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Criticality Safety in the Handling of Fissile Material

(Revision of SSG-27)

DS 516

DRAFT SPECIFIC SAFETY GUIDE

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, and activities in which fissile material is handled, are required to be managed in such a way as to ensure criticality safety in normal operation, anticipatedunder operational states and conditions that are referred to as credible abnormal conditions or conditions included in the design basis accidents (or the equivalent) [1]. , in accordance with Requirements 38 and 66 of IAEA Safety Standards Series No. SSR-4, Safety of Nuclear Fuel Cycle Facilities [1]. This requirement applies to large commercial facilities including those engaged in the production of fresh nuclear fuel, facilities dealing with the management of spent nuclear fuel and with radioactive waste containing fissile nuclides, including the handling, processing, use, storage and disposal of such waste. This requirement also applies toto some research and development facilities where fissile material is handled. Equivalent requirements apply to radioactive waste containing fissile material during their operational phase (SSR-5) and to transport of packages containing fissile material (SSR-6). All types of operation handling fissile material are covered, including its movement, processing, storage, inspection and disposal.

1.3 The subcriticality of a system depends on many parameters relating to the fissile material, including its mass, nuclide composition, geometry, volume, enrichment and density. Subcriticality is also affected by the presence of other materials such as neutron 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 alone or by limiting both mass and moderation. Such

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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.

parameters can be controlled by engineered and/or administrative measures.

1.4 In this safety guide, the phrase “nuclide composition” encompasses all the parameters inferred by the terms “enrichment”, “effective enrichment”, “plutonium vector” and “isotopic composition”. Other terms used in this publication are as defined in the IAEA Safety Glossary [9].

1.5 This Safety Guide supersedes the 2014 version of SSG-27[3].

OBJECTIVE

1.6 The objective of this Safety Guide is to provide guidance and recommendations on meeting the relevant requirements for ensuring;

- Ensuring subcriticality under normal and for planning the response to criticality accidents. The guidance and recommendations are applicable to both regulatory bodies and operating organizations. This credible abnormal conditions;
- Minimizing the consequences if a criticality accident were to occur;
- Estimating the credible consequences of a potential criticality accident;

in specific operations involving fissile material outside of reactor cores in order to ensure criticality safety at all times. Specifically, this Safety Guide provides recommendations on how to meet the requirements relating to criticality safety established in the following IAEA Safety Standards Series No: SSR-4 [1]; GSR Part 4 (Rev. 1), Safety Assessment for Facilities and Activities [2]; GSR Part 2, Leadership and Management System for Safety [3]; GSR Part 5, Predisposal Management of Radioactive Waste [4]; GSR Part 6, Decommissioning of Facilities Using Radioactive Material [5], SSR-6 (Rev. 1), Regulations for the Safe Transport of Radioactive Material, 2018 Edition ([6]; SSR-5, Disposal of Radioactive Waste [7]; and GSR Part 7, Preparedness and Response for a Nuclear or Radiological Emergency [8]. Terms used in nuclear safety are defined in the IAEA Safety Glossary [9].

SCOPE

1.7 The Safety Guide is intended for use by operating organizations, regulatory bodies and other

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

organizations involved in ensuring criticality safety of nuclear facilities and activities.

SCOPE

1.8 This Safety Guide applies to all types of facilities and activities that involve handling of fissile material, except those facilities that are intentionally designed to be critical, for example a reactor core in a nuclear reactor, or a critical assembly. In this publication, 'handling of fissile material' refers to all activities dealing with fissile material including its processing, use, inspection, storage, and transport as well as the management of radioactive waste containing fissile material.

1.9 The recommendations provided in this Safety Guide cover criticality safety during normal operation, anticipated operational occurrences, and during credible abnormal conditions, in design basis accidents from initial design, through commissioning, through operation, and through decommissioning. It also applies tothe design and operational phases of waste disposal. This Safety Guide also provides recommendations on planning the response to a criticality accident.

1.10 The recommendations provided in this Safety Guide encompass: approaches to and criteria for ensuring subcriticality; estimating credible fissile chain scenarios, conducting criticality safety assessments, including the validation of calculation methods; specifying safety measures to ensure subcriticality; management aspects, and response to criticality accidents.

1.11 In cases where criticality safety is specifically addressed by regulations, for example, the transport of fissile material in accordance with SSR-6 (Rev. 1) [6], this Safety Guide supplements but does not replace the recommendations and guidance provided in corresponding IAEA Safety Guides, e.g. Standards Series No. SSG-26, 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.

1.41.12 The recommendations provided in this Safety Guide may be applied to operations that are intended to remain subcritical in nuclear power plants and research reactors, for example, the 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

THIS SAFETY GUIDE CONSISTS OF SIX SECTIONS AND AN ANNEX. STRUCTURE

1.51.13 Section 2 provides an introduction to the processes that affect criticality safety and provides guidance for criticality safety 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 recommendations 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 recommendations 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, radioactive waste management (i.e. processing, storage and disposal) and decommissioning, transport of fissile material, and research and development laboratories. Section 6 provides recommendations on planning the response to a criticality accident and the basic responsibilities of those involved. In addition, it provides guidance on criticality detection and alarm systems. 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 THE 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 facilities are operated and activities are conducted within specified operational limits and conditions that ensure subcriticality. These safety measures should be identified, implemented, maintained and periodically reviewed to ensure that operations and activities stay within defined safety limits (see para. 2.9) in operational states and credible abnormal conditions.

2.2 Subcriticality is generally ensured through the control of a limited set of macroscopic parameters such as mass, concentration, moderation, geometry, nuclide composition, enrichment, density, and neutron reflection, interaction or absorption. The effective neutron multiplication factor[4] (k_{eff}) of a system may be estimated on the basis of values of these parameters for some systems. However, those parameters are insufficient for an accurate calculation, which requires nuclear data such as neutron fission cross-sections, capture cross-sections and scattering cross-sections for the materials of the system. Because of the large number of variables upon which the neutron multiplication factor depends, there are many examples of apparently 'anomalous' behaviour in fissile systems in which the effective neutron multiplication factor[5] (k_{eff}) changes in ways that seem counterintuitive. Nuclear data should only be used in full calculations of k_{eff} as attempts to estimate k_{eff} from trends in nuclear data can be misleading.

2.3 The assurance of subcriticality in accordance with Requirements 38 and 66 of SSR-4 [1] is an essential component of criticality safety. The operational states and conditions in these requirements, that are referred to as credible abnormal conditions or conditions included in the design basis, include initiating events with the potential to cause criticality listed in the Appendix to SSR-4 [1]. The determination of what constitutes a credible abnormal condition (outside normal operation) should be based on deterministic methods and complemented by probabilistic assessment where possible. In the identification

[4] 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 $k_{eff} > 1$.

