exemption criteria applied to fissile classification of transport packages (Ref. [6], para. 4.17).

2.9. The primary approach in seeking exemption should be to demonstrate that the inherent features of the fissile material itself are sufficient to ensure subcriticality, while the secondary approach should be to demonstrate that the maximum amounts of fissile nuclides involved are so far below critical values that no specific safety measures are necessary to ensure subcriticality in normal operation, anticipated operational occurrences or design basis accidents (or the equivalent).

2.10. Modifications to the facility and/or activities should be evaluated before being implemented, to determine whether the bases for the exemption are still met.

MANAGEMENT SYSTEM

2.11. Human error and related failures of supervisory or management oversight have been a feature in nearly all criticality accidents that have occurred to date.

Consequently, human factors and the interaction of individuals with technology and with organizations should be considered. Design, safety assessment and the implementation of criticality safety measures should be carried out within a clearly established and well controlled management system. The IAEA requirements and recommendations for the management system are established in Ref. [3] and provided in Refs [12–16], respectively.

2.12. In the context of criticality safety, the following items should be taken into account for the implementation of a management system:

- Management should establish a comprehensive criticality safety programme to ensure that safety measures for ensuring subcriticality are specified, implemented, monitored, audited, documented and periodically reviewed throughout the entire lifetime of the facility or activity.
- Management should ensure that a plan for corrective action is established, as required, is implemented and is updated when necessary.
- To facilitate implementation of operating procedures used to ensure subcriticality, management should ensure that operating personnel involved in the handling of fissile material are involved in the development of the operating procedures.
- Management should clearly specify which personnel have responsibilities for ensuring criticality safety.
- Management should ensure that suitably qualified and experienced staff for criticality safety are provided.
- Management should ensure that any modifications to existing facilities or activities or the introduction of new activities undergo review and assessment and approval at the appropriate level before they are implemented, and should also ensure that operating personnel, including supervisors, are retrained, as appropriate, prior to the implementation of the modifications.
- Management should ensure that operating personnel receive training and refresher training at suitable intervals, appropriate to their level of responsibility. In particular, operating personnel involved in activities with fissile material should understand the nature of the hazard posed by fissile material and how the risks are controlled with the established safety measures and operational limits and conditions.

- Management should arrange for internal and independent inspection⁵ of the criticality safety measures, including the examination of arrangements for emergency response, for example, emergency evacuation routes and signage. Independent inspections should be carried out by personnel who are independent of the operating personnel, but not necessarily independent of the operating organization. The data from inspections should be documented and submitted for management review and for action, if necessary.
- Management should ensure that criticality safety assessments and analyses are conducted, documented and periodically reviewed.
- Management should ensure that adequate resources will be available to the consequences mitigate of an accident.
- Management should ensure that an effective safety culture is established in the organization [1].
- Management should ensure that regulatory requirements are complied with.

2.13. The nature of the criticality hazard is such that deviations towards insufficient subcritical margins may not be immediately obvious; that is, there may be no obvious indication that the effective neutron multiplication factor is increasing. If unexpected operational deviations occur, operating personnel should immediately place the system into a known safe condition. Operating personnel handling fissile material should therefore inform their supervisor in the event of any unexpected operational deviations.

2.14. Inspection of existing facilities and activities as well as proper control of modifications to facilities and activities are particularly important for ensuring subcriticality; they should be carried out regularly and the results should be reviewed by management and corrective actions taken if necessary. There is also a danger that conditions may change slowly over time in response to factors such as ageing of the facility or owing to increased production pressures.

2.15. Most criticality accidents in the past have had multiple causes; often, initiating events could have been identified by operating personnel and supervisors and unsafe conditions corrected before the criticality accident occurred. This highlights the importance of sharing operating experience, of training operating personnel and of independent inspections. These activities should be part of the management system.

⁵ These inspections are in addition to the inspections performed by the regulatory body.

