

IAEA Safety Standards

for protecting people and the environment

Criticality Safety in the Handling of Fissile Material

Specific Safety Guide

No. SSG-27 (Rev. 1)



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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

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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: 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.

Other safety related IAEA publications are issued as **Emergency Preparedness and Response** publications, **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.

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 (Rev. 1)

CRITICALITY SAFETY IN THE HANDLING OF FISSILE MATERIAL

SPECIFIC SAFETY GUIDE

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2022

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FOREWORD

by Rafael Mariano Grossi
Director General

The IAEA's Statute authorizes it to "establish...standards of safety for protection of health and minimization of danger to life and property". These are standards that the IAEA must apply to its own operations, and that States can apply through their national regulations.

The IAEA started its safety standards programme in 1958 and there have been many developments since. As Director General, I am committed to ensuring that the IAEA maintains and improves upon this integrated, comprehensive and consistent set of up to date, user friendly and fit for purpose safety standards of high quality. Their proper application in the use of nuclear science and technology should offer a high level of protection for people and the environment across the world and provide the confidence necessary to allow for the ongoing use of nuclear technology for the benefit of all.

Safety is a national responsibility underpinned by a number of international conventions. The IAEA safety standards form a basis for these legal instruments and serve as a global reference to help parties meet their obligations. While safety standards are not legally binding on Member States, they are widely applied. They have become an indispensable reference point and a common denominator for the vast majority of Member States that have adopted these standards for use in national regulations to enhance safety in nuclear power generation, research reactors and fuel cycle facilities as well as in nuclear applications in medicine, industry, agriculture and research.

The IAEA safety standards are based on the practical experience of its Member States and produced through international consensus. The involvement of the members of the Safety Standards Committees, the Nuclear Security Guidance Committee and the Commission on Safety Standards is particularly important, and I am grateful to all those who contribute their knowledge and expertise to this endeavour.

The IAEA also uses these safety standards when it assists Member States through its review missions and advisory services. This helps Member States in the application of the standards and enables valuable experience and insight to be shared. Feedback from these missions and services, and lessons identified from events and experience in the use and application of the safety standards, are taken into account during their periodic revision.

I believe the IAEA safety standards and their application make an invaluable contribution to ensuring a high level of safety in the use of nuclear technology. I encourage all Member States to promote and apply these standards, and to work with the IAEA to uphold their quality now and 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.

Safety Guides

Safety Guides provide recommendations and guidance on how to comply with the safety requirements, indicating an international consensus that it

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

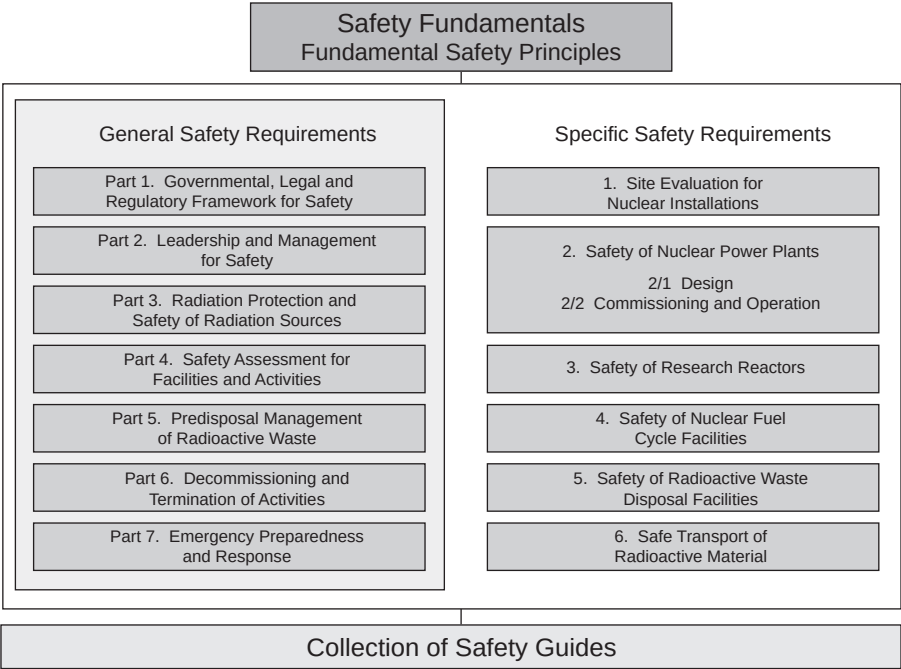


FIG. 1. The long term structure of the IAEA Safety Standards Series.

