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

IAEA SAFETY STANDARDS AND RELATED PUBLICATIONS

IAEA SAFETY STANDARDS

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

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

Information on the IAEA's safety standards programme is available 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.

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.

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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
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FOREWORD

by Yukiya Amano Director General

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

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

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

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

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

NOTE BY THE SECRETARIAT

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

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

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

THE IAEA SAFETY STANDARDS

BACKGROUND

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

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

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

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

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

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

THE IAEA SAFETY STANDARDS

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

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

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

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

Safety Fundamentals

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

Safety Requirements

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

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

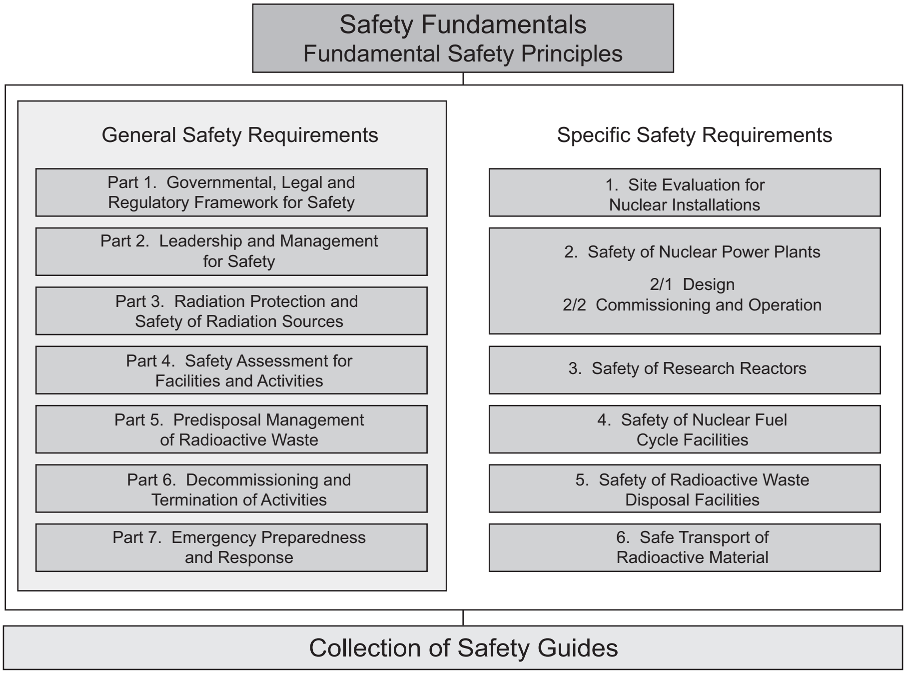

FIG. 1. The long term structure of the IAEA Safety Standards Series.

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

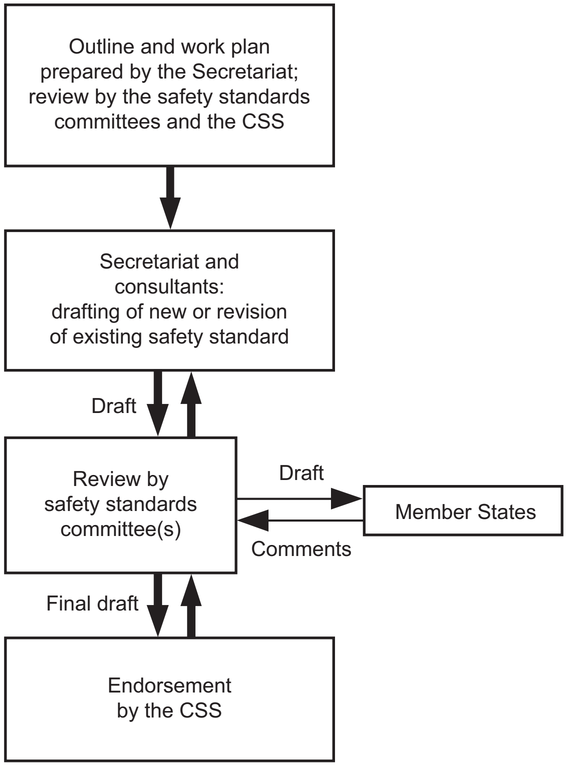

FIG. 2. The process for developing a new safety standard or revising an existing standard.

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.

CONTENTS

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 fissile[1], 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 material[2] 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.

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[1] Fissile nuclides are nuclides, in particular ^{233}U, ^{235}U, ^{239}Pu and ^{241}Pu, 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 factor[3] (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 value[4] 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 $k_{eff} = 1$; (b) subcritical if $k_{eff} < 1$; and (c) supercritical if $k_{eff} > 1$.

[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 exception 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 inspection[5] 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 tolerance[6]. 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 geometry[7]. 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.

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[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 or foam) can cause a significant change in the neutron multiplication factor. The inclusion or omission of any materials from the criticality safety assessment should be justified by evaluating the effect of their treatment on the neutron multiplication factor.

3.27. Interaction between units of fissile material should be considered, as this interaction can affect the neutron multiplication factor of the system. This control parameter can be used to ensure criticality safety, for example by specifying minimum separation distances (or in some cases maximum distances, e.g. to limit interstitial moderation between fissile material units) or by introducing screens of neutron absorbers. Wherever practicable, separation should be ensured by engineered means, for example fixed storage racks for storage of arrays of drums containing fissile material.

3.28. Heterogeneity of materials such as swarf (turnings, chips or metal filings) or fuel pellets can result in neutron multiplication factors greater than those calculated by assuming a homogeneous mixture, particularly for low enriched uranium systems or for mixed uranium and plutonium. Therefore, the degree of heterogeneity or homogeneity used or assumed in the criticality safety assessment should be justified. Safety measures should be applied that ensure that heterogeneity of the fissile material could not result in a higher neutron multiplication factor than considered.

3.29. The temperature of materials may cause changes in density and in neutron cross-section, which may affect reactivity. This should be considered in the criticality safety assessment.

ENGINEERED SAFETY MEASURES

Passive engineered safety measures

3.30. Passive engineered safety measures use passive components to ensure subcriticality. Such measures are highly preferred because they provide high reliability, cover a broad range of criticality accident scenarios, and require little operational support to maintain their effectiveness as long as ageing aspects are adequately managed. Human intervention is not necessary. Advantage may be taken of natural forces, such as gravity, rather than relying on electrical, mechanical or hydraulic action. Like active components, passive components are subject to (random) degradation and to human error during installation and maintenance activities. They require surveillance and, as necessary, maintenance.

Examples of passive components are geometrically favourable pipes, vessels and structures, solid neutron absorbing materials, and the form of fissile material.

3.31. In addition, certain components that function with very high reliability based on irreversible action or change may be designated as passive components.

3.32. Certain components, such as rupture discs, check valves, safety valves and injectors, have characteristics that require special consideration before designation as an active or passive component. Any engineered component that is not a passive component is designated an active component, although it may be part of either an active engineered safety measure or an administrative safety measure.

Active engineered safety measures

3.33. Active engineered safety measures use active components such as electrical, mechanical or hydraulic hardware to ensure subcriticality. Active components act by 'sensing' 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. Active engineered safety measures should be used when passive engineered safety measures are not feasible. However, active components are subject to random failure and degradation and to human error during operation and maintenance activities. Therefore, components of high quality and with low failure rates should be selected in all cases. Fail-safe designs should be employed, if possible, and failures should be easily and quickly detectable. The use of redundant systems and components should be considered, although it does not prevent common cause failure. Active engineered components require surveillance, periodic testing for functionality, and preventive and corrective maintenance to maintain their effectiveness.

3.34. Examples of active components are neutron or gamma monitors, computer controlled systems for the movement of fissile material, trips based on process parameters (e.g. conductivity, flow rate, pressure and temperature), pumps, valves, fans, relays and transistors. Active components that require human action in response to an engineered stimulus (e.g. response to an alarm or to a value on a weighing scale) are administrative safety measures, although they contain active engineered components.

ADMINISTRATIVE SAFETY MEASURES

General considerations

3.35. When administrative safety measures are employed, particularly procedural controls, it should be demonstrated in the criticality safety assessment that credible deviations from such procedures have been exhaustively studied and that combinations of deviations that could lead to a dangerous situation are understood. Specialists in human performance and human factors should be consulted to develop the procedural controls, to inform management as to the robustness, or otherwise, of the procedural controls and to seek improvements where appropriate.

3.36. The use of administrative safety measures should include, but are not limited to, consideration of the following and should be incorporated into the comprehensive criticality safety programme (see para. 2.12):

- Specification and control of the isotopic composition of the elements in the fissile material, the fissile nuclide content, the mass, density, concentration, chemical composition and degree of moderation of the fissile material, and the spacing between systems of fissile material.
- Determination and posting of criticality controlled areas (i.e. areas authorized to contain significant quantities of fissile material) and specification of the control parameters associated with such areas; specification and, where applicable, labelling for materials (e.g. fissile material, moderating materials, neutron absorbing materials and neutron reflecting materials); and specification and, where applicable, labelling for the control parameters and their associated limits on which subcriticality depends. A criticality controlled area is defined by both the characteristics of the fissile material within it and the control parameters used.
- Control of access to criticality controlled areas where fissile material is handled, processed or stored.
- Separation between criticality controlled areas and separation of materials within criticality controlled areas.
- Movement of materials within and between criticality controlled areas, and spacing between moved and stored materials.
- Procedural controls for record keeping systems (e.g. accounting for fissile material).
- Movement and control of fissile material between criticality controlled areas containing different fissile materials and/or with different control parameters.

— Movement and control of materials from areas without criticality safety control (e.g. wastewater processing areas) to criticality controlled areas or vice versa (e.g. flow of effluent waste streams from controlled to uncontrolled processes).
— Use of neutron absorbers, and control of their continued presence, distribution and effectiveness.
— Procedures for use and control of ancillary systems and equipment (e.g. vacuum cleaners in criticality controlled areas and control of filter systems in waste air and off-gas systems).
— Quality assurance, periodic inspection (e.g. control of continued favourable geometries), maintenance, and the collection and analysis of operating experience.
— Procedures for use in the event of an anticipated operational occurrence (e.g. deviations from operating procedures, credible alterations in process or system conditions).
— Procedures for preventing, detecting, stopping and containing leakages, and for removing leaked materials.
— Procedures for firefighting (e.g. the use of hydrogen-free fire extinguishing materials).
— Procedures for the control and analysis of design modifications.
— Procedures for criticality safety assessment and analysis.
— Procedures for the appointment of suitably qualified and experienced staff for criticality safety.
— Procedures covering the provision of training to operating personnel.
— Ensuring that the procedures are understood by operating personnel and contractors working at the facility.
— The safety functions and safety classification of the structures, systems and components important to safety (for example, this is applicable to the design, procurement, administrative oversight of operations, and maintenance, inspection, testing and examination).