2.16. Deviation from operational procedures and unforeseen changes in operations or in operating conditions should be reported and promptly investigated by management. The investigation should be carried out to analyse the causes of the deviation, to identify lessons to be learned, and to determine and implement corrective actions to prevent recurrences. The investigation should include an analysis of the operation of the facility and of human factors, and a review of the criticality safety assessment and analyses that were previously performed, including the safety measures that were originally established.

2.17. Useful information on the causes and consequences of previous criticality accidents and the lessons learned is provided in Ref. [17].

2.18. The management system should include a means of incorporating lessons learned from operating experience and accidents at facilities in the State and in other States, to ensure continuous improvement in operational practices and assessment methodology. Guidance on and recommendations for establishing a system for the feedback of operating experience are provided in Ref. [18].

3. MEASURES FOR ENSURING CRITICALITY SAFETY

GENERAL

3.1. The measures that should be taken for ensuring subcriticality of systems in which fissile material is handled, processed, used or stored are required to be based on the concept of defence in depth [1]. Two vital parts of this concept are passive safety features and fault tolerance⁶. For criticality safety, the double contingency principle is required to be the preferred means of ensuring fault tolerance [1].

Defence in depth

3.2. The facility or activity should be designed and operated or conducted so that defence in depth against anticipated operational occurrences or accidents is achieved by the provision of different levels of protection with the objective

⁶ To ensure safety, the design should be such that a failure occurring anywhere within the safety systems provided to carry out each safety function will not cause the system to achieve criticality.

of preventing failures, or, if prevention fails, ensuring detection and mitigating the consequences. The primary objective should be to adopt safety measures that prevent a criticality accident. However, in line with the principle of defence in depth, measures should also be put in place to mitigate the consequences of such an accident.

3.3. The concept of defence in depth is normally applied in five levels (see Table 1). In the general usage of defence in depth, as described in Ref. [1], application of the fourth level of defence in depth, which deals with ensuring the confinement function to limit radioactive releases, may not be fully applicable in the context of criticality safety. However, for mitigation of the radiological consequences of a criticality accident, the fifth level of defence in depth has to be applied, with consideration given to the requirements for emergency preparedness and response [8].

3.4. Application of the concept of defence in depth ensures that, if a failure occurs, it will be detected and compensated for, or corrected by appropriate measures. The objective for each level of protection is described in Ref. [1], on which the following overview of defence in depth is based.

Passive safety

3.5. The passive safety of the facility or activity should be such that the system will remain subcritical without the need for active engineered safety measures or administrative safety measures (other than verification that the properties of the fissile material are covered by the design). For example, the facility or activity might be designed using the assumption that fissile material is always restricted to equipment with a favourable geometry⁷. Special care is then necessary to avoid unintentional transfer to an unfavourable geometry.

Fault tolerance

3.6. The design should take account of fault tolerance in order to replace or complement passive safety (if any). The double contingency principle is required to be the preferred means of ensuring fault tolerance [1]. By virtue of this principle, a criticality accident cannot occur unless at least two unlikely, independent and concurrent changes in process conditions have occurred.

⁷ A system with a favourable geometry is one whose dimensions and shape are such that a criticality event cannot occur even with all other parameters at their worst credible conditions.

TABLE 1. OVERVIEW OF LEVELS OF DEFENCE IN DEPTH

Level	Objective	Means
Level 1	Prevention of deviations from normal operation and prevention of system failures	Conservative design, construction, maintenance and operation in accordance with appropriate safety margins, engineering practices and quality levels
Level 2	Detection and interception of deviations from normal operation in order to prevent anticipated operational occurrences from escalating to accident conditions	Control, indication and alarm systems and operating procedures to maintain the facility within operational states
Level 3	Control of the events within the design basis (or the equivalent) to prevent a criticality accident	Safety measures, and multiple and as far as practicable independent barriers and procedures for the control of events
Level 4	Mitigation of the consequences of accidents in which the design basis (or the equivalent) of the system may be exceeded and ensuring that the radiological consequences of a criticality accident are kept as low as practicable	Provision of criticality detection and alarm systems and procedures for safe evacuation and accident management Measures designed to terminate the criticality accident, e.g. injection of neutron absorbers Use of shielding and calculated dose contours to minimize exposure
Level 5	Mitigation of radiological consequences of release of radioactive material	Provision of an emergency control centre and plans for on-site and off-site emergency response

3.7. According to the double contingency principle, if a criticality accident could occur owing to the concurrent occurrence of two changes in process conditions, it should be shown that:

- The two changes are independent (i.e. not caused by a common mode failure);
- The probability of occurrence of each change is sufficiently low.