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 five Safety Standards Committees, for emergency preparedness and response (EPReSC) (as of 2016), 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.

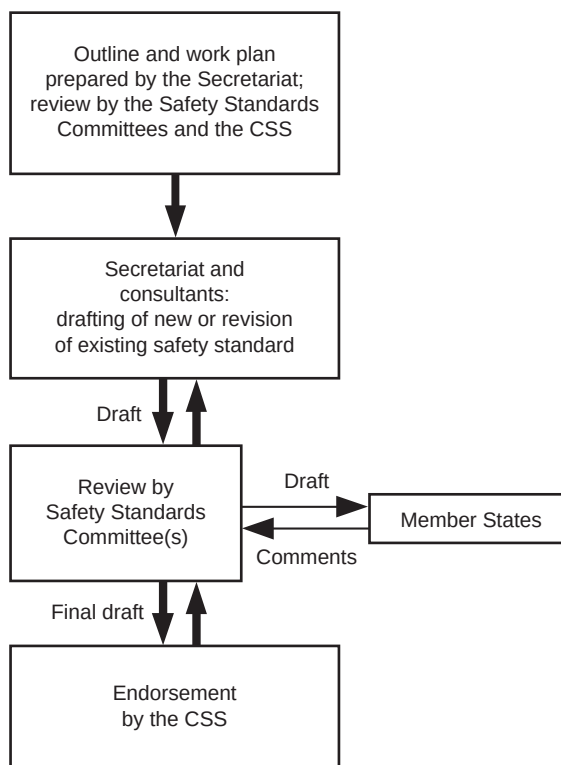


FIG. 2. The process for developing a new safety standard or revising an existing standard.

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 <https://www.iaea.org/resources/safety-standards/safety-glossary>). 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. Criticality can be achieved under certain conditions by most fissionable nuclides belonging to the actinide elements. Some of these nuclides are also fissile, meaning that they are able to support a self-sustaining nuclear chain reaction with neutrons of all energies, but predominantly with slow neutrons [1]. This Safety Guide addresses criticality safety for fissile material and covers mixtures of fissile and other fissionable nuclides.

1.2. Nuclear facilities containing fissile material, and activities in which fissile material is handled, are required to be managed in such a way as to ensure an adequate margin of subcriticality under operational states and under conditions referred to as ‘credible abnormal conditions’ or ‘conditions included in the design basis’ (see Requirements 38 and 66 of IAEA Safety Standards Series No. SSR-4, Safety of Nuclear Fuel Cycle Facilities [2]). This applies to facilities where fissile material is handled in the production of fresh nuclear fuel (including enrichment and fuel fabrication), facilities where irradiated nuclear fuel is handled, and research and development facilities where fissile material is handled. These requirements in SSR-4 [2] also apply to radioactive waste from nuclear fuel cycle facilities that contains fissile material.

1.3. Requirements for the transport of packages containing fissile material are established in IAEA Safety Standards Series No. SSR-6 (Rev. 1), Regulations for the Safe Transport of Radioactive Material, 2018 Edition [3].

1.4. The subcriticality of a system depends on many parameters relating to the fissile material, including its mass, concentration, moderation, geometry, nuclide composition, chemical form, temperature and density. Subcriticality is also affected by the presence of other materials such as neutron moderators, neutron absorbers and neutron reflectors, and by dynamic effects (in particular, for fluids). Subcriticality can be ensured through the control of an individual parameter or a combination of parameters, for example by limiting mass alone or by limiting both mass and moderation. Such parameters can be controlled by engineered and/or administrative measures.

1.5. In this Safety Guide, the term ‘nuclide composition’ encompasses the parameters ‘enrichment’, ‘effective enrichment’, ‘plutonium vector’ and ‘isotopic

composition'. Other terms used in this publication are as defined in the IAEA Safety Glossary [1].

1.6. This Safety Guide supersedes IAEA Safety Standards Series No. SSG-27, Criticality Safety in the Handling of Fissile Material¹.

OBJECTIVE

1.7. The objective of this Safety Guide is to provide recommendations on meeting the relevant requirements established in SSR-4 [2], as well as in SSR-6 (Rev. 1) [3] (see para. 1.13), in respect of the following:

- (a) Ensuring and demonstrating subcriticality under operational states and under conditions referred to as 'credible abnormal conditions' or 'conditions included in the design basis';
- (b) Estimating the credible consequences of a potential criticality accident;
- (c) Minimizing the consequences if a criticality accident were to occur.