3.37. Before a new activity with fissile material is initiated, the necessary engineered and administrative safety measures should be determined, prepared and independently reviewed by personnel knowledgeable in criticality safety. Likewise, before an existing facility or activity is changed, the engineered and administrative safety measures should be revised and again independently reviewed. The introduction of a new activity may be subject to authorization by the regulatory body before it can be initiated.

Operating procedures

3.38. Operating procedures should be written with sufficient detail for a qualified individual to be able to perform the required activities without the need for direct supervision. Furthermore, operating procedures:

- Should facilitate the safe and efficient conduct of operations;
- Should include those controls, limits and measures that are important for ensuring subcriticality;
- Should include mandatory operations, advice and guidance for anticipated operational occurrences and accident conditions;
- Should include appropriate links between procedures in order to avoid omissions and duplications, and, where necessary, should specify clearly conditions of entry to and exit from other procedures;
- Should be simple and readily understandable to operating personnel;
- Should be periodically reviewed in conjunction with other facility documents, such as the emergency response plan and the criticality safety assessment, to incorporate any changes and lessons learned from feedback of operating experience, and for training at predetermined intervals.

3.39. Procedures should be reviewed in accordance with the management system. As appropriate, this review should include review by supervisors and the relevant staff for criticality safety and should be made subject to approval by managers responsible for ensuring subcriticality.

Responsibility and delegation of authority

3.40. Management should be given the responsibility for overseeing the implementation of the criticality safety measures and for implementing appropriate quality assurance measures. Such authority and responsibility should be documented in the management system.

3.41. Management may delegate authority for the implementation of specific criticality safety measures to supervisors. The authority that is permitted to be delegated to a supervisor should be specified and documented in the management system.

3.42. Authority for the implementation of quality assurance measures and periodic inspections and the evaluation of the results of quality controls and periodic inspections should be assigned to persons who are independent of the operating personnel.

3.43. In addition to these organizational requirements, management and supervisors should promote, in accordance with the requirements established in Ref. [3], a safety culture that makes all personnel aware of the importance of ensuring subcriticality and the necessity of adequately implementing the criticality safety measures. For this purpose, management should provide the following:

- Staff for criticality safety who are independent of operating personnel;
- The organizational means for ensuring that the staff for criticality safety provide management, supervisors and operating personnel with periodic training on criticality safety, to improve their safety awareness and behaviour;
- The organizational means for ensuring that the staff for criticality safety themselves are provided with periodic training on criticality safety;
- The organizational means for ensuring that periodic reviews of criticality safety assessments are undertaken;
- The organizational means for ensuring that the criticality safety programme and its effectiveness are continually reviewed and improved.

3.44. Records of participation in criticality safety training should be maintained and used to ensure that routine refresher training is appropriately recommended and instigated.

3.45. The staff for criticality safety should be responsible for, at least, the following:

- Provision of documented criticality safety assessments for systems of, or areas with, fissile material;
- Ensuring the accuracy of the criticality safety assessment, by, whenever possible, directly observing the activity, processes or equipment, as appropriate, and encouraging operating personnel to provide feedback on operating experience;
- Provision of documented guidance on criticality safety for the design of systems of fissile material and for processes, and for the development of operating procedures;
- Specification of the criticality limits and conditions and required safety measures and support for their implementation;
- Determination of the location and extent of criticality controlled areas;
- Provision of assistance in determining the location of criticality detection and alarm systems and development of the associated emergency arrangements, and conduct of periodic reviews of these arrangements;

— Assisting and consulting operating personnel, supervisors and management and keeping close contact with them to ensure familiarity with all activities involving fissile material;
— Conducting regular walkdowns of the facility and inspections of the activities;
— Provision of assistance in the establishment and modification of operating procedures and review of these procedures;
— Documented verification of compliance with the criticality safety requirements for modifications or changes in the design of systems or in processes;
— Ensuring that training in criticality safety is provided periodically for operating personnel, supervisors and management.

3.46. Supervisors should be responsible for, at least, the following:

— Maintaining an awareness of the control parameters and associated limits relevant to systems for which they are responsible;
— Monitoring and documentation of compliance with the limits of the control parameters;
— If there is a potential for unsafe conditions to occur in the event of a deviation from normal operations, stopping work in a safe way and reporting the event as required;
— Promoting a questioning attitude from personnel and demonstrating safety culture.

3.47. In relation to criticality safety, the responsibilities of operating personnel and other personnel should be: to cooperate and comply with management instructions and procedures; to develop a questioning attitude and safety culture; and if unsafe conditions are possible in the event of a deviation from normal operations, to stop work and report the event as required.

IMPLEMENTATION AND RELIABILITY OF SAFETY MEASURES

3.48. Ensuring subcriticality in accordance with the concept of defence in depth usually requires the application of a combination of different engineered and administrative safety measures. Where applicable, reliance may be placed on safety measures already present in the facility or activity, or applied to the system of interest. However, the hierarchy of criticality safety measures specified in para. 3.12 should be observed.

3.49. Consideration of criticality safety should be used to determine:

— The design and arrangement of engineered safety measures;
— The need for instrumentation for ensuring that the operational limits and conditions are adequately monitored and controlled;
— The need for additional administrative measures for ensuring that the operational limits and conditions are adequately controlled.

3.50. Safety measures should include a requirement for quality assurance measures, in-service inspection and testing, and maintenance to ensure that the safety functions are fulfilled and requirements for reliability are met. Where administrative controls are required as part of a safety measure, these should be tested regularly.

3.51. Consideration should be given to other factors that could influence the selection of safety measures. These factors include, but are not limited to:

— The complexity of implementing the safety measure;
— The potential for common mode failure or common cause failure of safety measures;
— The reliability claimed in the criticality safety assessment for the set of safety measures;
— The ability of operating personnel to recognize abnormality or failure of the safety measure;
— The ability of operating personnel to manage abnormal situations;
— Feedback of operating experience.

3.52. Changes due to ageing of the facility should be considered. Ageing effects should be monitored and their impacts on criticality safety should be assessed. Periodic testing of items relied upon to ensure subcriticality should be performed to ensure that the criticality safety analysis remains valid for any actual or potential degradation in the condition of such items.

4. CRITICALITY SAFETY ASSESSMENT

GENERAL

4.1. Criticality safety assessments have generally been based on a deterministic approach in which a set of conservative rules and requirements concerning facilities or activities involving fissile material is applied. In such an approach the adequacy of safety measures in successfully minimizing, detecting and intercepting deviations in control parameters to prevent a criticality accident is judged mainly against a set of favourable characteristics, such as the independence, redundancy and diversity of the safety measures, or whether the safety measures are engineered or administrative, or passive or active. Such considerations may also include a qualitative judgement of the likelihood of failure on demand for these safety measures. If these rules and requirements are met, it is inferred that the criticality risk (see para. 4.2) is acceptably low.

4.2. It is also common to complement the deterministic approach to criticality safety assessment with a probabilistic approach. The probabilistic approach is based on realistic assumptions regarding operating conditions and operating experience, rather than the conservative representation typically used in the deterministic approach. The probabilistic approach provides an estimate of the frequency of each initiating event that triggers a deviation from normal conditions and of the probabilities of failure on demand of any safety measures applied to minimize, detect or intercept the deviation. The frequency of the initiating event and the probabilities of failure of the safety measures can be combined to derive a value for the frequency of occurrence of criticality. By using this value and a measure of the consequences, an estimate of the criticality risk can be made and compared with risk targets or criteria, if any, for the facility or activity.

4.3. The probabilistic approach is used to evaluate the extent to which overall operations at the facility are well balanced and to provide additional insights into possible weaknesses in the design or operation, which may be helpful in identifying ways of further reducing risk. Difficulties in applying the probabilistic approach are sometimes encountered in criticality safety assessment if one or more of the safety measures includes the action of operating personnel as a significant component. The reliability of safety measures of this type can be very difficult to quantify. Also, in some cases there may be a lack of data on reliability for new types of equipment, hardware and software. Consideration should be given to the uncertainties in the values of risk derived by these methods when using the insights provided, especially if such values are to be used as a basis for significant modifications to a facility or activity.

PERFORMANCE OF A CRITICALITY SAFETY ASSESSMENT

4.4. A criticality safety assessment should be performed prior to the commencement of any new or modified activity involving fissile material. A criticality safety assessment should be carried out during the design, prior to and during construction, commissioning and operation of a facility or activity, and also prior to and during post-operational clean-out and decommissioning of the facility, transport[8] and storage of fissile material.

4.5. The objectives of the criticality safety assessment should be to determine whether an adequate level of safety has been achieved and to document the appropriate limits and conditions and safety measures required to prevent a criticality accident. The criticality safety assessment should demonstrate and document compliance with appropriate safety criteria and requirements.

4.6. The criticality safety assessment should include a criticality safety analysis, which should evaluate subcriticality for all operational states, i.e. for normal operation and anticipated operational occurrences and also during and after design basis accidents (or the equivalent). The criticality safety analysis should be used to identify hazards, both internal and external, and to determine the radiological consequences.

4.7. All margins adopted in setting safety limits should be justified and documented with sufficient detail and clarity to allow an independent review of the judgements made and the chosen margins. When appropriate, justification should be substantiated by reference to national regulations, to national and international standards or codes of practice, or to guidance notes that are compliant with these regulations and standards.

4.8. The criticality safety assessment and criticality safety analysis should be carried out by suitably qualified and experienced staff for criticality safety who are knowledgeable in all relevant aspects of criticality safety and are familiar with

[8] Specific transport requirements for criticality safety are included in the Transport Regulations [6].

the facility or activity concerned, and should also include input from operating personnel.

4.9. In the criticality safety assessment, consideration should be given to the possibility of inappropriate (and unexpected) responses by operating personnel to abnormal conditions. For example, operating personnel may respond to leaks of fissile solutions by catching the material in geometrically unfavourable equipment.

4.10. A systematic approach to the criticality safety assessment should be adopted as outlined below, including, but not limited to, the following steps:

— Definition of the fissile material, its constituents, chemical and physical forms, nuclear and chemical properties, etc.;
— Definition of the activity involving the fissile material;
— Methodology for conducting the criticality safety assessment;
— Verification and validation of the calculation methods and nuclear data;
— Performance of criticality safety analyses.

Determination of the fissile material

4.11. The characteristics of the fissile material (e.g. mass, volume, moderation, isotopic composition, enrichment, absorber depletion, degree of fission product production or in-growth and interaction, irradiation transmutation of fissile material, results of radioactive decay) should be determined, justified and documented. Estimates of the normal range of these characteristics, including conservative or bounding estimates of any anticipated variations in the characteristics, should be determined, justified and documented.