3.8. The system’s characteristics should meet the recommendations of para. 2.7 so that each event can be detected (e.g. monitored) by suitable and reliable means within a time frame that allows the necessary countermeasures to be taken.

3.9. The system design should follow the fail-safe principle and the safety measures should fulfil the single failure criterion, i.e. no single failure or event, such as a component failure, a function control failure or a human error (e.g. an instruction not followed), can result in a criticality accident.

3.10. Where failures or maloperations of the system or perturbations or malfunctions in the system could lead to an unsafe condition, the characteristics of the system should be such that key parameters deviate from their normal operating values at a rate such that detection, intervention and recovery can be carried out properly in order to prevent a criticality accident. Where this is not possible, it should be ensured that sufficient and appropriate additional safety measures are provided to prevent the initiating event from developing into a criticality accident.

SAFETY FUNCTIONS AND MEASURES

3.11. The safety functions needed for ensuring subcriticality should be determined and the safety measures for implementing them should be defined. The definition and substantiation of the safety functions should be based on an analysis of all initiating or aggravating events relevant to criticality safety arising from credible abnormal conditions, including human error, internal and external hazards, and loss or failure of structures, systems and components important to safety in operational states and in design basis accidents (or the equivalent).

3.12. In accordance with the lessons learned from criticality accidents, the preventive safety measures put in place should observe the following hierarchy:

- Passive engineered safety measures that do not rely on control systems, active engineered safety measures or human intervention.
- Automatically initiated active engineered safety measures (e.g. an automatically initiated shutdown or process control system).
- Administrative safety measures:
 - Active engineered safety measures initiated manually by operating personnel (e.g. operating personnel initiate an automatic shutdown system in response to an indicator or alarm);
 - Safety measures provided by operating personnel (e.g. operating personnel close a shutdown valve in response to an indicator or alarm, or bring the system into normal operational limits by adjusting controls).

3.13. In addition to the hierarchy of preventive safety measures and consistent with the concept of defence in depth, mitigatory safety measures (e.g. shielding, criticality incident detection systems and emergency response) should be employed to the extent practicable.

3.14. Safety should be ensured by means of design features and characteristics of the system that are as near as possible to the top of the list provided in

para. 3.12, but this should not be interpreted to mean that the application of any safety measure towards the top of the list precludes the provision of other safety measures where they can contribute to defence in depth.

3.15. The hierarchy of safety measures gives preference to passive safety. If subcriticality cannot be ensured through this means, further safety measures should be employed.

3.16. The safety measures put in place should be related to the control of a number of parameters and their combinations. Examples of the control parameters are given in para. 3.17.

Control parameters

3.17. The subcriticality of the system can be demonstrated by calculating k_{eff} and/or controlled by limiting one or more parameters. The control parameters that may be considered for ensuring subcriticality include (but are not limited to) the following:

- Restriction on the dimensions or shape of the system to a favourable geometry.
- Limitation on the mass of fissile material within a system to a ‘safe mass’. For example, in order to apply the double contingency principle, the safe mass may be specified to be less than half the minimum critical mass (incorporating a suitable safety factor) so that inadvertent ‘double batching’ of fissile material does not lead to criticality. Consideration may also need to be given to the potential for multiple over-batching of fissile material.
- Limitation on the concentration of fissile nuclides, for example within an homogeneous hydrogenated mixture or within a solid.
- Limitation on the amount of moderating material associated with the fissile material.
- Limitation on the isotopic composition of the elements in the fissile material present in the system.
- Limitation on the density of the fissile material.
- Limitation on the amount and form of reflecting material surrounding the fissile material.
- Ensuring the presence and integrity of neutron absorbers in the system or between separate systems that are criticality safe.
- Limitation on the minimum separation distance between separate systems that are criticality safe.