[5] 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 $k_{eff} > 1$.

of abnormal events, the facility design and the characteristics of the activity as well as operational experience feedback should be considered (see also Ref. [11]).

2.4 In accordance with Requirement 13 of SSR-4 [1], items that are important for criticality safety are required to be identified and classified on the basis of their safety function and safety significance. This includes items providing engineered or administrative criticality safety measures such as items for the prevention of criticality accidents and for the mitigation of consequences of such accidents. For high-hazard facilities, the principles of SSG-30 should be used.

2.5 A graded approach is required to be used in developing and implementing the approach to ensuring criticality safety of facilities or activities that involve handling of fissile material (see Requirement 11 of SSR-4 [1]). Application of a graded approach should be based on the type of facility or activity and its potential risk and should not compromise safety. A graded approach should be applied to the scope and depth of the criticality safety assessment, the methods and enveloping criticality events within the safety analysis, to the complexity of criticality detection and alarm systems, to the level of training and qualification of criticality control personnel, to emergency preparedness and response, and to administrative criticality control measures. Facility specific attributes that are required to be taken into account in the application of a graded approach are listed in para 6.29 of SSR-4 [1].

2.6 Nuclear security measures should be planned and implemented in a coordinated manner with nuclear safety measures so as to ensure that safety and security objectives are met without compromising one another. The implications of security measures, in particular access control, should be assessed with respect to their effect on criticality safety. The training programme on criticality safety should include the relevant aspects of nuclear security and accounting for, and control of nuclear material. Similarly, security staff and staff responsible for accounting for, and control of, nuclear material should receive at least basic training on criticality safety.

~~2.3~~2.7 Feedback from operational experience, including awareness of the anomalies and accidents known to date, should be utilized to contribute to ensuring criticality safety. Useful information on the causes and consequences of many of the most important anomalies and accidents that have been observed in criticality safety is provided in Refs. [12], [13] and [14]. Events relating to criticality safety should be analysed and, combined with such useful information, a programme for feedback from operational experience should be developed and maintained, see para. 2.4 of SSG-50 Operating Experience Feedback for Nuclear Installations [20]. The requirements for feedback from operating experience for nuclear fuel cycle facilities are established in IAEA safety standards, paragraph 6.7 of GSR Part 2 [3] and requirement 73 of SSR-4 [1].

~~SAFETY CRITERIA~~SUBCRITICAL LIMITS AND SAFETY MARGINS

~~2.4~~2.8 Subcritical limits should be derived on the basis of one or both of the following 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[6] of one or more control parameters, such as mass, volume, concentration, geometry, moderation, reflection, interaction, nuclide composition and density, and with account taken of neutron production, leakage, scattering and absorption.

~~2.1.~~ Safety margins should be applied to determine the safety limits. Subcriticality implies a value of k_{eff} of less than one and/or of a control parameter whose 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.~~

~~2.5~~2.9 ~~In~~corresponds to a k_{eff} of less than one. SSR-4 requires use of conservative margins for safety (see Requirement 17 and paragraphs 6.21, 6.56 and 6.57). Consideration should be given to uncertainty in the calculation of k_{eff} when applying safety margins to k_{eff} ~~(relative to 1) and/or to a control parameter (relative to the critical value),~~. Alternatively, consideration should be given to uncertainty in the calculation of other control parameters when applying safety margins to their critical values. This should include the possibility of any calculation method bias~~,~~ and bias uncertainty, and the sensitivity with respect to changes in the control parameter or k_{eff} with values of the other parameters. The relationship between k_{eff} and other parameters may be significantly non-linear.

~~2.6~~2.10 The operational limits and conditions chosen for the facility or activity should be capable of being monitored and controlled, and if possible should not be derived parameters such as k_{eff} 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 prevent effectively 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.~~administrative errors and sensor delay should also be considered when assessing the appropriateness of safety measures.

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

EXEMPTIONS

2.11 Design features are required to be put in place to effectively prevent criticality being achieved: see Requirement 38 of SSR-4 [1], which also requires that prevention of criticality to be demonstrated in a criticality safety assessment if not exempted by the Regulatory Body. The criticality safety assessment should define operational limits and conditions for criticality safety, which should be expressed in terms of the process parameters affecting the reactivity characteristics of a system. These parameters include mass, density, concentration and nuclide composition, as well as the geometry, neutron moderation or reflection of the system, and the neutron absorption characteristics of the fissile material mixture and other system materials, liquid flow rates and temperature. The parameters quoted in limits and conditions should be expressed in terms that can be readily be understood, such as enrichment, packaging rules and moisture or hydrogen limit.

EXEMPTION CRITERIA

2.72.12 In some cases, the amount of fissile material may be so low, or the nuclide composition may be such, that a full criticality safety assessment is not be justified. Exemption criteria should be developed by the operating organization, reviewed by the management of this organization, and then agreed with the regulatory body, as appropriate. A useful starting point is the exception criteria applied to the classification of transport packages containing fissile material in para. 417 (in conjunction with paras. 423(f) and 424(d)) of SSR-6 (Rev. 1) [6].

2.82.13 The primary approach in seeking exemption should be to demonstrate that the inherent features of the fissile material itself are sufficient to ensure subcriticality. 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).accordance with IAEA Safety Requirements.

2.92.14 Modifications to facilities and/or activities should be evaluated before being implemented, to determine whether the bases for the exemption remain valid.

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

MANAGEMENT SYSTEM

2.2. A documented management system that integrates the safety, health, environmental, security, quality, human--and-organizational-factors of the operating organization is required to be in place and implemented with adequate resources, in accordance with Requirement 4 of SSR-4 [1]. As part of criticality safety measures should be carried out within a clearly established and well controlled management system. The IAEA requirements and recommendations for the integrated management system are established in Ref. [3] and provided, early in Refs [12–16], respectively.

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

2.102.16 Management should establish a comprehensive design stage a criticality safety programme should be established and put into effect by the operating organization, to ensure that safety measures for ensuring subcriticality are specified, implemented, monitored, audited, documented and periodically reviewed throughout the entire lifetime of the facility or the duration of the activity.

- Management should ensure that a plan for corrective action is established, as required, is implemented and is updated when necessary.

2.17 Requirements for the integrated management system are established in GSR Part 2 [3], and recommendations and guidance are provided in IAEA Safety Standards Series Nos: GS-G-3.1, Application of the Management System for Facilities and Activities [15]; GS-G-3.3, The Management System for the Processing, Handling and Storage of Radioactive Waste [16]; GS-G-3.4, The Management System for the Disposal of Radioactive Waste [17]; GS-G-3.5, The Management System for Nuclear Installations [18] and IAEA Safety Standards Series No. TS-G-1.4, The Management System for the Safe Transport of Radioactive Material [18].