Determination of the activity involving the fissile material

4.12. The operational limits and conditions of the activity involving the fissile material should be determined. A description of the operations being assessed should be provided, which should include all relevant systems, processes and interfaces. To provide clarity and understanding, the description of the operations should be substantiated by relevant drawings, illustrations and/or graphics as well as operating procedures.

4.13. Any assumptions made about the operations and any associated systems, processes and interfaces that could impact the criticality safety assessment should be pointed out and justified. Such systems include, but are not limited to, administrative systems, for example non-destructive assay, systems for accounting for and control of materials, and control of combustible material.

4.14. If the criticality safety assessment is limited to a particular aspect of a facility or activity, the potential for interactions with other facilities, systems, processes or activities should be described.

Methodology for conducting the criticality safety assessment

4.15. The criticality safety assessment should identify all credible initiating events, i.e. all incidents that could lead to an anticipated operational occurrence or a design basis accident (or the equivalent). These should then be analysed and documented with account taken of possible aggravating events. The following should be considered when performing the analysis:

(a) All credible scenarios should be identified. A structured, disciplined and auditable approach should be used to identify credible initiating events. This approach should also include a review of lessons learned from previous incidents, including accidents, and also the results of any physical testing. Techniques available to identify credible scenarios include, but are not limited to, the following:
  - "What-if" or cause–consequence methods;
  - Qualitative event trees or fault trees;
  - Hazard and operability analysis (HAZOP);
  - Bayesian networks;
  - Failure modes and effects analysis (FMEA).

(b) Input into the criticality safety assessment should also be obtained from operating personnel and process specialists who are thoroughly familiar with the operations and initiating events that could credibly arise.

4.16. The criticality safety assessment should be performed by using a verified and validated methodology. The criticality safety assessment should provide a documented technical basis that demonstrates that subcriticality will be maintained in operational states and in design basis accidents (or the equivalent) in accordance with the double contingency principle or the single failure approach (see paras. 3.6–3.10). The criticality safety assessment should identify the safety measures required to ensure subcriticality, and should specify their safety functions, including requirements for reliability, redundancy, diversity and independence, and also any requirements for equipment qualification.

4.17. The criticality safety assessment should describe the methodology or methodologies used to establish the operational limits and conditions for the activity being evaluated. Methods that may be used for the establishment of these limits include, but are not limited to, the following:

— Reference to national and international standards;
— Reference to accepted handbooks;
— Reference to experiments, with appropriate adjustments of limits to ensure subcriticality when the uncertainties of parameters reported in the experiment documentation are considered;
— Use of validated calculation models and techniques.

4.18. The applicability of reference data to the system of fissile material being evaluated should be justified. When applicable, any nuclear cross-section data used should be specified (i.e. cross-section data sets and release versions), together with any cross-section processing codes that were used.

4.19. The overall safety assessment for the facility or activity should also be reviewed and used to identify and provide information on initiating events that should be considered as credible initiators of criticality accidents; for example, activation of sprinklers, rupture of a glovebox, buildup of material in ventilation filters, collapse of a rack, movement of fissile material during package transport and natural phenomena.

Verification and validation of the calculation methods and verification of nuclear data

4.20. Calculation methods such as computer codes and nuclear data used in the criticality safety analysis to calculate k_{eff} should be verified to ensure the accuracy of their derived values and to establish their limits of applicability, code bias and level of uncertainty. Verification is the process of determining whether a calculation method correctly implements the intended conceptual model or mathematical model [2].

4.21. Verification of the calculation methods should be performed periodically and should test the methods, mathematical or otherwise, used in the model and for computer codes, and should ensure that changes of the operating environment, i.e. operating system, software and hardware, do not adversely affect the execution of the codes.

4.22. The results of the calculations should be cross-checked by using independent nuclear data or different computer codes when available.

4.23. After verification of the calculation method is complete and prior to its use in performing a criticality safety analysis, it should be validated. Validation relates to the process of determining whether the overall calculation method adequately reflects the real system being modelled, and enables the quantification of any calculation/code bias and uncertainty, by comparing the predictions of the model with observations of the real system or with experimental data [2]. The calculation method should be validated against selected benchmarks that are representative of the system being evaluated. The relevance of benchmarks for use in performing validation should be determined from comparison of the characteristics of the benchmarks with the characteristics of the system of fissile material being evaluated.

4.24. In selecting benchmarks, consideration should be given to the following:

- Benchmarks should be used that have relatively small uncertainties compared with any arbitrary or administratively imposed safety margin.
- Benchmarks should be reviewed to ensure that their neutronic, geometric, physical and chemical characteristics encompass the characteristics of the system of fissile material to be evaluated. Examples of neutronic, geometric, physical or chemical characteristics that should be used for all materials include, but are not limited to, the following:
  - Molecular compounds, mixtures, alloys and their chemical formulae.
  - Isotopic proportions.
  - Material densities.
  - Relative proportions or concentrations of materials, such as the moderator to fissile nuclide ratio. Effective moderators are typically materials of low atomic mass. Common materials that can be effective moderators include water (i.e. hydrogen, deuterium and oxygen), beryllium, beryllium oxide and graphite (i.e. carbon). In the presence of poorly absorbing materials, such as magnesium oxide, oxygen can be an effective moderator.
  - Degree of homogeneity or heterogeneity and uniformity or non-uniformity, including gradients, of fissile and non-fissile materials (e.g. spent fuel rods, settling of fissile materials such as waste).
  - Geometric arrangements and compositions of fissile material relative to non-fissile material such as neutron reflectors and including materials contributing to the absorption of neutrons (e.g. cadmium, hafnium and gadolinium are commonly used, but other materials such as iron also act as slow neutron absorbers).

  - The sensitivity of the system to any simplification of geometry, for example elimination of pipes or ducts.
  - Neutron energy spectrum.
- Calculation methods should be reviewed periodically to determine whether relevant new benchmark data have become available for further validation.
- Calculation methods should also be re-verified following changes to the computer code system and periodically.

4.25. Once the calculation method has been verified and validated, it should be managed within a documented quality assurance programme as part of the overall management system. The quality assurance programme should ensure that a systematic approach is adopted in designing, coding, testing and documenting the calculation method.

Criticality safety analyses

4.26. If no benchmark experiments exist that encompass the system being evaluated (as may be the case, for example, for low moderated powders and waste), it may be possible to interpolate or extrapolate from other existing benchmark data to that system, by making use of trends in the bias. Where the extension from the benchmark data to the system at hand is large, the method should be supplemented by other calculation methods to provide a better estimate of the bias, and especially of its uncertainty in the extended area (or areas), and to demonstrate consistency of the computed results. An additional margin may be necessary to account for validation uncertainties in this case. Sensitivity and uncertainty analysis may be used to assess the applicability of benchmark problems to the system being analysed and to ensure an acceptable safety margin. An important aspect of this process is the quality of the basic nuclear data and uncertainties in the data.

4.27. When computer codes are used in the analysis, the type of computing platform, i.e. hardware and software, together with relevant information on the control of code configuration should be documented.

4.28. Quality control of the input data and the calculation results is an important part of criticality safety analysis. This includes, for example, verification that Monte Carlo calculations have properly converged.

5. CRITICALITY SAFETY FOR SPECIFIC PRACTICES

GENERAL

5.1. Criticality safety concerns many areas of the nuclear fuel cycle, for example, enrichment, fuel fabrication, fuel handling, transport and storage, reprocessing of spent fuel, and processing of radioactive waste and its disposal.

5.2. Fuel cycle facilities may be split into two groups: facilities for which a criticality hazard is not credible, for example, facilities for mining, processing and conversion of natural uranium; and facilities for which the criticality hazards may be credible, for example, enrichment facilities, uranium and mixed oxide fuel fabrication facilities, fresh fuel storage facilities, spent fuel storage facilities, reprocessing facilities, waste processing facilities and disposal facilities. Facilities in this second group should be designed and operated in a manner that ensures subcriticality in operational states and in design basis accidents (or the equivalent).

5.3. The scope and level of detail to be considered for the criticality safety assessment can be influenced by the type of facility and its operation.[9]

SPECIFIC PRACTICES

5.4. This section provides guidance on specific issues that should be taken into account to ensure criticality safety in each of the main areas of the nuclear fuel cycle.

Conversion and uranium enrichment

5.5. In conversion facilities, typically natural uranium ore concentrate is purified and converted to the chemical forms required for the manufacture of nuclear fuel — that is, uranium metal, uranium oxides, uranium tetrafluoride or uranium hexafluoride — in preparation for enrichment.

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[9] Experimental facilities tend to have lower amounts of fissile material and flexible working procedures, and so human errors may be more prevalent. Fuel production facilities and fuel utilization facilities often have large amounts of fissile material and high production demands and use well defined processes, which may depend on both human performance and the proper functioning of process equipment.

5.6. Because of the isotopic composition of natural uranium (i.e. ~0.7 at.% ^{235}U) in the homogeneous processes of conversion, no criticality safety hazards are encountered in the conversion of natural uranium.

5.7. Uranium enrichment facilities have the potential for criticality accidents; as such, criticality safety measures, as described in the previous sections, should be applied. Further guidance on criticality safety for conversion facilities and uranium enrichment facilities is provided in Ref. [19].

5.8. Conversion facilities can also be used for the conversion of enriched or reprocessed uranium, which has a higher enrichment than natural uranium and under certain conditions can achieve criticality.

Fuel fabrication

5.9. Fuel fabrication facilities process powders, solutions, gases and metals of uranium and/or plutonium that may have different content in either fissile material (e.g. in ^{235}U enrichment) or in absorber material (e.g. gadolinium).

5.10. Such facilities can be characterized by the ^{235}U content, for uranium fuel fabrication, or, for facilities mixing powders of uranium and plutonium (i.e. mixed oxide fuel fabrication facilities), by the isotopic composition of the plutonium in the mixture (principally ^{239}Pu, ^{240}Pu and ^{241}Pu), by the fissile fraction of plutonium (i.e. ($^{239}Pu + ^{241}Pu$)/(total Pu) as a measure of plutonium quality), by the ^{235}U content in the uranium and by the ratio of PuO_2 to the total amount of oxides (i.e. the PuO_2 concentration).

5.11. A typical control parameter used in fuel fabrication is moderation. Where moderator control is employed, the following should be considered in the criticality safety assessment:

— Buildings containing fissile material should be protected from inundations of water from internal sources (e.g. from firefighting systems, leaks or failure of pipework) or ingress of water from external sources (e.g. rainfall and flooding).
— In order to prevent water leakage and unexpected changes in conditions of criticality safety control, air rather than water should be used for heating and cooling in facilities for fissile material storage or processing. If this is not practicable, measures to limit the amount of water that can leak should be considered.