3.18. The parameter limitations set out in para. 3.17 can be evaluated either by multiplying the critical parameter value determined for the system's particular conditions by a safety factor, or by calculating the parameter value that meets the criterion that k_{eff} is less than unity. In deriving safety margins, consideration should be given to the degree of uncertainty in a system's conditions, the probability and rate of change in those conditions, and the consequences of a criticality accident.

Factors affecting reactivity

3.19. Limitation on the isotopic composition of the elements in the fissile material, or restriction to a certain type and chemical compound of the fissile material, or a combination of both, is essential for ensuring criticality safety in many cases. Effective safety measures should be applied to ensure that:

- The limits on the isotopic composition of the elements in the fissile material are complied with;
- The compound to be used cannot change to become a more reactive compound;
- A mixture of different types or different compounds resulting in a higher effective neutron multiplication factor cannot occur.

3.20. As the last two events listed above could, in specific situations, occur — for example, the precipitation of a U/Pu nitrate solution — they should be taken into account in the criticality safety assessment and proven to be subcritical.

3.21. The presence of neutron moderating materials should be considered, as these can significantly reduce the critical mass of the fissile material. Hydrogen and carbon contained in materials such as water, oil and graphite are common moderators. Low atomic mass, low neutron absorption materials (such as deuterium, beryllium and beryllium oxide) are less common but can be very effective moderators. Consideration should be given to replacement of a moderator with an alternative substance having lower or no moderating properties; in the case of oils, for example, there is the possibility that long chain CH_2 type oils (i.e. aliphatic hydrocarbons) could be replaced with oils containing (for instance) fluorine or chlorine.

3.22. The presence of neutron reflecting material should be considered. Material present outside the system of fissile material will act as a neutron reflector and can increase the neutron multiplication factor of the system. Criticality safety assessments usually consider a light water reflector of a thickness sufficient to

achieve the maximum neutron multiplication factor, known as ‘total reflection’ or ‘full light water reflection’. However, the possible presence of other reflector materials (such as polyethylene, concrete, steel, lead, beryllium and aluminium), or several reflector materials used in combination, should be considered, if this could result in a greater increase of the neutron multiplication factor than by full light water reflection.

3.23. The presence of neutron absorbers should be considered. Neutron absorbers are mainly effective for thermal neutron systems. Therefore, any neutron spectrum hardening, i.e. an increase in the distribution of neutron energy, caused by operating conditions or accident conditions, should be considered, as this may result in a decrease in the effectiveness of the neutron absorption. Therefore, when the safety function of a neutron absorber is necessary, safety measures should be applied to ensure that the effectiveness of the neutron absorber is not reduced. Consideration should be given to monitoring the credible long term degeneration and/or degradation of neutron absorbers.

3.24. The geometrical distribution of neutron absorbers and credible changes in their distribution should be considered. Changes in the geometrical distribution of neutron absorbers could include slumping, evaporation or compression.

3.25. Neutron absorbers that are homogeneously distributed in a thermal neutron system are usually more effective than if they were heterogeneously distributed (however, heterogeneously distributed absorbers may be easier to control by administrative means). In a thermal neutron system consisting of a heterogeneous arrangement of fissile material and a fixed neutron absorber (e.g. the storage of fuel assemblies), the neutron absorber may be more effective the closer it is located to the fissile material. Any material (e.g. water, steel) located between the absorber and the fissile material can change the effectiveness of the absorber. Solid, fixed neutron absorbers should be tested and/or validated prior to first use in order to demonstrate the presence and uniformity of the distribution of the absorber isotope (e.g. ^{10}B). Demonstration of the continued presence and effectiveness of neutron absorbers throughout their operational lifetime should be considered.

3.26. Material (e.g. steam, water mist, polyethylene, concrete) located between or around fissile material may act not only as a reflector but also as a moderator and/or a neutron absorber and can therefore increase or decrease the neutron multiplication factor of the system. Any change in the neutron multiplication factor will be dependent on the type and density of the material positioned between or around the fissile material. Materials with low density (such as steam