2.18 The management system (which is required to cover all items, services and processes important to safety, (see para. 4.8 of SSR-4 [1]), and should include criticality safety activities, thereby providing confidence that they are performed according to the established requirements. In determining how the requirements of the management system for criticality safety are to be applied, a graded approach based on the relative importance to safety of each item or process is required to be used: see Requirement 7 of GSR Part 2 [3]. The management system is required to support the development and maintenance of a strong safety culture, including in all aspects of criticality safety: see Requirement 12 of GSR Part 2 [3]. The management system should ensure that the facility or activity meets the requirements for criticality safety as derived from: the requirements of regulatory body; the design requirements and assumptions; the safety analysis report, and operational limits and conditions, including the administrative requirements.

2.19 The management system should address the following four functional areas: (a) management responsibility; (b) resource management; (c) process implementation; and (d) measurement, assessment and improvement. In accordance with paras 4.15–4.23 of SSR-4 [1]:

— Management responsibility includes the support and commitment of management necessary to achieve the objectives of the operating organization.

— Resource management includes the measures necessary to ensure that the resources essential to the implementation of strategy and the achievement of the objectives of the operating organization are identified and made available.

— Process implementation includes the activities and tasks necessary to achieve the goals of the organization.

— Measurement, assessment and improvement provide an indication of the effectiveness of management processes and work performance compared with objectives or benchmarks; it is through measurement and assessment that opportunities for improvement are identified.

Management responsibility

2.20 The prime responsibility for safety, including criticality safety, rests with the operating organization. The documentation of the management system for criticality safety should include:

— A description of the organizational structure;

— Functional responsibilities;

— Levels of authority;

— The interactions of those managing, performing and assessing the adequacy of the criticality safety programme and activities.

The documentation should also cover other management measures, including planning, scheduling and resource allocation (see para. 9.8 of SSR-4 [1]).

2.21 There should be a designated person who is made responsible and accountable for criticality safety, including: developing and documenting all aspects of criticality safety assessment, monitoring the performance of activities and processes, ensuring that all staff are adequately trained, and ensuring the existence of a system for keeping records that ensures control of performance and verification of activities that are important to criticality safety. The record keeping system should provide for the identification, approval, review, filing, retrieval, and disposal of records.

2.22 Provision is required to be made for ensuring effective communication and clear assignment of responsibilities, to ensure that processes and activities that are important for nuclear criticality safety are controlled and performed in a manner that ensures that safety objectives are achieved: see para. 4.15 of SSR-4 [1].

2.23 The operating organization is required to ensure that criticality safety assessments and analysis are conducted, documented and periodically reviewed: see Requirements 24 and paragraph 4.65 of GSR Part 4 (Rev. 1) [2] and Requirement 5 of SSR-4 [1]. It should arrange for both internal audits and independent audits of the criticality safety measures, including the examination of arrangements for emergency response, for example, emergency communications, evacuation routes and signage. Audits should be carried out by personnel who are independent of those that performed the safety assessments or conducted the criticality safety activities. The data from audits should be documented and submitted for management review and for action, if necessary.

Resource management

2.24 The operating organization is required to provide adequate resources (both human and financial) for the safe operation of the facility or activity (Requirement 9 of GSR Part 2 [3]), including resources for mitigating the consequences of criticality accidents. The management of the operating organization, in particular the person responsible for criticality safety, should participate in the activities by:

— Determining the required competence of criticality staff and providing training, as necessary;

— Preparing and issuing specifications and procedures on criticality safety;

— Supporting and participating in criticality safety assessment;

— Having frequent personnel contact with staff, including observing work in progress.

2.25 Qualified staff with responsibilities for ensuring criticality safety, should be clearly specified and appointed. Criticality safety staff should be knowledgeable about the physics (both static and kinetic) of nuclear criticality and the associated safety standards, codes and best practices, and should be familiar with the design and operation of relevant facilities and the conduct of relevant activities. The criticality safety staff should be independent of the operations management, to the extent necessary.

2.26 All activities that may affect criticality safety are required to be performed by suitably qualified and competent staff: see para. 9.83 of SSR-4 [1]. The operating organization should ensure that such staff receive training and refresher training at suitable intervals, appropriate to their level of responsibility. In particular, personnel involved in activities with fissile material are required to understand the nature of the hazard posed by fissile material and how the risks are controlled by the established safety measures, operational limits and conditions, and operating procedures. The criticality safety staff should provide assistance in the training of personnel, provide technical guidance and expertise for the development of operating procedures, and check and validate all operations that may require criticality control.

2.27 The management system for criticality safety is required to include procurement activities and should be extended to include suppliers: see para. 4.35 and Requirement 11 of GSR Part 2 [3]. The operating organization should ensure, through audits, that suppliers (e.g. designers and safety analysts) have management systems that are adequate for criticality safety.

2.28 The hardware and software-based process items and equipment that are necessary for work to be carried out in a safe manner should be identified, provided and maintained. Calculation tools (e.g. computer codes) that are used for criticality safety assessment should be identified and validated. Equipment and items that are used for criticality safety monitoring, data collection, verifications and tests should be qualified for the operating environmental conditions and should be calibrated as necessary.

Process implementation

2.29 All operations to which criticality safety is pertinent are required to be performed in accordance with approved procedures and instructions: see para. 9.83 of SSR-4 [1]. The operating procedures should cover all normal operation and credible abnormal conditions. As stated in para 9.83 of SSR-4 [1] "The procedures shall specify all the parameters that they are intended to control and the criteria to be fulfilled."

2.112.30 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 anyThe assessments (which are required by SSR-4 [1]) for modifications to existing facilities or activities, or proposals for 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 , should cover their implications for criticality safety. The safety assessments required for modifications affecting fissile material and having safety measures and operational limits and conditions.
- Management should arrange for internal and independent inspection[7] of the criticality safety measures, including the examination of arrangements for emergency response, for example, emergency evacuation routes and signage. Independent inspectionssignificance should be notified

[7] These inspections are in addition to the inspections performed by the regulatory body.

to the regulatory body to allow review before they are implemented. These modifications 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 subjected to procedures for design, fabrication, construction, commissioning and operation that are similar to those applied to the whole facility or activity. The facility or activity documentation is required to be updated to reflect modifications, and the operating personnel, including supervisors, should receive adequate resources will be available to mitigate the consequences of an accident.