— For firefighting, procedures should be provided to ensure the safe use of extinguishants (e.g. control of materials and densities of materials to be used, such as CO_2, water, foam, dry powders and sand).
— The storage of fissile material should be designed to prevent its inadvertent rearrangement in events such as firefighting with high pressure water jets.
— Powders may absorb moisture. The maximum powder moisture content that could be reached from contact with humid air should be taken into account in the criticality safety analysis. If necessary, inert and dry glovebox atmospheres should be maintained to ensure safety and quality of packaged powders. Furthermore, the application of hydrogenated materials — for example, materials used as lubricants in the manufacture of pellets — should be applied with safety factors consistent with the double contingency principle. Criticality safety analyses for these types of material may be difficult to carry out on account of the limited number of experimental benchmarks that can be used in validating computer codes. Care should therefore be taken in the extrapolation of available benchmark data for these applications. Guidance on such situations is provided in para. 4.26.
— The introduction and removal of moderating material — for example, equipment or cleaning material, within moderation controlled environments, such as in gloveboxes, packaging areas or criticality controlled areas — should be monitored (e.g. by weighing moderating material) and controlled to avoid unsafe accumulations of moderated fissile material.

5.12. Buildings and equipment (e.g. gloveboxes) should be designed to ensure the safe retention of fissile material in the event of an earthquake or other external event. Similarly, multiple separated systems relying on distance or neutron absorbers should be suitably fixed in place to ensure that an appropriate distance is maintained between them and to ensure the integrity of the neutron shielding.

5.13. The generation and collection of waste throughout the fuel fabrication process should be identified and evaluated to ensure that the quantities of fissile nuclides in any waste remain within specified limits.

Material cross-over

5.14. Production operations may be intermittent. To ensure adequate control during and between fuel production campaigns, the fundamental fissile material parameters that should be monitored include the mass per container, including the identification of the container (e.g. in the case of manipulated powders or pellets) and/or the identification of fuel rods and fuel rod assemblies. This identification should ensure that the movement and storage of these items is traceable and that the containers and work stations remain subcritical.

Machining, grinding and cutting

5.15. The different steps in the manufacturing process may create accumulations of fissile material that may or may not be readily visible. A method for periodic cleaning and for accounting for and control of fissile material at the facility and at workstations should be defined that allows the identification and recovery of the fissile material. For credible accumulations of fissile material that are not readily visible, a method for estimating and tracking these residues should be developed to ensure that the workstations and ancillary systems remain subcritical. Such methods could be based on quantification using spectral measurements, such as gamma spectrometry, or using a structured evaluation that estimates the volume, with account taken of the contents and the densities of the material. These methods should take into account operating experience, previous interventions and recording of information. Consideration should be given to the possibility of entrainment of fissile material in process equipment or ancillary systems due to the velocity of the transport medium. Periodic inspection of equipment in which fissile material could accumulate may be necessary.

5.16. Machining, grinding and cutting should ideally be undertaken without the use of coolants. However, it might not be possible to eliminate coolants entirely from the process or to replace them with non-moderating coolants. The collection of accumulated residues and/or coolant is likely to necessitate control of other parameters, in particular control of favourable geometry.

5.17. Further guidance on criticality safety for uranium fuel fabrication facilities and uranium and plutonium mixed oxide fuel fabrication facilities is provided in Refs [20, 21], respectively.

Handling and storage of fresh fuel

5.18. The storage area for fresh fuel should meet the requirements specified in the criticality safety assessment and should be such that the stored fresh fuel will remain subcritical at all times, even in the event of credible internal or external flooding or any other event considered credible in the design safety assessment. Engineered and/or administrative measures should be taken to ensure that fuel is handled and stored only in authorized locations in order to prevent a critical configuration from occurring. It should be verified that the fuel's enrichment level complies with the criticality limitations of the storage area.

5.19. For wet and dry storage systems that use fixed solid neutron absorbers, a surveillance programme should be put in place to ensure that the absorbers are installed, and, if degradation of the absorbers is predicted, to monitor their effectiveness and to ensure that they have not become displaced.

5.20. Drains in dry storage areas for fresh fuel should be properly kept clear for the efficient removal of any water that may enter, so that such drains cannot constitute a possible cause of flooding.

5.21. Fire risks in the fuel storage area should be minimized by preventing the accumulation of combustible material in the storage area. Instructions for firefighting and firefighting equipment suitable for use in the event of a fire involving fuel should be readily available.

5.22. Further guidance for ensuring criticality safety in the handling and storage of fresh fuel at nuclear power plants is provided in Ref. [22].

Spent fuel operations (prior to reprocessing, long term storage or disposal)

5.23. Spent fuel operations are generally characterized by a need to handle large throughputs and to retain large inventories of fissile material in the facility. In contrast to criticality safety assessments for operations earlier in the fuel cycle, credit may now be taken for the effects of fuel irradiation. In determining the criticality safety measures, the following factors should be noted:

- At this stage in the fuel cycle, the material is highly radioactive and will generally need to be handled remotely in shielded facilities or shielded packages.
- Much of the material will need cooling (e.g. in spent fuel ponds) for several years following its removal from the reactor.
- The isotopic, physical and chemical composition of the fissile material will have changed during irradiation in the reactor and subsequent radioactive decay.
- The fuel assemblies will have undergone physical changes during irradiation.

Handling accidents

5.24. The need for remote handling and the presence of heavy shielding necessary for radiation protection necessitates consideration of a set of design basis accidents in which there is a potential for damage to fuel elements (e.g. leading to a loss of geometry control) or damage to other structures (e.g. leading to a loss of fixed absorbers). Safety measures associated with prevention of such events should include robust design of supporting structures, engineered or administrative limits on the range of movement of fuel elements and other objects in the vicinity of fuel elements, and regular testing and/or maintenance of handling equipment.

Maintaining fuel geometry

5.25. The geometry of spent fuel has to be maintained during storage and handling operations to ensure subcriticality, and this should be assessed for all operational states and for design basis accidents (or the equivalent). This recommendation should also apply to the handling and storage of any degraded fuel (e.g. fuel with failed cladding) that has been stored in canisters. The potential for dispersion of fuel due to degradation of fuel cladding or due to failures of fuel cladding or fuel assembly structures should be assessed and included in the criticality safety assessment. Control over fuel geometry may also be affected by corrosion of structural materials and by embrittlement and creep of the fuel as a result of irradiation.

5.26. For stored fuel there is sometimes a need to remove or repair fuel pins or rods, which can change the moderation ratio of the fuel element and thus potentially increase its reactivity. Criticality safety assessments should be performed to consider the impact of such operations.

Loss of soluble or fixed absorbers

5.27. In some storage ponds for spent fuel one criticality safety measure may be the inclusion of a soluble neutron absorber (e.g. boron) in the storage pond water. In this case, the potential for accidental dilution of the soluble neutron absorber by unplanned additions of unpoisoned water should be considered in the criticality safety assessment. Further guidance on safety of spent nuclear fuel storage is provided in Ref. [23].

5.28. In some facilities, the presence of high radiation fields can lead to detrimental changes in the physical and chemical form of the fixed absorber materials used as a criticality safety measure. For example, Boraflex sheets (a material composed of boron carbide, silica and polydimethyl siloxane polymer) used in some storage ponds for pressurized water reactor and boiling water reactor spent fuel have been found to shrink as a result of exposure to radiation, creating gaps in the material and reducing the effectiveness of the neutron absorbers. For certain accident scenarios, such as a drop of a fuel assembly, limited credit for soluble neutron absorbers may be allowed.

5.29. The potential for degradation of criticality safety measures involving soluble or fixed absorbers should be included in the criticality safety assessment. Safety measures associated with events of this type may include restrictions on the volume of fresh water available to cause dilution, periodic sampling of levels of soluble neutron absorbers and periodic inspection and/or surveillance of fixed absorber materials. Sampling of soluble boron in the pond water should be carried out in such a manner as to verify that the level of boron is homogeneous across the pond. Where soluble boron is used as a criticality safety measure, operational controls should be implemented to maintain water conditions in accordance with specified values of temperature, pH, redox, activity, and other applicable chemical and physical characteristics, so as to prevent boron dilution. Additionally, appropriate measures to ensure boron mixing by, for example, thermal convection caused by decay heat in the storage pond should be taken into account.

Changes in storage arrangements within a spent fuel facility

5.30. Spent fuel is often stored in pond facilities for several years following its removal from the reactor core. During that time, changes may need to be carried out to the storage configuration. For example, in some nuclear power plants it has been found necessary to reposition the spent fuel in the storage pond, that is, to 're-rack' the spent fuel, in order to increase the storage capacity of the pond. Increasing the density of fuel storage may have significant effects on the level of neutron absorbers necessary to ensure subcriticality. A reduction in the amount of interstitial water between spent fuel assemblies in a storage rack may also cause a reduction in the effectiveness of fixed absorbers (see Ref. [11]). These effects should be taken into account in the criticality safety assessment for such modifications.

5.31. Consideration should also be given to the potential for changes in the storage arrangement due to accidents involving fuel movements (e.g. a flask being dropped onto the storage array).

Misloading accidents

5.32. For spent fuel facilities on a single reactor site where the facility may contain more than one type of fuel element and/or have storage areas with different requirements for acceptable storage within the same facility, the possibility of misloading of a fuel element into a wrong storage location should also be considered in the criticality safety assessment.

5.33. Some spent fuel storage facilities accept material from a range of reactor sites. To accommodate the different types of fuel, the facility is usually divided into areas with distinct design features and requiring different degrees of criticality safety measures. In these situations, the potential for misloading of spent fuel into the wrong storage location should be considered in the criticality safety assessment. Safety measures associated with events of this type should include engineered features to preclude misloading (e.g. based on the physical differences in fuel assembly design); alternatively, administrative controls and verification of the fuel assembly markings should be applied.

Taking account of changes in spent fuel composition as a result of irradiation

5.34. Usually, in criticality safety assessments for operations involving spent fuel, the spent fuel is conservatively assumed to have the same composition as fresh fuel. Alternatively, it may be possible to take credit for reductions in k_{eff} as a result of changes in the spent fuel composition due to irradiation. This more realistic approach is commonly known as 'burnup credit', and can be applied instead of the 'peak k_{eff} approach' (i.e. peak reactivity achieved during irradiation), for which an assessment is required whenever k_{eff} could increase due to irradiation. The application of burnup credit is covered in paras. 5.37–5.40.

5.35. Taking credit for the burnup of individual fuel assemblies will increase the potential for misloading accidents of these fuel assemblies. Consequently, protection against misloading accidents, mentioned in para. 5.33, should form one of the key considerations in the criticality safety assessment for spent fuel operations.