1.8. The recommendations on criticality safety provided in this Safety Guide are also relevant to meeting other requirements established in the safety standards, including IAEA Safety Standards Series Nos GSR Part 4 (Rev. 1), Safety Assessment for Facilities and Activities [4]; GSR Part 2, Leadership and Management for Safety [5]; GSR Part 5, Predisposal Management of Radioactive Waste [6]; GSR Part 6, Decommissioning of Facilities [7]; SSR-5, Disposal of Radioactive Waste [8]; and GSR Part 7, Preparedness and Response for a Nuclear or Radiological Emergency [9].

1.9. The Safety Guide is intended for use by operating organizations, regulatory bodies and other organizations involved in ensuring criticality safety of nuclear facilities and activities.

SCOPE

1.10. This Safety Guide applies to all facilities and activities in which fissile material is handled, except those facilities that are intentionally designed to be critical, for example a reactor core in a nuclear reactor, or a critical assembly.

¹ INTERNATIONAL ATOMIC ENERGY AGENCY, Criticality Safety in the Handling of Fissile Material, IAEA Safety Standards Series No. SSG-27, IAEA, Vienna (2014).

In this publication, ‘handling of fissile material’ refers to all activities involving fissile material, including its processing, use, storage, movement (i.e. within the site) and transport (i.e. off the site), as well as the management of radioactive waste containing fissile material.

1.11. The recommendations provided in this Safety Guide cover criticality safety during operational states and during conditions referred to as ‘credible abnormal conditions’, from initial design, through commissioning and operation, to decommissioning. It also applies to the design, operation and post-closure stages of waste disposal facilities. This Safety Guide also provides recommendations on planning the emergency response to a criticality accident.

1.12. The recommendations provided in this Safety Guide address approaches to and criteria for ensuring subcriticality; identification of credible abnormal conditions; performance of criticality safety assessments; verification, benchmarking and validation of calculation methods; safety measures to ensure subcriticality; and management of criticality safety.

1.13. In cases where criticality safety is specifically addressed by regulations — for example, the transport of fissile material in accordance with SSR-6 (Rev. 1) [3] — this Safety Guide supplements but does not replace the recommendations and guidance provided in corresponding Safety Guides, for example IAEA Safety Standards Series No. SSG-26 (Rev. 1), Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material (2018 Edition) [10].

1.14. The recommendations provided in this Safety Guide may be applied to operations that are intended to remain subcritical in nuclear power plants and research reactors, for example the handling of fresh fuel and irradiated fuel.

STRUCTURE

1.15. This Safety Guide consists of six sections and an Annex. Section 2 provides recommendations on the factors that affect criticality safety and provides guidance for criticality safety specialists. It also provides recommendations on the management system that should be in place, subcritical limits and safety margins, and criteria for determining exemptions to certain criticality safety measures. Section 3 provides recommendations on the safety measures necessary for ensuring criticality safety, 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 recommendations on conducting criticality safety assessments, the role of deterministic and probabilistic approaches, and the methodology by which the criticality safety assessment should be performed. Section 5 provides recommendations on criticality safety for specific practices in the various areas of conversion and enrichment, fuel fabrication, irradiated fuel operations prior to reprocessing or disposal, reprocessing, radioactive waste management (i.e. processing, storage and disposal), decommissioning, transport and on-site movement of fissile material, and research and development laboratories. Section 6 provides recommendations 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.

1.16. The Annex provides a bibliography of useful background information on criticality safety, covering the methodology for criticality safety assessment, standards, handbooks, computational methods, training and education, and operating experience.

2. THE APPROACH TO ENSURING CRITICALITY SAFETY

GENERAL CONSIDERATIONS FOR ENSURING CRITICALITY SAFETY

2.1. Ensuring subcriticality in accordance with Requirements 38 and 66 of SSR-4 [2] is an essential component of criticality safety. Safety measures, both engineered measures and administrative measures (see para. 6.139 of SSR-4 [2]), ensure that facilities are operated, and that activities are conducted, within specified operational limits and conditions that ensure subcriticality. These safety measures should be identified, implemented, maintained and periodically reviewed to ensure that operations and activities stay within defined safety limits (see para. 2.9) during operational states and during credible abnormal conditions (see para. 2.3).

2.2. Subcriticality is generally ensured through the control of a set of macroscopic parameters such as mass, concentration, moderation, geometry, nuclide composition, chemical form, temperature, density, and neutron reflection, interaction or absorption. The determination of limits for these parameters

is generally performed on the basis of the effective neutron multiplication factor² (k_{eff}) of a system, for which nuclear data are needed. Because k_{eff} depends on a large number of variables, there are many examples of apparently ‘anomalous’ behaviour in which changes are counterintuitive.