2.122.31 Management should ensure that an effective safety culture is established in the organizationtraining on the modifications: see Requirement 61 of SSR-4 [1].

- Management should ensure that regulatory requirements are complied with.

2.132.32 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 consult the criticality safety staff to 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.

2.33 Throughout the lifetime of the facility or the duration of an activity, operations to which criticality safety is pertinent involve different groups and interface with other areas, such as those related to nuclear security and to the system of accounting for and control of nuclear material. These operations are required to be identified, coordinated, planned, and conducted to ensure effective communication and clear assignment of responsibilities: see Requirement 75 of SSR-4 [1]. Communications regarding safety and security should ensure that confidentiality of information is maintained. This includes the system of accounting for, and control of, nuclear material, for which information security should be coordinated in a manner ensuring that subcriticality is maintained.

Measurement, assessment, evaluation and improvement

2.142.34 Audits performed by the operating organization of facilities and activities as well as proper control of modifications to facilities and activities are particularly important for ensuring subcriticality. Independent audits should also be implemented. These audits should also cover measures for emergency preparedness and response. These audits should be carried out regularly, and the results should be evaluated by the operating organization and corrective actions should be 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.~~implement recommendations and suggestions for safety improvements.

~~2.15~~2.35 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~~,~~ without breaching confidentiality of information that is required for security purposes. This also highlights the importance of training operating personnel and of independent ~~inspections. These activities should be part of the management system.~~audits.

~~2.16~~2.36 Deviation from operational procedures and unforeseen changes in operations or in operating conditions are required to be reported to the regulatory body and promptly investigated by the operating organization: see paras 9.34 and 9.35 of SSR-4 [1]. The investigation is required to 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 a recurrence. The investigation should include an analysis of the operation of the facility or conduct of the activity 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.

~~2.4. Useful information on the causes and consequences of previous criticality accidents and the lessons learned is provided in Ref. [17].~~

~~2.17~~2.37 The management system is required to include a means of incorporating lessons learned from operating experience and accidents at facilities in the State and in other States, to identify relevant implications for safety (Requirement 73 of SSR-4 [1]) and should identify areas for improvement in operational practices and assessment methodology (para 2.23 of SSG-50). Recommendations for establishing a system for the feedback of operating experience are provided in IAEA Safety Standards Series No. SSG-50, Operating Experience Feedback for Nuclear Installations [20].

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 consider the concept of defence in depth: see para. 6.141 of SSR-4 [1]. Two vital parts of this concept are passive safety features and fault tolerance[8]. For criticality safety in design, the double contingency principle (which is required by para 6.142 of SSR-4 [1]) should ~~to~~ be ~~the~~ used to ~~preferred means of~~ ensure~~ing~~ fault tolerance [1].

Defence in depth

3.2 The ~~facility or activity should be designed and operated or conducted so that~~ requirements for defence in depth against credible abnormal conditions or accidents are found in SSR-4 [1]. Defence in depth is provided by five independent levels of protection. The third level provides robustness against the escalation of unlikely events, such as autocatalytic events where a supercriticality excursion power coefficient is positive and causes a cliff-edge effect. This leads to the requirement that inherent and/or engineered safety features, fail-safe design and procedures be provided to control the consequences of such accidents, see para 2.10 of SSR-4 [10]. Additional guidance can be found in para 3.10 of this publication.

~~3.1.~~ The objective of defence in depth is to prevent failures, or~~,~~ if prevention fails, ~~ensuring detection and mitigating the consequences. The primary objective should be to adopt safety~~ the defence in depth ensures that the failure is detected and compensated for or corrected. This is achieved through the successful application of 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~~ in the other levels with mitigation provided to the extent practicable, as described in para. 6.19 and Requirement 10 *Application of the concept of defence in depth*, SSR-4 [1]. The fourth and fifth levels provide mitigation, which, with account taken to the above requirements, leads to the following considerations for criticality:

- Application of the fourth level of defence~~ in depth~~, which deals with ensuring the confinement function to limit radioactive releases, might not be fully applicable in the context of criticality safety, but it should nevertheless be applied to the extent practicable. Level five requires the consideration of mitigation for the radiological

[8] ~~To ensure safety, the~~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.

consequences of a criticality accident, the fifth level of defence in depth has to be applied, with consideration given to the to which the requirements for emergency preparedness and response in GSR Part 7 [8] also apply;

3.2. 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.

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

In some operating nuclear facilities, heavy biological shielding may be credited for protecting people and the environment from hazards including criticality. The assessment should consider all the hazards and where possible, prevention of criticality should still be preferred. The safety criteria used in the assessment should be commensurate with the consequences of criticality, taking other hazards into consideration (for instance, where a requirement for emergency cooling conflicts with criticality safety).

Passive safety

~~3.2~~3.4 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 and changes in reflection and moderation are covered by the design). For example, the facility or activity could be designed using the assumption that fissile material is always restricted to equipment with a favourable geometry[9]. Special care is then necessary to avoid unintentional transfer to an unfavourable geometry.

Fault tolerance

~~3.3~~3.5 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 by design: see para 6.142 of SSR-4 [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~~.~~: see Requirement 23 of SSR-4 [1].

~~3.4~~3.6 According to the double contingency principle (see para. 6.142 of SSR-4 [1]), 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 cause failure);-

— The probability of occurrence of each change is sufficiently low.

~~3.5~~3.7 The system's characteristics should meet the recommendations in para 2.10~~2.102.102.11~~ of this Safety Guide, in order that each change in process conditions can be detected (e.g. monitored) by suitable and reliable means within a time frame that allows the necessary countermeasures to be taken.

~~3.6~~3.8 The system design is required to 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

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[9] 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.

control failure or a human error (e.g. an instruction not followed), can result in a criticality accident: see Requirement 23 of SSR-4 [1].

3.73.9 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 may only 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

3.83.10 The safety functions needed for ensuring subcriticality should be determined and the safety measures for fulfilling these functions 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)..

3.93.11 In IAEA Safety Standards arequire ccordance with para 6.68 of SSR-4 [1], the preventive safety measures put in place to observe the following hierarchy:

(a) Inherent safety of the process.

(a)(b) Passive engineered safety measures that do not rely on control systems, active engineered safety measures or human intervention.

(b)(c) Automatically initiated active engineered safety measures (e.g. an automatically initiated shutdown or process control system).

(c)(d) Administrative safety measures:

(i) Active engineered safety measures initiated manually by operating personnel (e.g. operating personnel initiating an automatic shutdown system in response to an indicator or alarm);

(ii) Safety measures provided by operating personnel (e.g. operating personnel closing a shutdown valve in response to an indicator or alarm, or ringing the system into normal operational limits by adjusting controls).