5.36. Further guidance on criticality safety at spent fuel storage facilities is provided in Ref. [23], and guidance on ensuring subcriticality during the handling and storage of spent fuel at nuclear power plants is provided in Ref. [22].

Burnup credit

5.37. The changes in the composition of spent fuel during irradiation will eventually result in a reduction in k_{eff}. The application of burnup credit in the criticality safety assessment may present several advantages, as follows:

— Increased flexibility of operations (e.g. acceptance of a wider range of spent fuel types);

— Verified properties of the sufficiently irradiated fuel, possibly resulting in an inherently subcritical material;
— Increased loading densities in spent fuel storage areas.

5.38. The application of burnup credit may significantly increase the complexity, uncertainty and difficulty in demonstrating an adequate margin of subcriticality. The criticality safety assessment and supporting analysis should reliably determine the k_{eff} for the system, by taking into account the changes to the fuel composition during irradiation and changes due to radioactive decay after irradiation. Spatial variations in the spent fuel composition should be taken into account in calculating k_{eff} for the relevant configuration of the spent fuel. The increase in complexity presents several challenges for the criticality safety assessment. In a criticality safety assessment carried out on the basis of burnup credit, the following should be addressed:

— Validation of the calculation methods used to predict the spent fuel composition using the guidelines presented in paras. 4.20–4.28.
— Validation of the calculation methods used to predict k_{eff} for the spent fuel configurations using the guidelines presented in paras. 4.20–4.28 (note that calculations for spent fuel may now include many more isotopes than are present for fresh fuel calculations).
— Specification and demonstration of a suitably conservative representation of the irradiation conditions, for example, the amount of burnup, the presence of soluble absorbers, the presence of burnable poisons, coolant temperature and density, fuel temperature, power history and cooling time. For fuel assemblies with burnable poisons, the criticality safety assessment should take account of the depletion of burnable poisons and should consider the possibility that the most reactive condition may not be for the fresh fuel.
— Justification of any modelling assumptions, for example, the representation of smoothly varying changes in composition (i.e. as a result of radial and axial variations in burnup) as discrete zones of materials in the calculation model.
— Justification of the inclusion or exclusion of specific isotopes such as fission products, of the in-growth of fissile nuclides and of the loss of neutron absorbers.

5.39. Generally, the operational limits and conditions for ensuring subcriticality in spent fuel storage on the basis of an assessment of burnup credit are based on a conservative combination of the fuel’s initial enrichment and the burnup history (in which the amount of burnup is an important parameter). This approach is commonly known as the ‘safe loading curve’ approach[10] (see Ref. [24]). In such circumstances, the criticality safety assessment should determine the operational measures necessary to ensure compliance with this curve during operation; for example, the measurements that are necessary to verify the initial enrichment and burnup. The criticality safety assessment should also consider the potential for misloading of fuel from outside the limits and conditions specified in the safe loading curve.

5.40. Further information and guidance on the application of burnup credit is available in Ref. [24].

Reprocessing

5.41. Spent fuel reprocessing involves operations to recover the uranium and plutonium from waste products (e.g. fission products, minor actinides in fuel assemblies) after the fuel has been irradiated.

5.42. Reprocessing operations can also include the treatment of fresh fuel or low burnup fuel. Consideration should be given to specific criticality safety measures for controlling the dissolution phase, since fresh fuel or low burnup fuel can be more difficult to dissolve than spent fuel. In addition, uranium and plutonium mixed oxide fuels tend to be more difficult to dissolve than UO_2 fuels.

5.43. The following issues are of particular importance and should be considered for criticality safety in reprocessing facilities:

— The wide range of forms of fissile material involved in reprocessing, potentially making the use of multiple control parameters necessary.
— The mobility of solutions containing fissile nuclides and the potential for their misdirection.
— The need for chemistry control in order to prevent:
  - Precipitation, colloid formation and increases of concentration in solution;
  - Unplanned separation and extraction of fissile nuclides.

[10] The safe loading curve joins pairs of values of initial enrichment and burnup that have been demonstrated to be safely subcritical.

— The possibility for hold-up and accumulations of fissile material owing to incomplete dissolution of materials, accumulation of fissile material in process equipment (e.g. conditioning and vacuum vessels) or ventilation systems, or chronic leaks (including leaks of liquors onto hot surfaces).
— The need for moderator control during furnace operations causing condensation in powders.

Wide range of forms of fissile material

5.44. The forms of fissile material involved in reprocessing are diverse and could include:

— Fuel assemblies;
— Fuel rods;
— Sheared fuel;
— Fines or swarf;
— Solutions of uranium and/or plutonium;
— Oxides of uranium or plutonium, or mixed oxides of uranium and plutonium;
— Plutonium oxalate or mixed uranium oxalate and plutonium oxalate;
— Uranium or plutonium metals;
— Other compositions (e.g. materials containing minor actinides).

Mobility of solutions and the potential for their misdirection

5.45. Many fissile materials are in a liquid form and, because of the existence of many connections between items of equipment, the possibility for misdirection of the fissile material should be considered in the criticality safety assessment. The criticality safety assessment should be such as to identify the safety measures necessary to avoid this possibility; for example, the use of overflow lines and siphon breaks. Misdirection can lead to uncontrolled chemical phenomena (e.g. concentration or precipitation of plutonium or dilution of neutron absorbers in solution) or misdirection of fissile material to systems of unfavourable geometry.

5.46. The criticality safety assessment should give particular consideration to the impact of interruptions to normal operations (e.g. owing to corrective maintenance work), which have the potential to create unplanned changes to the flow of fissile material. The possibility that external connections could be added in an ad hoc manner to approved pipework and vessels should also be considered.

5.47. Operational experience has shown that misdirections of fissile material can occur owing to unexpected pressure differentials in the system (e.g. due to sparging operations during cleanup). The criticality safety assessment should include consideration of these effects.

5.48. In any facility employing chemical processes, leaks are a constant hazard. Leaks may occur as a result of faulty welds, joints, seals, etc. Ageing of the facility may also contribute to leaks through corrosion, vibration and erosion effects. In general, drains, drip trays, recovery pans and vessels of favourable geometry should be provided to ensure that fissile materials that could leak will be safely contained. Consideration should also be given to the provision of monitored sumps of favourable geometry for the detection of leaks. It should not be assumed that leaks will be detected in sumps, as they may evaporate and form solid accumulations over time. Consideration should be given to carrying out inspections to prevent any long term buildup of fissile material, especially in areas where personnel are not present (see Ref. [25]).

Maintaining chemistry control

5.49. Particular consideration should be given to chemistry control during reprocessing. Some of the most important process parameters that could affect criticality include: acidity, concentration and/or density, purity of additives, temperature, contact area (i.e. during mixing of materials), flow rates and quantities of reagents. Loss of control of any of these process parameters could lead to a range of unfavourable changes, for example:

— Increased concentration of fissile nuclides (by precipitation, colloid formation or extraction);
— Unplanned separation of plutonium and uranium;
— Carry-over of uranium and plutonium into the raffinate stream[11];
— Incomplete dissolution of fissile material.

[11] A raffinate stream is the liquid stream that remains after the solutes from the original liquid are removed through contact with an immiscible liquid.

5.50. The potential for such changes to affect criticality safety should be considered in the criticality safety assessment. The selection of suitable safety measures will vary depending on the details of the process and may include:

— Monitoring of the concentration of fissile nuclides (e.g. in-line neutron monitoring, chemical sampling);
— Monitoring of flow rates and temperatures;
— Testing of acidity and quality control of additives.

5.51. The effectiveness and reliability of these safety measures should be considered as part of the criticality safety assessment. A process flow sheet[12] helps in determining the response and sensitivity of the facility to changes in the process parameters, control parameters or safety parameters. This information should be used to ensure that the safety measures are able to respond quickly enough to detect, correct or terminate unsafe conditions in order to prevent a criticality accident. Time lags in process control should be considered in maintaining chemistry control.

5.52. Particular consideration should be given to the control of restart operations following interruptions to normal operating conditions. Some changes in chemical characteristics may occur during any period of shutdown (e.g. changes in the valence state of plutonium leading to reduction in acidity, which could result in formation of colloids), and these effects should be accounted for in re-establishing a safe operating state.

Hold-up and accumulation of material

5.53. In a reprocessing facility there are many sites where material may credibly accumulate and many mechanisms (both physical and chemical) by which fissile material could be diverted from the intended process flow. In addition, owing to the high throughput of material, these losses may be hard to detect solely on the basis of material accounting.

5.54. The start of the reprocessing operation usually involves mechanical operations, such as shearing and/or sawing of the fuel to facilitate its dissolution. Such operations are usually conducted in a dry environment, and so the risk of criticality will often be lower than in a wet environment. However, particular consideration should be given to the possibility of accumulations of fissile nuclides

[12] A process flow sheet depicts a chemical or operational engineering process and describes the materials, rates of flow, volumes, concentrations, enrichments and masses necessary to attain intended results or products.

in swarf, fines and other debris becoming moderated through entrainment during subsequent parts of the process with wet chemistry conditions. For this reason, regular inspections and housekeeping should be carried out. See also para. 3.21.

5.55. The next mechanism by which accumulation could occur is dissolution. Incomplete dissolution may occur as a result of a range of fault conditions; for example, low acidity, low temperature, short dissolution time, overloading of fuel and low acid volume. Criticality safety measures to be considered should include, but are not limited to, the following:

— Pre-dissolution control on the conditioning of acids;
— Monitoring of temperature and dissolution time;
— Post-dissolution monitoring for gamma radiation (e.g. to detect residual undissolved fuel in hulls);
— Controls on material balance;
— Density measurements.

5.56. The effectiveness, reliability and accuracy of these measures should be considered as part of the criticality safety assessment. In particular, the possibility that sampling may not be representative should be considered. Similarly, the potential for settling of fines in the bottom of vessels throughout subsequent processes should also be considered. In these cases, neutron monitoring of the lower parts of vessels and periodic emptying and flushing of vessels may be necessary.

5.57. The potential for fissile nuclides to remain attached to cladding following dissolution should be considered. For example, in some cases residual plutonium can bond to the inside surface of cladding as a result of polymerization.

5.58. Recommendations to trap leaks in equipment with favourable geometry and to provide monitored sumps to detect such leaks are provided in para. 5.48. However, it is possible that very slow leaks or leaks onto hot surfaces, where the material crystallizes before reaching the measuring point, may occur. These types of loss of material can be very difficult to detect. Safety measures for events of this type may include, but are not limited to, periodic inspections of the areas below vessels and pipework, and the review of operational records to identify such chronic loss of material. The criticality safety assessment should consider the timescales over which unsafe accumulations of fissile material could occur so that suitable inspection frequencies can be determined.