2.3. The operational states and credible abnormal conditions that could lead to criticality conditions include the postulated initiating events listed in the appendix to SSR-4 [2]. The credible abnormal conditions should be determined on the basis of deterministic analysis complemented, where practicable, by probabilistic safety assessment. In the identification of the credible abnormal conditions, the facility design and the characteristics of the activity, as well as operating experience feedback, should be considered (see also Refs [11, 12]).

2.4. In accordance with Requirement 13 of SSR-4 [2], items that are important to criticality safety are required to be identified and classified on the basis of their safety function and safety significance. This includes items providing engineered or administrative criticality safety measures, such as items for the prevention of criticality accidents and for the mitigation of consequences of such accidents.

2.5. A graded approach may be used in developing and implementing the approach to ensuring criticality safety of facilities or activities that involve handling of fissile material (see Requirement 11 of SSR-4 [2]). The application of a graded approach should be determined on the basis of the type of facility or activity and its potential risk. The application of a graded approach should not compromise safety. The graded approach should be applied to the following:

- (a) The scope and level of detail of the criticality safety assessment;
- (b) The methods and enveloping criticality events used in the criticality safety assessment;
- (c) The design of criticality detection and alarm systems;
- (d) The level of training and qualification of personnel involved in criticality safety;
- (e) Emergency preparedness and response for criticality accidents;
- (f) Administrative measures for criticality control.

² The k_{eff} 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 $k_{\text{eff}} > 1$. The effective multiplication factor might also be defined in different ways, for example through the concept of reactivity.

Facility specific attributes that are required to be taken into account in the application of a graded approach are listed in para. 6.29 of SSR-4 [2].

2.6. Safety measures and nuclear security measures should be planned and implemented in an integrated manner, and as far as possible in a complementary manner, so that security measures do not compromise safety and safety measures do not compromise security. The implications of security measures, in particular access control, should be assessed with respect to their effect on criticality safety. The training programme on criticality safety should include the relevant aspects of nuclear security and of accounting for and control of nuclear material. Similarly, security personnel and those personnel responsible for accounting for and control of nuclear material should receive at least basic training in criticality safety.

2.7. Feedback of operating experience, including awareness of previous anomalies and accidents, should be used to contribute to ensuring criticality safety. Information on the causes and consequences of important events that have been observed in criticality safety is provided in Refs [12–14] and in the IAEA’s Fuel Incident Notification and Analysis System³. Events relating to criticality safety should be analysed and included in the operating experience programme. Requirements for feedback from operating experience for all facilities and activities are established in para. 6.7 of GSR Part 2 [5] and, for nuclear fuel cycle facilities, in Requirement 73 of SSR-4 [2]. Further recommendations are provided in IAEA Safety Standards Series No. SSG-50, Operating Experience Feedback for Nuclear Installations [15].

SUBCRITICAL LIMITS AND SAFETY MARGINS

2.8. Subcritical limits should be derived on the basis of one or both of the following:

- (a) The subcritical value of k_{eff} for the system under analysis.
- (b) A set of one or more macroscopic control parameters whose values, individually or in combination, for the system under analysis correspond to a k_{eff} of less than 1. Examples of such control parameters are mass, concentration, moderation, geometry, nuclide composition, chemical form, temperature, density, and neutron reflection, interaction or absorption.

³ <https://finas.iaea.org/>

2.9. Safety margins should be applied to determine the criticality safety limits. Acceptance criteria should be defined, and it should be demonstrated that these criteria will not be exceeded. Furthermore, the upper bound of the uncertainty and sensitivity analysis of k_{eff} calculations (see para. 2.10) should not exceed the acceptance criteria. Subcriticality implies a k_{eff} value of less than 1 and/or a control parameter whose value corresponds to a k_{eff} of less than 1. Paragraph 6.21 and Requirement 17 of SSR-4 [2] require the use of conservative margins for design.

2.10. Consideration should be given to the uncertainties associated with the calculation of k_{eff} when applying safety margins to k_{eff} . Alternatively, consideration should be given to uncertainty in the calculation of other control parameters when applying safety margins to their corresponding critical values. This should include, for example, the possibility of bias or bias uncertainty in the calculation method and the sensitivity of parameter values to changes in the control parameter or k_{eff} . The relationship between k_{eff} and other parameters might be significantly non-linear.