3.12 This hierarchy of safety measures gives preference to inherently safe design and passive safety. If subcriticality cannot be ensured through these means, further safety measures should be employed, for instance the potential criticality consequences should be minimized. This should not be interpreted to mean that the application of any safety measure towards the top of the hierarchy precludes the provision of other safety measures where they can contribute to defence in depth.

3.103.13 In addition to the hierarchy of preventive safety measures in para. 3.11, 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.

3.3. 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.

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

3.113.14 The safety measures put in place should be related to the control of more than one parameter should be preferred over the control of a single parameter, when practicable. Examples of the control parameters are given in para. 3.15.

Control parameters

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

(a) Restriction on the dimensions or shape of the system to a favourable geometry.

(b) Limitation on the mass of fissile material within a system to a subcritical mass. For example, in order to apply the subcritical mass limit may be specified to be less than half the minimum critical mass (incorporating a suitable safety factor) so that inadvertent 'over-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 as a credible abnormal condition.

(c) Limitation on the concentration of fissile nuclides, for example within a homogeneous hydrogenated mixture or within a solid.

(d) Limitation on the type and quantity of neutron moderating material associated with the fissile material..

(e) Limitation on the nuclide composition of the elements in the fissile material present in the system.

(f) Limitation on the density of the fissile material.

(g) Limitation on the amount and form of neutron reflecting material surrounding the fissile material.

(h) Ensuring the presence and integrity of neutron absorbers in the system or between separate systems that are individually subcritical.

(i) Limitation on the minimum separation distance between separate systems that are individually subcritical.

~~3.13~~3.16 The control parameter limitations set out above 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 value of the parameter ~~value~~ that ~~meets the criterion that k_{eff}~~ is subcritical. 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 subcriticality

~~3.14~~3.17 Limitation on the nuclide 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:

(a) The limits on the nuclide composition of the elements in the fissile material are complied with;

(b) The compound to be used cannot change to become a more reactive compound;

(c) A mixture of different types or different compounds resulting in a higher effective neutron multiplication factor cannot occur.

The events in (b) and (c) could occur in specific situations~~, occur~~ — for example, the precipitation of a U/Pu nitrate solution — and they should be taken into account in the criticality safety assessment and proven to be subcritical.

~~3.15~~3.18 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 and hydrocarbon plastics 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 oils based on hydrocarbons could be replaced with oils containing (for instance) fluorine or chlorine.

~~3.16~~3.19 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 (full density water) with 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.

3.173.20 If the presence of neutron absorbers is considered, the following factors should be assessed. Neutron absorbers are mainly effective for thermal neutron systems. Therefore, any neutron spectrum hardening, i.e. an increase in the distribution of higher energy neutrons, caused by operating conditions or credible abnormal 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 remains sufficient. Consideration should be given to monitoring the credible long term degeneration and/or degradation of neutron absorbers.

3.183.21 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.

3.193.22 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.

3.203.23 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 containing hydrogen and 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.

3.213.24 Neutron 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 units of 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.

3.223.25 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.

3.233.26 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

3.243.27 Passive engineered safety measures use only passive components to ensure subcriticality. Such measures are highly preferred because they provide high reliability, cover a broad range of criticality accident scenarios, and need 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.

3.253.28 Certain components that function with very high reliability based on irreversible action or change may be designated as passive components.-

3.263.29 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 as an active component, although it may be part of either an active engineered safety measure or an administrative safety measure.

Active engineered safety measures

3.273.30 Active engineered safety measures use active components such as electrical, mechanical or hydraulic hardware to ensure subcriticality. Active components act by responding to a process variable that is 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. Independently redundant or diversified systems and components are required to be considered (Requirement 23 of SSR-4 [1]), which should be sufficient to limit the possibility of common cause failure. Active engineered components require surveillance, periodic testing for functionality, and preventive and corrective maintenance to maintain their effectiveness: see Requirements 26 and 65 of SSR-4 [1].

3.283.31 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. the response to an alarm or to a value on a weighing scale) should be considered as administrative safety measures, although they contain active engineered. The reliability of these types of components should consider also administrative failure modes.

ADMINISTRATIVE SAFETY MEASURES

General considerations

3.293.32 When administrative safety measures are employed, particularly procedural controls, it should be demonstrated in the criticality safety assessment that credible deviations from such administrative measures 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.

3.303.33 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. 2.12.12.12.17), and the use of such measures should include consideration of the following;

(a) Specification and control of the nuclide 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.

(b) Determination and demarcation 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~~,~~ or neutron moderating ~~materials, neutron~~ , absorbing or 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.

(c) Control of access to criticality controlled areas ~~where fissile material is handled, processed or stored~~. .

(d) Separation between criticality controlled areas, and separation of materials within criticality controlled areas.

(e) Movement and control of materials within and between criticality controlled areas (including those areas containing different fissile materials and/or with different control parameters), and spacing between moved and stored materials.

(f) 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.~~

(g) 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).

(h) Use of neutron absorbers, and control of their continued presence, distribution and effectiveness.

(i) 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).

(j) Quality assurance, periodic inspection (e.g. control of continued favourable geometries), maintenance, and the collection and analysis of operating experience.

(k) Procedures for use in the event of credible abnormal conditions (e.g. deviations from operating procedures, credible alterations in process or system conditions).

(l) Procedures for preventing, detecting, stopping and containing leakages, and for removing leaked materials.

(m) Procedures for firefighting (e.g. the use of hydrogen-free fire extinguishing materials).

(n) Procedures for the control and analysis of design modifications.

(o) Procedures for criticality safety assessment and analysis.

(p) Procedures for the appointment of suitably qualified and experienced staff for criticality safety.

(q) Procedures for training to operating personnel and criticality safety personnel.

(r) Ensuring that the procedures are understood by operating personnel and contractors working at the facility.

(s) Control of the facility configuration.

(s)(t) 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 to maintenance, inspection, testing and examination).

3.313.34 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 personnel. Likewise, before an existing facility or activity is changed, the engineered and administrative safety measures should be revised and again independently reviewed and, as appropriate, revised. The introduction of a new activity may be subject to authorization by the regulatory body before it can be initiated.-

Operating procedures

3.323.35 The operating procedures (which are required by SSR-4), 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:

(a) Should facilitate the safe and efficient conduct of operations;

(b) Are required to be consistent with, and should include, those controls, limits and measures that are important for ensuring subcriticality;

(c) Are required to cover mandatory operations for safety, advice and guidance for anticipated operational occurrences and accident conditions;

(d) 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;

(e) Are required to be developed in collaboration with operating personnel to ensure that the procedures are simple and readily understandable to operating personnel;

(f) Are required to be periodically reviewed in conjunction with other facility documents, such as the emergency plans and procedures and the criticality safety assessment, to incorporate any changes and lessons learned from feedback of operating experience, and for training at predetermined intervals. See 6.18 (Bullet e) and 6.36 of GSR Part 7 regarding emergency plans and procedures.