Moderator control in furnace operations

5.59. For most furnace operations carried out as part of the conversion process (e.g. precipitation, drying, oxidation), it may be practicable to use vessels with favourable geometry. It may also be practicable to ensure that the internal volume of the furnace has a favourable geometry. However, the oxide powders produced in subsequent operations may require moderation control to allow feasible storage arrangements. The conversion process should not lead to the production of material with excessive moderator content. The criticality safety assessment should therefore consider mechanisms by which the moderator might be carried over (e.g. incomplete drying) or introduced (e.g. condensation during cooling).[13]

Waste management and decommissioning

5.60. The collection and storage of unconditioned radioactive waste before its processing should be made subject to the same considerations in the criticality safety assessment as the processes from which the waste was generated. Additionally, special considerations may be necessary if such waste streams are mixed with other radioactive waste streams of different origin, which is frequently the case in research centres. Although the inventory of fissile material may generally be small, significant accumulations of such material may occur in the subsequent waste collection and waste processing procedures.

5.61. Waste management operations cover a very wide range of facilities, processes and materials. The following recommendations apply to packaging, interim storage and disposal operations. The recommendations are intended to cover the long term management and disposal of waste arising from operations involving fissile material (e.g. 'legacy waste')[14]. Waste management operations may be shielded or unshielded and may involve remote or manual handling operations. Generally, waste management operations, particularly in a disposal facility, involve large inventories of fissile material from a wide range of sources. In the case of legacy waste, there may also be considerable variation in and uncertainty about the material properties (e.g. in the physical form and chemical composition of the non-fissile and fissile components of the waste material).

[13] A Safety Guide on the safety of reprocessing facilities is in preparation.

[14] Legacy waste is radioactive waste that may contain fissile material that has remained from historic fissile material facilities and past activities that (a) were never subject to regulatory control or (b) were subject to regulatory control but not in accordance with the requirements of the International Basic Safety Standards [26].

In contrast, decommissioning operations typically involve small inventories of fissile material.

5.62. Waste is commonly wrapped in materials that can act as more effective moderators than water — for example, polyethylene or polyvinyl chloride — and this should be taken into account in the criticality safety assessment.

5.63. Criticality safety for waste operations should be based on the application of appropriate limits on the waste package contents. Criticality safety measures may include the design of the packages and the arrangements for handling, storage and disposal of many packages within a single facility. Where practicable, package limits should be applicable to all operations along the waste management route, including operations at a subsequent disposal facility, so that subsequent repacking, with its associated hazards, may be avoided. The future transport of the waste packages should also be considered to avoid potential repackaging of the waste to meet the criticality safety requirements and other transport requirements (see Ref. [6]).

5.64. For the storage of waste containing fissile nuclides, consideration should be given to the possible consequences of a change in the configuration of the waste, the introduction of a moderator or the removal of material (such as neutron absorbers) as a consequence of an internal or external event (e.g. movement of the waste, precipitation of solid phases from liquid waste, loss of confinement of the waste, a seismic event) [27].

5.65. Assessment of criticality safety for the period after closure for a disposal facility presents particular challenges. Among these are the very long timescales that need to be considered. Following closure of a disposal facility, engineered barriers provided by the package design and the form of the waste will tend to degrade, allowing the possibility of separation, relocation and accumulation of fissile nuclides (as well as the possible removal of absorbers from fissile material). In addition, a previously dry environment may be replaced by a water saturated environment. Consideration of the consequences of criticality after closure of a disposal facility will differ from that for, for example, fuel stores or reprocessing plants, where a criticality accident may have immediate recognizable effects. In the case of a disposal facility, disruption of protective barriers and effects on transport mechanisms of radionuclides are likely to be more significant than the immediate effects of direct radiation from a criticality event, because the radiation would be shielded by the surrounding host rock formation and/or backfill materials.

5.66. In the criticality safety assessment of waste management operations, consideration should be given to the specific details of the individual facilities and processes involved. Consideration should be given to the following particular characteristics of waste management operations with respect to criticality safety:

- — The radiological, physical and chemical properties of the waste as parameters for waste classification;
- — Variation and uncertainty in the form and composition of the waste;
- — The need to address the degradation of engineered barriers and the evolution of waste packages after emplacement over long timescales;
- — Criticality safety requirements and other transport requirements to facilitate future transport of the waste.

Variation and uncertainty in waste forms

5.67. Variation and uncertainty in waste forms is a particular challenge for some types of legacy waste for which the accuracy and completeness of historical records may be limited. Therefore, criticality safety assessments for legacy waste to be disposed of should be performed in a comprehensive and detailed manner. If conservative deterministic methods are applied, in which bounding values are applied to each material parameter, the resulting limits on packages may prove to be very restrictive. This might then lead to an increase in the number of packages produced, resulting in more handling and transport moves and higher storage volumes, each of which is associated with a degree of risk (e.g. radiation doses to operating personnel, road or rail accidents, construction accidents). Therefore particular consideration should be given to optimization of the margins to be used in the criticality safety assessment. If an integrated risk approach is used, consideration should be given to the balance of risk between the criticality hazard and the other hazards.

Degradation of engineered barriers over long timescales

5.68. The fissile inventory of spent fuel mainly consists of the remaining ^{235}U and the plutonium isotopes ^{239}Pu and ^{241}Pu. Over the very long timescales considered in post-closure criticality safety assessments, some reduction and change in the fissile inventory of the nuclear waste will occur owing to radioactive decay. However, such assessments should also take account of credible degradation of the engineered barriers of waste packages, with consequential relocation and accumulation of fissile and non-fissile components.

Decommissioning

5.69. To account for criticality safety during decommissioning, a graded approach should be applied to consider the type of facility and therefore the fissile inventory present. Generally, this Safety Guide should be applied as long as fissile material in relevant amounts is handled, so that criticality safety needs to be considered. Additional guidance and recommendations on the decommissioning of nuclear fuel cycle facilities are given in Ref. [28].

5.70. Before beginning decommissioning operations, accumulations of fissile materials should be identified in order to assess the possibilities for recovery of these materials. Consideration should be given to the potential for sites with unaccounted for accumulations of fissile material (e.g. active lathe sumps). A method for estimating and tracking accumulations of fissile material that are not readily visible should be developed to ensure that workstations remain subcritical during decommissioning operations. This should take into account operating experience, any earlier interventions to remove fissile material, recorded information of physical inventory differences, process losses and measured hold-up. The estimation of such accumulations of fissile material could be based on quantification using spectral measurements (e.g. gamma spectrometry) or by a structured evaluation of the volume of material, with account taken of the contents and densities of the material.

5.71. The approach used to ensure subcriticality in decommissioning may be similar to that used for research laboratory facilities (see paras. 5.78–5.84), where setting a low limit on allowable masses of fissile material provides the basis for allowing other parameters (e.g. geometry, concentration, moderation, absorbers) to take any value. In accordance with the requirements on decommissioning of facilities established in Ref. [5], an initial decommissioning plan for a facility is required to be developed during facility design and construction, and it should be maintained during facility operation. When a facility approaches shutdown, a final decommissioning plan is required to be prepared. In facilities handling significant amounts of fissile material, consistent with the graded approach, all decommissioning plans should be supported by criticality safety assessments, in order to ensure that practices carried out in the operating lifetime of the facility do not create avoidable problems later in decommissioning.

Transport of fissile material

5.72. Movement or transfer of radioactive material within a licensed site should be considered to be other on-site operations. Requirements on the safe transport of radioactive material off the site (i.e. in the public domain), including consideration of the criticality hazard, are established in Ref. [6], and recommendations are provided in Refs [10, 16, 29].

5.73. The requirements for criticality safety assessment for off-site transport differ considerably from the requirements for criticality safety assessments for facilities and other activities. Principally owing to the potential for closer contact with the public, the criticality safety assessment for transport is more stringent and is required to be conducted solely on the basis of a deterministic approach.

5.74. The state of a transport package before, during and after the tests specified in Ref. [6] (e.g. water spray and immersion, drop and thermal tests) provides the basis for the criticality safety assessment and analysis of the design. Additional safety assessment is required for the actual transport operation (see para. 5.76).

5.75. Although the regulations established in Ref. [6] provide a prescriptive system for assessment, they are not entirely free of engineering judgement. Often, especially for determining the behaviour of a package under accident conditions, considerable engineering expertise is required to interpret test results and to incorporate these into a criticality safety assessment. The criticality safety assessment for transport should therefore be carried out only by persons with suitable knowledge and experience of the transport requirements.

5.76. The assessment for the package design referred to in para. 5.75 provides a safety basis, but the final safety is ensured by confirming that the real transport conditions comply with the requirements set forth in the package design approval. Reference [6] states that:

> "*Fissile material* shall be transported so as to:
>
> (a) Maintain subcriticality during routine, normal and accident conditions of transport; in particular, the following contingencies shall be considered:
>
> (i) Leakage of water into or out of *packages*;
>
> (ii) Loss of efficiency of built-in neutron absorbers or moderators;
>
> (iii) Rearrangement of the contents either within the *package* or as a result of loss from the *package*;
>
> (iv) Reduction of spaces within or between *packages*;

(v) *Packages* becoming immersed in water or buried in snow;
(vi) Temperature changes."[15]

5.77. Hazards to be considered for on-site transfer should include, but are not limited to, the following:

— Provisions to ensure that packages of fissile material remain reliably fixed to vehicles;
— Vehicular speeds and road conditions;
— Potential for transport accidents (e.g. collisions with other vehicles);
— Releases of fissile material out of the confinement system (e.g. into storm drains);
— Interaction with other fissile material that may come close in transit.

Research and development laboratories

5.78. Research and development laboratories are dedicated to the research and development of systems and products that utilize fissile material. These facilities are generally characterized by the need for high flexibility in their operations and processes, but typically have low inventories of fissile material and can include hands-on and/or remote handling operations. The general assumption of low inventories of fissile material may not be applicable for laboratories that are used for fuel examinations or experiments, or their respective waste treatment facilities.

Access to a wide range of fissile and non-fissile materials

5.79. Owing to the research and development nature of laboratory operations, laboratories can use a wide range of fissile and non-fissile materials and separated isotopes, typically including low, intermediate and high enriched uranium, plutonium that is high in ^{241}Pu content (e.g. >15 wt%), plutonium that is low in ^{240}Pu content (e.g. <5 wt%), graphite, boron, gadolinium, hafnium, heavy water, zirconium, pore former[16], aluminium and various metal alloys. Examples of special fissile and non-fissile materials sometimes encountered include ^{233}U,

[15] In the context of the Transport Regulations, fissile material includes only ^{233}U, ^{235}U, ^{239}Pu and ^{241}Pu subject to a number of exceptions [6].