2.11. In accordance with Requirement 38 of SSR-4 [2], the subcriticality of the design is required to be demonstrated in a full criticality safety assessment.⁴ The criticality safety assessment should define criticality safety limits and, in turn, operational limits and conditions for criticality safety, which should be expressed in terms of the process parameters affecting the reactivity characteristics of a system. These parameters include mass, concentration, moderation, geometry, nuclide composition, chemical form, temperature, density, and neutron reflection, interaction or absorption. The parameters quoted in limits and conditions should be expressed in terms that can readily be understood, such as enrichment, packaging rules, or a moisture or moderator material limit or restriction.

2.12. The operational limits and conditions specified for the facility or activity should be lower than or equal to the criticality safety limits and should be suitable for being monitored and controlled. Sufficient and appropriate safety measures should be applied to detect and react to deviations from normal operation before any criticality safety limit is exceeded. Uncertainties in measurement, administrative errors and sensor delay should also be considered when assessing the appropriateness of safety measures.

⁴ Except where the quantity of fissile material involved is so low or the isotopic composition is such that it meets exemption criteria (see paras 2.13–2.16) specified by, or agreed with, the regulatory body.

EXEMPTION CRITERIA FOR FISSILE MATERIAL

2.13. In some cases, the amount of fissile material is so low, or the nuclide composition is such, that a full criticality safety assessment is not justified. Exemption criteria, if not specified by the regulatory body, should be developed by the operating organization, reviewed by the management of the operating organization and then agreed by the regulatory body, as appropriate. A useful starting point is the exception criteria applied to the classification of transport packages containing fissile material in para. 417, in conjunction with para. 570, of SSR-6 (Rev. 1) [3].

2.14. The primary approach in seeking exemption should be to demonstrate that the inherent features of the fissile material are sufficient to ensure subcriticality. The secondary approach should be to demonstrate that the maximum amounts of fissile nuclides involved are so far below minimum critical values that no specific safety measures are necessary to ensure subcriticality.

2.15. Modifications to facilities or activities are required to be evaluated before being implemented, to determine whether the bases for the exemption remain valid (see paras 6.141 and 9.83 of SSR-4 [2]).

2.16. The basis for meeting exemption criteria should be documented and justified.

MANAGEMENT SYSTEM FOR CRITICALITY SAFETY

2.17. A documented management system that integrates the safety, health, environmental, security, quality, and human and organizational factors of the operating organization is required to be established and implemented with adequate resources, in accordance with Requirement 4 of SSR-4 [2]. As part of the management system, early in the design stage a criticality safety programme should be established and put into effect by the operating organization to ensure that safety measures for ensuring subcriticality are specified, implemented, monitored, audited, documented and periodically reviewed throughout the lifetime of the facility or the duration of the activity.

2.18. Requirements for the management system are established in GSR Part 2 [5], and associated recommendations are provided in IAEA Safety Standards Series Nos GS-G-3.1, Application of the Management System for Facilities and Activities [16]; GSG-16, Leadership, Management and Culture for Safety in Radioactive Waste Management [17]; GS-G-3.5, The Management System for

Nuclear Installations [18]; and TS-G-1.4, The Management System for the Safe Transport of Radioactive Material [19].

2.19. The management system (which is required to cover all items, services and processes important to safety (see para. 4.8 of SSR-4 [2])) should include activities in relation to criticality safety, thereby providing confidence that they are performed correctly. In determining how the management system for criticality safety is to be applied, a graded approach on the basis of the relative importance to safety of each item or process is required to be used (see Requirement 7 of GSR Part 2 [5]). The management system is required to support the development and maintenance of a strong safety culture, including in all aspects of criticality safety (see Requirement 12 of GSR Part 2 [5]).

2.20. The management system should ensure that the facility or activity achieves the necessary level of criticality safety, as derived from regulatory requirements; the design requirements and assumptions; the safety analysis report; and operational limits and conditions, including administrative requirements.

2.21. In accordance with paras 4.15–4.23 of SSR-4 [2], the management system should address the following functional areas:

- (a) Management responsibility, which includes the support and commitment of management necessary to achieve the objectives of the operating organization.
- (b) Resource management, which includes the measures necessary to ensure that the resources essential to the implementation of strategy and the achievement of the objectives of the operating organization are identified and made available.
- (c) Process implementation, which includes the activities and tasks necessary to achieve the goals of the organization.
- (d) Measurement, assessment, evaluation and improvement, which provide an indication of the effectiveness of management processes and work performance compared with objectives or benchmarks. It is through measurement and assessment that opportunities for improvement are identified.