~~3.33~~3.36 Procedures are required to be reviewed in accordance with the management system (see para. 2.17). 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

~~3.34~~3.37 The operating organization has 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 (see paras. 2.20~~2.202.202.21~~ and 2.21~~2.212.212.22~~).

~~3.35~~3.38 The operating organization 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. The primary responsibility for safety remains with the operating organization: see Requirement 2 of SSR-4 [1].

~~3.36~~3.39 Authority for the implementation of quality assurance measures and periodic inspections and the evaluation of the results of quality control and periodic inspections should be assigned to persons who are independent of the operating personnel.

~~3.37~~3.40 In accordance with Requirement 12 of GSR Part 2 [3], managers and supervisors are required to promote~~, in accordance with the requirements established in Ref. [3],~~ a strong safety culture. This should make all personnel aware of the importance of ensuring subcriticality and the necessity of adequately implementing the criticality safety measures. For this purpose, the operating organization should provide the following:

(a) Staff for criticality safety who are independent of operating personnel and report, along with other safety experts, to a manager with overall responsibility for safety at the highest level of the organisation;

(b) The organizational means for ensuring that the ~~relevant~~ staff for criticality safety provide managers, supervisors and operating personnel with periodic training on criticality safety, to improve their safety awareness and behaviour;

(c) The organizational means for ensuring that the ~~relevant~~ staff for criticality safety ~~themselves~~ are provided with periodic training on criticality safety;

(d) The organizational means for ensuring that periodic reviews of criticality safety assessments are undertaken;

(e) The organizational means for ensuring that the criticality safety programme and its effectiveness are continually reviewed and improved.

~~3.38~~3.41 Records of participation in criticality safety training should be maintained and used to ensure that routine refresher training is appropriately recommended and instigated.

~~3.39~~3.42 The ~~relevant~~ staff for criticality safety should be responsible for~~, at least,~~ the following:

(a) Provision of documented criticality safety assessments for systems of, or areas with, fissile material;

(b) 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;

(c) 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;

(d) Specification of the criticality limits and conditions and required safety measures and support for their implementation;

(e) Determination of the location and extent of criticality controlled areas;

(f) 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;

(g) Assisting and consulting operating personnel, supervisors and management and keeping close contact with them to ensure familiarity with all activities involving fissile material;

(h) Conducting regular walkdowns of the facility and inspections of the activities;

(i) Provision of assistance in the establishment and modification of operating procedures and review of these procedures;

(j) Documented verification of compliance with the criticality safety requirements for modifications or changes in the design of systems or in processes;

(k) Ensuring that training in criticality safety is provided periodically for operating personnel, supervisors and management.

3.403.43 Supervisors should be responsible for, at least, the following:

(a) Maintaining an awareness of the control parameters and associated limits relevant to systems for which they are responsible;

(b) Monitoring- and documentation of compliance with the limits of the control parameters;

(c) 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;

(d) Promoting a questioning attitude from personnel and demonstrating a strong safety culture.

3.413.44 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.include the following:

(a) To cooperate and comply with management instructions and procedures;

(b) To espouse and contribute to a questioning attitude and strong safety culture; and

(c) To stop work and report the event as required, if unsafe conditions are possible in the event of a deviation from normal operations.

IMPLEMENTATION AND RELIABILITY OF SAFETY MEASURES

3.423.45 Ensuring subcriticality in accordance with the concept of defence in depth usually requires the application of Application of a combination of different engineered and administrative safety measures is essential for the assurance of subcriticality. In accordance with the principles of redundancy, diversity and independence (as required by Requirement 23 of SSR-4 [1]) reliance can be placed on safety measures already present in the facility or activity or applied to the system of interest. However, the application of hierarchy of criticality safety measures is required and the guidance specified in para. 3.11 should be observed.-

3.433.46 Consideration of criticality safety should be used to determine:

(a) The design and arrangement of engineered safety measures;

(b) The need for instrumentation for ensuring that the operational limits and conditions are adequately monitored and controlled;

(c) The need for additional administrative measures for ensuring that the operational limits and conditions are adequately controlled.

3.443.47 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 that criteria for reliability are met. Where administrative controls are necessary as part of a safety measure, these should be tested regularly.

3.453.48 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.

3.49 The ageing management programme, required by Requirement 60 of SSR-4, is required to be coordinated with the criticality safety programme required by requirement 66, see para 9.53 [1]. Changes affecting criticality safety due to ageing of the facility should be considered.

Ageing effects should be monitored and their impacts on criticality safety should be assessed. Where ageing has reduced criticality safety below acceptable levels, corrective measures should be identified, assessed and approved as appropriate. Changes that have been approved should be implemented in a timely manner. 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 should be 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 should be 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 theThe 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. should be considered.

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. (see also Ref [50]).

4.3 The probabilistic approach is used to evaluate the extent to which the safety of operations at the facility is 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. If the probabilistic assessment reveals an unusually high reliance of subcriticality protection on a single safety measure, strengthening or supplementing that measure should be considered. 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.

4.4 A criticality safety assessment, which is required by SSR-4, should be conducted 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 transport[10], and prior to and during storage of fissile material and post-operational clean-out and decommissioning of the facility, transport[11] and storage of fissile material.

4.5 The objectives of the criticality safety assessment is required 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 is required to include a criticality safety analysis, which evaluates 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).credible abnormal conditions. 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 subcritical limits (see paras 2.8–2.12) are required to be justified and documented and there should be 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.

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

4.8 In the criticality safety assessment, consideration is required be given to the possibility of inappropriate (and unexpected) responses by operating personnel to abnormal conditions. The potential for operating personnel to respond to leaks of fissile solutions by catching the material in geometrically unfavourable equipment should be considered, for example.

4.9 The systematic approach to the criticality safety assessment required be adopted is outlined

[10] Specific requirements for criticality safety during the transport of radioactive material are established in SSR-6 (Rev. 1) [6].

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

below, including, but not limited to, the following steps:

(a) Definition of the fissile material, its constituents, chemical and physical forms, nuclear and chemical properties, etc.;;

(b) Definition of the processes and operations involving the fissile material;

(c) Methodology for conducting the criticality safety assessment;

(d) Demonstration of subcriticality for normal operation and credible abnormal conditions, including application of the double contingency principle (as appropriate), the identification of which criticality parameters are being controlled, and their associated limits;

(d)(e) Verification and validation of the calculation methods including the computer codes, nuclear data and procedures for using them;

(f) Performance of criticality safety analyses, including a description of the calculation method and nuclear data.