[16] Pore former is an additive that is used in the blending of nuclear fuel oxides for the purpose of creating randomly distributed closed pores in the blended oxide prior to pelletizing and sintering for the purpose of producing pre-sintered fuel pellets that are free of flaws and have improved strength. Pore former has a neutron moderating effect.

^{237}Np, ^{242}Pu, ^{241}Am, ^{242m}Am, enriched boron (e.g. ^{10}B) and enriched lithium (e.g. ^{6}Li). These materials have diverse energy dependent nuclear reaction properties (e.g. neutron fission, neutron absorption, neutron scattering, gamma neutron reaction and gamma fission properties), which can result in non-linear and seemingly incongruent variations of critical mass. Such materials should therefore receive specific consideration in the criticality safety assessments and analyses. Useful references for determining the properties of some of these materials include Refs [30, 31].

Overlap of operating areas and interfaces between materials

5.80. Owing to the significant flexibility in operations, criticality safety measures on the location and movement of fissile material within the laboratory are important in ensuring subcriticality. Any associated limits and conditions should be specified in the criticality safety assessment. The criticality safety assessment should define criticality controlled areas and should specify their limiting content and boundaries.

5.81. Particular consideration should therefore be given to the potential for an overlap of these controlled areas and interfaces between materials in such overlaps. The management system should ensure that the combining of material from another criticality controlled area or the movement of moderators into an area is restricted and such movement is subjected to a criticality safety assessment before it is carried out.

Inadvertent consolidation of fissile material

5.82. Frequently, activities in a specific laboratory area may be interrupted to perform a different operation. In such cases, laboratory operating personnel should exercise particular care to avoid any unanalysed or unauthorized accumulation of fissile material that could occur as a result of housekeeping or consolidation of materials, prior to admitting more fissile and non-fissile materials into the laboratory area.

Specialized education and training of operating personnel

5.83. Because of the diverse characteristics of materials and laboratory operations, laboratory operating personnel and management should be appropriately educated and trained about the seemingly anomalous characteristics of typical and special fissile and non-fissile materials under different degrees of neutron moderation.

Additional information

5.84. Particular challenges will be encountered in determining the critical mass of unusual materials, such as some of those listed in para. 5.79 and other exotic trans-plutonium materials (e.g. ^{243}Cm, ^{245}Cm), because frequently there are no criticality experiment benchmarks with which criticality computations with these materials can be validated.

6. PLANNING FOR EMERGENCY RESPONSE TO A CRITICALITY ACCIDENT

GENERAL

6.1. This section provides recommendations on emergency response for nuclear facilities. Recommendations on planning and preparing for emergency response to an incident involving fissile material are provided in Refs [32–34].

6.2. Priority should always be given to the prevention of criticality accidents by means of defence in depth. Despite all the precautions that are taken in the handling and use of fissile material, there remains a possibility that a failure (i.e. of instrumentation and controls, or an electrical, mechanical or operational error) or an event may give rise to a criticality accident. In some cases, this may give rise to exposure of persons or a release of radioactive material within the facility and/or to the environment, which may necessitate emergency response actions. Adequate preparations are required to be established and maintained at the local and national levels, and, where agreed between States, at the international level, for response to a nuclear or radiological emergency [8, 33, 34].

CAUSES AND CONSEQUENCES OF A CRITICALITY ACCIDENT

6.3. In demonstrating the adequacy of the emergency arrangements, the expected worker dose and, if relevant, the dose to a member of the public due to external exposure should be calculated.

6.4. Of the 22 criticality accidents in fuel processing facilities reported in Ref. [17], all but one involved fissile material in solutions or slurries. In these events, the key physical parameters affecting the fission yield (i.e. the total number of fissions in a nuclear criticality excursion) were the following:

— Volume of fissile region (particularly for systems with fissile nuclides in solution).
— Reactivity insertion mechanism and reactivity insertion rate.
— Parameters relating to reactivity feedback mechanisms, for example:
  • Doppler feedback[17];
  • Duration time and time constant of reaction;
  • Degree of confinement of the fissile material;
  • Neutron spectral shifts;
  • Degree of voiding;
  • Change of temperature;
  • Density changes.

6.5. Guidance on estimating the magnitude of the fission yield can be found in Ref. [35].

6.6. Typically, criticality accidents in solution systems have been characterized by one or several fission excursion spikes[18], particularly at the start of the transient, followed by a 'quasi-steady state' or plateau phase in which fission rates fluctuate much more slowly.

6.7. An assessment of these 22 criticality accidents identified a common theme in terms of the reactivity excursion mechanism: the majority of the accidents were caused by an increase in concentration of fissile nuclides, which resulted from movement of fissile material by gravity or by flow through pipework. A detailed description of the dynamic behaviour in these criticality accidents can be found in Ref. [17].

[17] Doppler feedback is a phenomenon whereby the thermal motion of fissile and non-fissile material nuclei changes the 'relative' energy between the nuclei and interacting neutrons, thereby causing an effective broadening of neutron reaction cross-sections of the materials. Depending upon the enrichment or composition of the materials, this phenomenon can increase or decrease the effective neutron multiplication factor (k_{eff}) of a system.

[18] A fission excursion spike is the initial power pulse of a nuclear criticality excursion, limited by quenching mechanisms and mechanical damage [17].

EMERGENCY PREPAREDNESS AND RESPONSE

6.8. Each facility in which fissile material is handled and for which the need for a criticality detection and alarm system has been determined (see paras 6.49–6.51) should have in place an emergency response plan, programme and capabilities to respond to credible criticality accidents. In some circumstances where a criticality detection and alarm system is not installed (e.g. shielded facilities), analyses should still be conducted to determine whether an emergency response plan is necessary for the facility.

6.9. Experience has shown that the main risk in a criticality accident is to operating personnel in the immediate vicinity of the event. Generally, radiation doses to operating personnel more than a few tens of metres away are not life threatening. However, it is common for some types of system, particularly fissile nuclides in solution, to display oscillatory behaviour with multiple bursts of radiation continuing over hours or even days. Because of this, a key element in emergency planning should be to ensure prompt evacuation of persons to a safe distance. Following this, sufficient information should be gathered to enable a planned re-entry to the facility.

6.10. The radiation dose from a criticality accident may still be significant, even for people located at some distance from the accident. Thus a mechanism for identifying appropriate evacuation and assembly points should be developed.

6.11. The design should provide a diversity of communication systems to ensure reliability of communication under operational states and accident conditions.

6.12. The provision for additional means of shielding should also be considered in minimizing the radiological consequences of a criticality accident. In employing shielding as a protective measure, the implications that penetrations through the shielding may have for radiation dose should be evaluated. When planning additional shielding measures (e.g. walls) for emergency cases, priority should be given to safe escape routes for operating personnel.

Emergency response plan

6.13. In general, the emergency response plan specific to a criticality accident should include the following:

— Definition of the responsibilities of the management team and the technical personnel, including the criteria for notifying the relevant local and national authorities;
— Evaluation of locations in which a criticality accident would be foreseeable and the expected or possible characteristics of such an accident;
— Specification of appropriate equipment for use in a criticality accident, including protective clothing and radiation detection and monitoring equipment;
— Provision of individual personal dosimeters capable of measuring radiation emitted during a criticality accident;
— Consideration of the need for appropriate medical treatment and its availability;
— Details of the actions to be taken on evacuation of the facility, the evacuation routes and the use of assembly points;
— A description of arrangements and activities associated with re-entry to the facility, the rescue of persons and stabilization of the facility;
— Training, exercises and evacuation drills;
— Assessment and management of the interface between physical protection and criticality safety in a manner to ensure that they do not adversely affect each other and that, to the degree possible, they are mutually supportive.

Responsibilities

6.14. Emergency procedures should be established and made subject to approval in accordance with the management system. Management should review and update the emergency response plan on a regular basis (e.g. owing to modifications in the facility operations or changes in the organization).

6.15. Management should ensure that personnel with relevant expertise are available during an emergency.

6.16. Management should ensure that organizations, including the emergency services, both on-site and off-site, that are expected to provide assistance in an emergency are informed of conditions that might be encountered and are offered training as appropriate. These organizations should be assisted by technical experts in preparing suitable emergency response procedures.

6.17. Management should conduct emergency exercises on a regular basis to ensure that personnel are aware of the emergency procedures and should conduct an awareness programme for local residents.

6.18. Management, in consultation with staff for criticality safety, should specify the conditions and criteria under which an emergency is declared, and should designate the persons with the authority to declare such an emergency.

6.19. During an emergency response, the staff for criticality safety should be available to advise and assist the nominated emergency coordinator in responding to the criticality accident.

6.20. The operating organization should have the capability to conduct, or should engage external experts to conduct, an assessment of radiation doses appropriate for a criticality accident.

Evaluation of foreseeable accidents

6.21. Locations at which a criticality accident would be foreseeable should be identified and documented, together with an appropriate description of the facility. The predicted accident characteristics should be evaluated and documented in sufficient detail to assist emergency planning. Such an evaluation of foreseeable criticality accidents should include an estimate of the fission yield and the likelihood of occurrence of the criticality.

6.22. In the design and operation stages and as part of periodic safety review, consideration should be given to identifying further measures to prevent a criticality accident and to mitigate the consequences of a criticality accident, for example, measures for intervention in order to stop the criticality. Possible approaches include the installation of isolation valves, remote control systems (e.g. for ensuring the availability of neutron absorbers and the means of introducing them into the system where the criticality has occurred), portable shielding or other means of safely altering the process conditions to achieve a safe state.

6.23. The process of calculating the radiation dose from a criticality accident is subject to various uncertainties. The final dose estimate will therefore also include uncertainty. The acceptable level of uncertainty (or the level of confidence that the dose is not greater than predicted) will be a decisive factor in determining the method to be used or the assumptions that can be made to produce the estimate.

The methodology for determining the dose from a criticality accident is complex but should follow the following basic steps:

— Decision on the location of the criticality accident;
— Decision on the power of the criticality accident (i.e. the number of fissions that have occurred);
— If desired, calculation of the effect of any shielding (including the source of the criticality itself) between the location of the criticality system and those likely to be affected (i.e. operating personnel);
— Calculation of the dose received by those likely to be affected (i.e. operating personnel).

6.24. The determination of the doses should be conservative but not so conservative that it endangers personnel through measures such as unnecessary evacuation.

6.25. The emergency response plan should be implemented, consistent with the initial evaluation of the criticality accident.

Initial evaluation of the criticality accident

6.26. Information on the event will come from a number of sources (e.g. radiation monitors, eyewitness accounts, facility records), and it is possible that a clear picture of the location and cause of the accident may not emerge for several hours. The key information will be:

— The location of the event, including details of the items of equipment involved;
— The radiological, physical and chemical properties of the fissile material, including quantities;
— The reactivity insertion mechanism that caused the system to achieve criticality;
— Feedback and quenching mechanisms[19] present (such as venting).