Management responsibility

2.22. The prime responsibility for safety, including criticality safety, rests with the operating organization. In accordance with para. 4.11 of GSR Part 2 [5], the

documentation of the management system for criticality safety is required to include the following:

- (a) A description of the organizational structure;
- (b) Functional responsibilities;
- (c) Levels of authority.

The documentation should describe the interactions among the individuals managing, performing and assessing the adequacy of the criticality safety programme and activities. The documentation should also cover other management measures, including planning, scheduling and resource allocation (see para. 9.8(b) of SSR-4 [2]).

2.23. There should be a designated person (or persons) who is responsible and accountable for criticality safety, including, as appropriate, the following:

- (a) Developing and documenting all aspects of criticality safety assessment.
- (b) Monitoring the performance of activities and processes.
- (c) Ensuring that personnel are adequately trained.
- (d) Operating a system for keeping records that ensures control of performance and verification of activities important to criticality safety. The record keeping system should provide for the identification, approval, review, filing, retrieval and disposal of records.

2.24. Paragraph 4.15 of SSR-4 [2] states:

“[T]he management system shall include provisions for ensuring effective communication and clear assignment of responsibilities, in which accountabilities are unambiguously assigned to individual roles within the organization and to suppliers, to ensure that processes and activities important to safety are controlled and performed in a manner that ensures that safety objectives are achieved.”

Arrangements for empowering relevant personnel to stop unsafe operations should also be made.

2.25. The operating organization is required to ensure that criticality safety assessments and analyses are conducted, documented and updated (see Requirement 24 and para. 4.65 of GSR Part 4 (Rev. 1) [4] and Requirement 5 of SSR-4 [2]).

2.26. In accordance with para. 4.2(d) of SSR-4 [2], the operating organization is required to arrange audits of criticality safety measures. This should include the examination of arrangements for emergency response, for example emergency communications, evacuation routes and signage. Checks should be performed by the criticality safety staff who performed the safety assessments to confirm that the data used, and the implementation of criticality safety measures, are correct. Audits should be performed by personnel who are independent of those who performed the safety assessments or conducted the criticality safety activities. The data from audits should be documented and submitted for management review and for action, if necessary.

Resource management

2.27. The operating organization is required to provide adequate resources (both human and financial) for the safe operation of the facility or activity (see Requirement 9 of GSR Part 2 [5]), including resources for mitigating the consequences of criticality accidents. The management of the operating organization, in particular the person responsible for criticality safety, should participate in the following:

- (a) Determining the necessary competence of criticality safety staff and providing training, as necessary;
- (b) Preparing and issuing specifications and procedures on criticality safety;
- (c) Supporting and performing criticality safety assessments;
- (d) Having frequent personal contact with personnel, including observing work in progress.

2.28. The responsibilities, knowledge and training for ensuring criticality safety should be clearly specified by the operating organization. The individuals having these responsibilities should be formally appointed by the operating organization. Criticality safety staff should be knowledgeable about the physics (both static and kinetic) of nuclear criticality and the associated national and international safety standards, codes and best practices, and should be familiar with the design and operation of relevant facilities and the conduct of relevant activities. The criticality safety staff should be independent of the operations management, to the extent necessary.

2.29. All activities that might affect criticality safety are required to be performed by suitably qualified and competent personnel (see para. 9.83 of SSR-4 [2]). The operating organization should ensure that these personnel receive training and refresher training at suitable intervals, appropriate to their level of responsibility.

In particular, personnel involved in activities with fissile material should understand the nature of the hazard posed by fissile material and how the risks are controlled by the established safety measures, operational limits and conditions, and operating procedures. The criticality safety staff should provide assistance in the training of operating personnel, provide technical guidance and expertise for the development of operating procedures, and check and validate all operations that might need criticality control.

2.30. The management system for criticality safety is required to include procurement activities and should be extended to include suppliers (see para. 4.35 and Requirement 11 of GSR Part 2 [5]). The operating organization should ensure, through audits, that suppliers (e.g. designers, safety analysts) have management systems that adequately address criticality safety.

2.31. Any hardware and software based process items and equipment necessary for work to be performed in a safe manner should be identified, provided and maintained. Calculation tools (e.g. computer codes) used for criticality safety assessment should be identified and are required to be verified and validated in accordance with para. 6.145 of SSR-4 [2]. Equipment and items used for criticality safety monitoring, data collection, verifications and tests should be qualified for the operating environmental conditions and should be calibrated, as necessary.