4.10 During development of the criticality safety assessment, the staff performing the assessment should personally observe all relevant aspects of the process or activity being assessed, including any relevant equipment, activities, and processes.

4.11 Before the start of an operation, or before an existing operation is changed:

- An independent review should be performed that confirms the adequacy of the criticality safety assessment. The reviewer should be familiar with the physics of criticality and associated practices, as well as the operation or activity concerned. The review should include at a minimum validation of the calculation method, the methodology for performing the criticality safety assessment, and the demonstration of subcriticality under normal operation and all identified credible abnormal conditions.

- The supervisor responsible for the operation should confirm that the scenarios described in the criticality safety assessment are verifiable and compatible with the operation, and that the criticality safety assessment adequately identifies all associated normal operating conditions and credible abnormal conditions.

Determination of the fissile material

4.104.12 The characteristics of the fissile material (e.g. mass, volume, moderation, nuclide composition, enrichment, absorber depletion, degree of nuclide decay or in-growth and interaction, irradiation (transmutation of fissile material, results of radioactive decay) is required to 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

~~4.11~~4.13 The ~~operational~~ limits and conditions of each operation 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.

~~4.12~~4.14 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.

~~4.13~~4.15 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

~~4.14~~4.16 The criticality safety assessment is required to 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).~~credible abnormal conditions. These should then be analysed and documented with account taken of possible aggravating events. Additionally, a justification is required to be provided to identified initiating events that were excluded from the design: see para. 6.64 of SSR-4 [1]. 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.

~~4.15~~4.17 The criticality safety assessment is required to be performed by using a verified and validated methodology. The criticality safety assessment is required to provide a documented technical basis that demonstrates that subcriticality will be maintained in normal operation and in ~~design basis accidents (or the equivalent)~~credible abnormal conditions in accordance with the double contingency principle or the single failure approach (see paras. 3.5–3.9). The criticality safety assessment is required to identify the safety measures necessary to ensure subcriticality, and should specify their safety functions, including requirements for reliability, redundancy, diversity and independence, and also any requirements for equipment qualification.

~~4.16~~4.18 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 and conditions include~~, but are not limited to,~~ the following:

(a) Reference to national and international standards;

(b) Reference to accepted handbooks on criticality safety;

(c) Reference to experiments, with appropriate adjustments of limits to ensure subcriticality when the uncertainties of parameters reported in the experiment documentation are considered;

(d) Use of validated calculation models and techniques.

~~4.17~~4.19 The applicability of reference data to the system of fissile material being evaluated should be justified. ~~When applicable, any~~ The calculation methods, computer codes and nuclear ~~cross-section~~ data used should be specified (~~i.e. cross-section data sets and~~including their release versions), together with any cross-section pre-processing codes that were used.

~~4.18~~4.20 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.

4.21 The results of the calculations should be cross-checked by using independent nuclear data or different computer codes when available. In addition, the uncertainties of the calculated results due to the uncertainties of the nuclear data used should be determined. These uncertainties are required to be taken into account if the calculated results are compared to the established upper subcritical limits (see para.

4.33).

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

4.22 Calculation methods such as computer codes and nuclear data used in the criticality safety analysis to calculate k_{eff} are required to be verified and validated to ensure the reliability of their derived values. This includes to establish their limits of applicability, code bias and level of uncertainty: see para. 6.145 of SSR-4 [1].

~~4.19~~4.23 Verification of the calculation methods should be performed prior to validation and periodically thereafter. Verification is the process of determining whether a calculation method correctly implements the intended conceptual model or mathematical model (see Requirement 18 of GSR Part 4 (Rev. 1) [2]). Verification should test the methods, mathematical or otherwise, used in the model and computer codes, while ensuring that changes of the operating environment, i.e. operating system, software and hardware, do not adversely affect the execution of the codes. Verification of the calculation method is required to be managed as part of the management system.

~~4.2. 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.~~

~~4.3. The results of the calculations should be cross-checked by using independent nuclear data or different computer codes when available.~~

4.24 After verification of the calculation method is complete and prior to its use in performing a criticality safety analysis, the method is required to be validated: see para. 6.145 of SSR-4 [1]. 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 or code bias and uncertainty, by comparing the predictions of the model with observations of the real system of fissile material or with experimental data (see Requirement 18 of GSR Part 4 (Rev. 1) [2]).

~~4.20~~4.25 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. A useful source of benchmark data can be found in Ref. [21].

~~4.21~~4.26 In selecting benchmarks, consideration should be given to the following:

(a) Experiments that are used for benchmarking should be reviewed to ensure that information is complete and accurate prior to use as benchmarks.

(b) Benchmarks should be selected from multiple independent sets in order to minimize uncertainty and/or systematic error.

~~(a)~~(c) Benchmarks should be used that have relatively small uncertainties compared with any arbitrary or administratively imposed safety margin.

~~(b)~~(d) 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:~~-~~

(i) Chemical compounds, mixtures, alloys and their compositions or formulae.

(ii) Isotopic proportions.

(iii) Material densities.

(iv) 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.

(v) The 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).

(vi) 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).

(vii) The sensitivity of the system to any simplification of geometry, for example elimination of pipes or ducts.

(viii) Relevant neutron reflectors.

~~(viii)~~(ix) Neutron energy spectrum.

~~(c)~~(e) Calculation methods should be reviewed periodically to determine whether relevant new benchmark data have become available for further validation.

~~(d)~~(f) Calculation methods should also be re-verified following changes to the computer code system, and periodically thereafter.

4.4. 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

4.224.27 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. In cases Wwhere 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. Anan 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. Comparison of one computer code's result with the result from using another computer code should not be used to validate a calculation method.

4.28 Modelling of benchmarks performed by organizations other than that which performs the validation should be evaluated to confirm that the models use appropriate calculation methods and analysis techniques for the intended use.

4.29 The calculation methods and analysis techniques used in the validation to analyse benchmarks should be the same as those used to analyse the system or process to which the validation is applied; otherwise justification should be provided for the use of different techniques.

4.30 Appropriate statistical methods should be used as the primary means of establishing bias and bias uncertainty in the comparison for validation (i.e. comparing the calculation method to the benchmark experiments). Under certain circumstances, a non-statistical approach may be appropriate.

Calculation methods in criticality safety analyses

4.31 In the performance of criticality safety analyses, the calculation method should only be used within its validated area(s) of applicability; alternatively, any use of the calculation method outside of its area(s) of applicability should be documented and justified.