6.27. On the basis of this information, the staff for criticality safety should make a reasonable prediction as to the likely evolution of the system with time and

[19] A quenching mechanism is a physical process other than mechanical damage that limits a fission spike during a nuclear criticality excursion, for example, thermal expansion or micro-bubble formation in solutions [17].

should advise the emergency response team on possible options for terminating the criticality and returning the system to a safe subcritical state.

6.28. Once the information listed in para. 6.26 is available, useful comparisons can be made with details available from other criticality accidents (see Refs [17, 36, 37]). This will help with predictions of the likely evolution of the current event and may also provide information as to possible methods to terminate the power excursion. In some cases termination may be achieved by reversing the reactivity insertion mechanism that initiated the criticality accident.

6.29. In some accidents, there have been instances where improper actions of operating personnel have inadvertently initiated a further power excursion after the initial criticality accident. It should be borne in mind that following the initial fission spike(s), the system might return to a state at or very close to critical but with a continuing low fission rate. This typically occurs in solution systems in which inherent negative reactivity feedback effects will tend to balance out the excess reactivity inserted in the initial stages of the event. In such situations, very small additions of reactivity could then be sufficient to initiate further fission spikes.

Instrumentation and equipment

6.30. On the basis of the accident evaluation, provision should be made for appropriate protective clothing and equipment for emergency response personnel. This equipment could include respiratory protection equipment, anti-contamination suits and personal monitoring devices.

6.31. Emergency equipment (and an inventory of all emergency equipment) should be kept in a state of readiness at specified locations.

6.32. Appropriate monitoring equipment, for use to determine whether further evacuation is needed and to identify exposed individuals, should be provided at personnel assembly points.

Evacuation

6.33. Emergency procedures should designate evacuation routes, which should be clearly indicated. Evacuation should follow the quickest and most direct routes practicable, with consideration given to the need to minimize radiation exposure. Any changes to the facility should not impede evacuation or otherwise lengthen evacuation times.

6.34. The emergency procedures should stress the importance of speedy evacuation and should prohibit return to the facility (re-entry) without formal authorization.

6.35. Personnel assembly points, located outside the areas to be evacuated, should be designated, with consideration given to the need to minimize radiation exposure.

6.36. Means should be developed for ascertaining that all personnel have been evacuated from the area in which the criticality event has occurred.

6.37. The emergency procedures should describe the means for alerting emergency response personnel, the public and the relevant authorities.

Re-entry, rescue and stabilization

6.38. An assessment of the state of the facility should be conducted by nominated, suitably qualified and experienced staff for criticality safety, with the support of operating personnel, to determine the actions to be taken on the site to limit radiation dose and the spread of contamination.

6.39. The emergency procedures should specify the criteria and radiological conditions on the site that would lead to evacuation of potentially affected areas and a list of persons with the authority to declare such an evacuation. If these areas could exceed the site limits, relevant information should be provided to off-site emergency services and appropriate information should be included in the emergency procedures.

6.40. Radiation levels should be monitored in occupied areas adjacent to the immediate evacuation zone after initiation of the emergency response. Radiation levels should also be monitored periodically at the assembly points.

6.41. Re-entry to the facility during the emergency should be only by personnel trained in emergency response and re-entry. Persons re-entering should be provided with personal dosimeters.

6.42. Re-entry should be made only if radiological surveys indicate that the radiation levels are acceptable. Radiation monitoring should be carried out during re-entry using monitors that have an alarm capability.

6.43. The emergency response plan should describe the provisions for declaring the termination of an emergency, and the emergency procedures should address procedures for re-entry and the make-up of response teams. Lines of authority and communication should be included in the emergency procedures.

Medical care

6.44. Arrangements should be made in advance for the medical treatment of injured and exposed persons in the event of a criticality accident. The possibility of contamination of personnel should be considered.

6.45. Emergency planning should also include a programme for ensuring that personnel are provided with dosimeters and for the prompt identification of exposed individuals.

6.46. Planning and arrangements should provide for a central control point for collecting and assessing information useful for emergency response.

Training and exercises

6.47. References [17, 36, 37] provide detailed descriptions of the dynamic behaviour of criticality accidents that have occurred in the past. These references could be used to develop training exercises.

6.48. Staff for criticality safety should familiarize themselves with publications on criticality accidents to ensure that learning from past experience is factored into criticality safety analyses and the emergency response plan.

CRITICALITY DETECTION AND ALARM SYSTEMS

6.49. The need for a criticality detection and alarm system should be evaluated for all activities involving, or potentially involving, the risk of exceeding a safe mass. In determining this safe mass for each type of fissile material, consideration should be given to all processes, including those in which neutron moderators or reflectors more effective than water may be present.

6.50. In determining the need for a criticality detection and alarm system, individual areas of a facility may be considered unrelated if the boundaries are such that there could be no inadvertent interchange of material between areas and neutron coupling is negligible.

6.51. A criticality detection and alarm system should be provided to minimize the total dose received by personnel from a criticality accident and to initiate mitigating actions.

6.52. Exceptions to the recommendation to provide a criticality detection and alarm system may be justified in the following cases:

— Where a documented assessment concludes that no foreseeable set of circumstances could initiate a criticality accident, or where the provision of a criticality detection and alarm system would offer no reduction in the risk from a criticality accident or would result in an increase in total risk; that is, the overall risk to operating personnel from all hazards, including industrial hazards.
— Shielded facilities in which the potential for a criticality accident is foreseeable but the resulting radiation dose at the outer surface of the facility would be lower than the acceptable level. Examples of such facilities might include hot cells and closed underground repositories.
— Licensed or certified transport packages for fissile material awaiting shipment or during shipment or awaiting unpacking.

6.53. Where the potential for criticality exists but no criticality alarm system is employed, a means to detect the occurrence of a criticality event should still be provided.

Performance and testing of criticality detection and alarm systems

Limitations and general recommendations

6.54. The criticality detection and alarm system should be based on the detection of neutrons and/or gamma radiation. Consequently, consideration should be given to the deployment of detectors that are sensitive to gamma radiation or neutrons, or both.

Detection

6.55. In areas in which criticality alarm coverage is necessary, means should be provided to detect excessive radiation doses or dose rates and to signal an evacuation of personnel.

Alarm

6.56. The alarm signal should meet the following criteria:

— It should be unique (i.e. it should be immediately recognizable to personnel as a criticality alarm).
— It should actuate as soon as the criticality accident is detected and continue until manually reset, even if the radiation level falls below the alarm point.
— Systems to manually reset the alarm signal, with limited access, should be provided outside areas that require evacuation.
— The alarm signal should be audible in all areas to be evacuated.
— It should continue to alarm for a time sufficient to allow a complete evacuation.
— It should be supplemented with visual signals in areas with high background noise.

Dependability

6.57. Consideration should be given to the need to avoid false alarms, for example, by using concurrent response of two or more detector channels to trigger the alarm. In the evaluation of the criticality detection and alarm system, consideration should be given to other hazards that may result from the triggering of a false alarm.

6.58. Criticality detection systems, without immediate evacuation alarms, should be considered for special situations where it is demonstrated that mitigating actions could be executed to automatically bring the system back to a safe state and to reduce the radiation dose to personnel.

6.59. Warning signals indicating a malfunction but not actuating the alarm should also be provided.

Design criteria

6.60. The design of the criticality detection and alarm system should be single failure tolerant and should be as simple as is consistent with the objectives of ensuring reliable actuation of the alarm and avoiding false alarms.

6.61. The performance of the detectors should be carefully considered in order to avoid issues such as omission of an alarm signal or saturation of signals.

6.62. Uninterruptible power supplies should be available for the criticality detection and alarm system.

Trip point

6.63. The trip point for the criticality detection and alarm system should be set sufficiently low to detect the minimum accident of concern, but sufficiently high to minimize false alarms. Indications should be provided to show which detector channels have been tripped.

Positioning of the detectors

6.64. The location and spacing of detectors should be chosen to minimize the effect of shielding by equipment or materials. The spacing of detectors should be consistent with the selected alarm trip point.

6.65. In the decommissioning of facilities, it is common practice to establish interim storage areas for items such as waste drums or to position modular containment systems around items of equipment requiring size reduction or dismantling. The implications of the location of such interim storage areas for the continuing ability of the criticality detectors to 'see' the minimum incident of concern should be subject to prior evaluation.

Testing

6.66. The entire criticality detection and alarm system should be tested periodically. Testing periods should be determined from experience and should be kept under review. Performance testing of the criticality detection and alarm systems should include the periodic calibration of the radiation detectors used in the criticality detection and alarm systems.

6.67. Each audible signal generator should be tested periodically. Field trials should be carried out to verify that the signal is audible above background noise throughout all areas to be evacuated. All personnel in affected areas should be notified in advance of a test of the alarm.

6.68. Where tests reveal inadequate performance of the criticality detection and alarm system, management should be notified immediately and corrective actions should be agreed with management and taken without delay. Other measures (e.g. mobile detection systems) may need to be installed to compensate for defective criticality and alarm systems.

6.69. Management should be given advance notice of the testing of subsystems of the alarm system and of any periods of time during which the system will be taken out of service. Operating rules should define the compensatory measures to be taken when the system is out of service.

6.70. Records of the tests (e.g. of the response of instruments and of the entire alarm system) should be maintained in accordance with approved quality assurance plans as part of the overall management system.

6.71. Further guidance on criticality detection and alarm systems is provided in Ref. [38].

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US Department of Energy Nuclear Criticality Safety Program Nuclear Criticality Safety Engineer Training,
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- Module 12: Preparation of Nuclear Criticality Safety Evaluations (PDF)
- Module 13: Measurement and Development of Cross Section Sets (PDF)
- Module 14: A Review of Criticality Accidents by Thomas McLaughlin (video presentation taped 10 Dec. 1999)
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US Department of Energy Nuclear Criticality Safety Program Oak Ridge Critical Experiment Facility History Videos

- Chapter 1: Early History of Criticality Experiments
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CONTRIBUTORS TO DRAFTING AND REVIEW

Cousin, R.	Institute for Radiological Protection and Nuclear Safety, France
De Vita, A.	AREVA/Melox, France
Dunn, L.	Atomic Energy of Canada Limited, Canada
Farrington, L.	World Nuclear Transport Institute, United Kingdom
Galet, C.	Institute for Radiological Protection and Nuclear Safety, France
Gulliford, J.	Nexiasolutions, United Kingdom
Hopper, C.	Oak Ridge National Laboratory, United States of America
Irish, D.	Atomic Energy of Canada Limited, Canada
Jones, G.	International Atomic Energy Agency
Neuber, J.	AREVA NP GmbH, Germany
Scowcroft, D.	Office for Nuclear Regulation, United Kingdom
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