Process implementation

2.32. All operations to which criticality safety is pertinent are required to be performed in accordance with approved procedures and instructions that specify all the parameters they are intended to control and the criteria to be fulfilled (see para. 9.83 of SSR-4 [2]). The operating procedures should cover operational states and credible abnormal conditions.

2.33. To facilitate the implementation of operating procedures used to ensure subcriticality, managers should ensure that operating personnel involved in the handling of fissile material are also involved in the development of the operating procedures.

2.34. Assessments of modifications to facilities or activities, or proposals for the introduction of new activities, are required to consider the implications for criticality safety (see paras 6.141 and 9.83 of SSR-4 [2]). Safety assessments of modifications affecting fissile material that have a safety significance should be provided to the regulatory body to allow for review before the modifications are implemented. Modifications having major safety significance are required to be

subjected to procedures for design, construction and commissioning equivalent to those applied to the whole facility or activity (see para. 9.59 of SSR-4 [2]). The facility or activity documentation is required to be updated to reflect modifications, and the operating personnel, including supervisors, should receive adequate training on the modifications (see Requirement 61 of SSR-4 [2]).

2.35. The nature of the criticality hazard is such that deviations towards insufficient subcritical margins might not be immediately obvious; that is, there might be no obvious indication that k_{eff} is increasing. If operational deviations occur that are not foreseen in the criticality safety assessment, operating personnel should immediately consult the criticality safety staff for advice on how to place the system into a known safe condition. Operating personnel handling fissile material should therefore inform their supervisor in the event of any unforeseen operational deviations.

2.36. Throughout the lifetime of the facility or the duration of an activity, operations to which criticality safety is pertinent involve different groups and interfaces with other areas, such as those related to nuclear security and to the system of accounting for and control of nuclear material (see Requirement 75 of SSR-4 [2]). Operations with such interfaces should be identified, coordinated, planned and conducted to ensure effective communication and clear assignment of responsibilities. Communications regarding safety and security should ensure that confidentiality of information is maintained. This includes the system of accounting for and control of nuclear material, for which information security should be coordinated in a manner ensuring that subcriticality is not compromised.

Measurement, assessment, evaluation and improvement

2.37. Audits performed by the operating organization of facilities and activities (see para. 2.26), as well as proper control of modifications to facilities and activities (see para. 2.34), are particularly important for ensuring subcriticality. The results are required to be evaluated by the operating organization and corrective actions taken where necessary (see para. 4.2(d) of SSR-4 [2]).

2.38. Most criticality accidents and near-miss events have had multiple causes. In many cases, 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 (i.e. without breaching any arrangements for information security), of training operating personnel, of promoting a strong culture for safety and of independent audits.

2.39. Any deviation from operating procedures and unforeseen changes in operations or in operating conditions is required to be reported and promptly investigated by the operating organization (see paras 9.34, 9.35 and 9.84 of SSR-4 [2]). The investigation should analyse the causes of the deviation to identify lessons and to determine and implement corrective actions to prevent a recurrence. In accordance with the graded approach, the depth and extent of the investigation should be proportionate to the safety significance of the event. The investigation should include an analysis of the operation of the facility, or the conduct of the activity, including human factors. It should also include a review of the criticality safety assessment and analyses previously performed, including the safety measures originally established.

2.40. Requirement 73 of SSR-4 [2] states that **“The operating organization shall establish a programme to learn from events at the facility and events at other nuclear fuel cycle facilities and in the nuclear industry worldwide.”** Recommendations on operating experience programmes are provided in SSG-50 [15] (see also para. 2.7).

3. MEASURES FOR ENSURING CRITICALITY SAFETY

GENERAL PRINCIPLES FOR ENSURING CRITICALITY SAFETY

3.1. Consideration of criticality safety should be used to determine the following:

- (a) The design and arrangement of engineered safety measures;
- (b) The need for instrumentation to ensure that the operational limits and conditions are adequately monitored and controlled;
- (c) The need for additional administrative measures to ensure that the operational limits and conditions are adequately controlled.

3.2. When determining the measures for ensuring the criticality safety of systems in which fissile material is handled, the concept of defence in depth is required to be considered (see para. 6.141 of SSR-4 [2]). Two vital parts of this concept are passive safety features and fault tolerance (i.e. the design should be such that a failure occurring anywhere within the systems provided to fulfil each safety function will not cause the system to achieve criticality).

3.3. With regard to fault tolerance, para. 6.142 of SSR-4 [2] states:

“For the prevention of criticality by means of design, the double contingency principle shall be the preferred approach. For application of the double contingency principle, the design for a process shall include sufficient safety factors to require at least two unlikely, independent and concurrent changes in process conditions before a criticality accident is possible.”

Defence in depth

3.4. The facility or activity is required to be designed and operated or conducted such that it provides defence in depth against credible abnormal conditions and accidents (see Requirement 10 of SSR-4 [2]). This is achieved by the provision of different levels of protection, with the objective of preventing failures or, if prevention fails, of ensuring that the failure is detected and compensated for or corrected. The primary objective is to adopt safety measures that prevent a criticality accident. However, in line with the concept of defence in depth, safety measures are also required to mitigate the consequences of such an accident (see para. 6.19 of SSR-4 [2]).

3.5. An overview of the levels of defence in depth (see para. 2.12 of SSR-4 [2]) in relation to criticality safety is provided in Table 1. In applying the concept of defence in depth, application of the fourth level of defence, which deals with ensuring the confinement function to limit radioactive releases, might 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 established in GSR Part 7 [9] (see also Section 6 of this Safety Guide).

Passive safety

3.6. The passive safety of the facility or activity should be such that the system will remain subcritical without the need for active engineered safety measures⁵ or administrative safety measures (i.e. other than verification that the properties

⁵ Active engineered safety measures use active components, such as electrical, mechanical or hydraulic hardware, to ensure subcriticality. Active components act by responding to a process variable important to criticality safety (or by being actuated through the instrumentation and control system) and providing automatic action to place the system in a safe condition, without the need for human intervention.

TABLE 1. OVERVIEW OF LEVELS OF DEFENCE IN DEPTH IN
RELATION TO CRITICALITY SAFETY

Level	Objective	Means of protection
Level 1	Prevention of deviations from normal operation and prevention of failures of systems important to safety.	Incorporation of the double contingency principle in design (see para. 3.3); assurance of subcriticality under normal and all credible abnormal conditions, with an appropriate margin of subcriticality for safety.
Level 2	Detection and control of deviations from normal operation in order to prevent credible abnormal conditions from escalating to accident conditions.	In the event that an unlikely change in process conditions occurs, administrative or engineered features (or combinations thereof) to detect and correct the change in process conditions in order to limit the likelihood of a second change in process conditions occurring concurrently.
Level 3	Control of accidents within the design basis.	Not directly applicable. In most cases, when a criticality accident is triggered, it cannot be controlled because it would occur almost instantaneously and without warning signs. Consequently, the third level of defence in depth, as described in para. 2.12 of SSR-4 [2], calling for controlling accidents, cannot be directly transposed to a criticality accident.
Level 4	Mitigation of the consequences of accidents in which the design basis (or the equivalent) of the system might be exceeded, and ensuring that the consequences of an 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. Provision of an emergency control centre and plans for on-site and off-site emergency response.
Level 5	Mitigation of the consequences of a radioactive release.	

of the fissile material and changes in reflection, absorption and moderation are covered by the design). For example, the facility or activity could be designed using the assumption that fissile material is always restricted to equipment with a favourable geometry⁶. Special care is then necessary to avoid unintentional transfer to an unfavourable geometry.

Fault tolerance

3.7. The design should take into account fault tolerance in order to replace or complement passive safety measures (if any). The double contingency principle (see para. 3.3) is the preferred means of ensuring fault tolerance by design. By applying this principle, a criticality accident cannot occur unless at least two unlikely, independent and concurrent changes in process conditions have occurred (see also Requirement 23 of SSR-4 [2]).

3.8. In accordance with the double contingency principle, if a criticality accident could occur because of the concurrent occurrence of two changes in process conditions, it should be shown that (a) the two changes are independent (i.e. not caused by a common cause failure) and (b) the probability of occurrence of each change is sufficiently low.

3.9. The characteristics of a system should meet the recommendations in para. 2.11, in order that each change in process conditions can be detected (e.g. monitored) by suitable and reliable means within a time frame that allows the necessary corrective actions to be taken.

3.10. The system design should follow the fail-safe principle, such that a component failure will not result in a criticality accident. In meeting Requirement 23 of SSR-4 [2], the safety measures should be designed to ensure that 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 (the single failure criterion).

3.11. Where failures or incorrect operation 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 only deviate from their normal operating values at a rate such that detection, intervention and recovery can be

⁶ An item of equipment with a favourable geometry is one whose dimensions, shape and construction materials are such that a criticality event cannot occur, even with all other parameters at their worst credible configuration.