4.32 An additional subcritical margin (i.e. administrative margin) should be used to bound any unknown (or difficult to quantify) uncertainty beyond that identified in the validation, and the additional margin should be justified.

4.33 An upper subcritical limit (i.e. a direct limit on k_{eff}) should be established based on the bias and bias uncertainty of the calculation method, the administrative margin, and any related penalties (e.g. penalty for use of the calculation method outside of its area(s) of applicability). When comparing the calculated keff values with this upper subcritical limit, the remaining uncertainties of the calculated keff values (e.g. statistical uncertainties in case of Monte Carlo calculations or uncertainties due to the uncertainties of the nuclear data used) are required to be taken into account (see SSR-4 para 6.144).

4.234.34 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.

4.244.35 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. All input data and nuclear data used in calculations, the assumptions, approximations and simplifications used to prepare the input data and the associated uncertainties as well as the derived results and their uncertainties (see 4.33) are required to be documented as part of the overall management system (see SSR-4, para. 4.18).

4.36 Once the calculation method has been verified and validated, it is required to be controlled and documented as part of the overall management system to ensure that a systematic approach is adopted in designing, coding, testing and documenting the calculation method: see para 4.18 of SSR-4 [1].

Optimum Neutron Moderation

4.37 The nuclear safety assessments fundamentally depend on the ratio of neutron-multiplying materials and neutron-moderating materials that are proposed in the models used in the analysis. This ratio, which leads to the maximum neutron multiplication factor, is called optimum neutron moderation. Optimum neutron moderation should be analysed regardless of whether the system has an actual moderator (for example, for dry storage facilities).

4.38 The criticality safety assessment should demonstrate that the system will remain subcritical in normal operation and credible abnormal conditions even in optimum neutron moderation. Water is conventionally proposed as the moderator in this analysis (but it may be required to analyse several moderators depending on specific system characteristics). Optimum neutron moderation is determined as the fractional density (from 0 to 1 kg/cm^3) at which the neutron multiplication factor reaches the maximum value in the system. See Safety of Nuclear Power Plants: Design Requirements SSR-2/1.

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 The facilities and activities of the nuclear fuel cycle may be split into two groups: those for which a criticality hazard is not credible and those for which criticality may be credible;

a) Not credible, for example, facilities for; mining of natural uranium and thorium ores and their processing, transportation and conversion of natural uranium; and facilities for which the criticality hazards may be credible; ; and

a)b) 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 Facilities and packages in this second group should be designed and operated in a manner that ensures subcriticality according to the relevant IAEA specific safety requirements. The different types of facility and activity in this second group are the "practices" of this section.

5.25.4 The scope and level of detail to be considered for the criticality safety assessment is required to reflect the type of practice and its operation[12], in accordance with a graded approach: see Requirement 1 of GSR Part 4 (Rev. 1) [2].

SPECIFIC PRACTICES

5.35.5 This section provides recommendations on specific issues that should be taken into account to ensure criticality safety in each of the practices described below, which cover all the main areas of the nuclear fuel cycle. In all these practices the IAEA safety standards require rigorous control of the physical

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[12] 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.

inventory of fissile material as a minimum standard of operation. Thus, the potential for criticality resulting from common errors such as double-batching, or addition of water to vessels thought to be empty, should be eliminated where these are credible possibilities.

Conversion and uranium enrichment

~~5.4~~5.6 In conversion facilities, ~~typically natural~~ uranium concentrates are purified and converted to the chemical forms required for the manufacture of nuclear fuel usually uranium tetrafluoride or uranium hexafluoride — if enrichment is needed.

~~5.5~~5.7 Because of the isotopic composition of natural uranium (i.e. ~0.7 wt.% ^{235}U), in the homogeneous processes of conversion, and in the absence of moderators more effective than water, no criticality safety hazards are encountered in the conversion of natural or depleted uranium and the safety assessment should justify the absence of more reactive material.

~~5.6~~5.8 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].~~Sections 2 and 3, should be applied.

5.9 Before any process equipment or cylinder wet cleaning process can be started, a safe uranium holdup should be defined, and it should be verified that the uranium holdup is below the subcritical limit. See also the requirements established in para. 9.88(b) of SSR-4 [1].

~~5.7~~5.10 Particular consideration should be given to criticality safety in conversion facilities that are used for the conversion of enriched or reprocessed uranium, which has a higher enrichment than natural uranium and under certain conditions can achieve criticality.

5.11 A particular hazard associated with uranium enrichment facilities is the potential for over-enrichment and the hazards associated with varying levels of enrichment.

5.12 In meeting the requirement established in para. 9.126(b) of SSR-4 [1], methods to mitigate the consequences of a fire or a UF_6 release should consider the use of borated water and/or favourable geometry to collect the water.

5.13 Further recommendations on criticality safety for conversion facilities and uranium enrichment facilities are provided in IAEA Safety Standards Series No. SSG-5, Safety of Conversion Facilities and Uranium Enrichment Facilities [22].

Fuel fabrication

~~5.8~~5.14 Fuel fabrication facilities process powders, solutions, gases and metals of uranium and/or plutonium that may have different content in terms of either fissile material (e.g. in ^{233}U or ^{235}U enrichment) or ~~in~~ absorber material (e.g. gadolinium).

~~5.9~~5.15 Such facilities can be characterized by their fissile uranium 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), and by the fissile content in the uranium and by the ratio of PuO_2 to the total amount of oxides (i.e. the PuO_2 concentration).

~~5.10~~5.16 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:

(a) 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).

(b) In order to prevent water leakage and unexpected changes in conditions of criticality safety control, air rather than water should be used as the heating and cooling medium 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.

(c) For firefighting, procedures should be provided to ensure the safe use of fire extinguishing media (e.g. control of materials and densities of materials to be used, such as CO_2, water, foam, dry powders and sand). Combustible materials should be minimized in moderator controlled areas in order to reduce the likelihood of introducing moderating materials due to firefighting. Moderator control requirements should be specified in firefighting procedures.

(d) The storage of fissile material should be designed to prevent its inadvertent rearrangement in events such as firefighting with high pressure water jets.

(e) 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 the 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. 4.27.

(f) The introduction and removal of moderating material under normal operation and credible abnormal conditions — 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.

(g) The properties of all existing materials that could impact moderator content (e.g., hydric, hygroscopic, adsorptive, absorptive, and radiolytic properties).

(h) The spatial distribution of moderators within fissile material units, and non-uniform distribution due to chemical, thermal, or mechanical (e.g., mixing) processes.

(i) The tolerance and changes in physical and chemical properties of moderators.

(j) The integrity of containers that are used to store and transfer moderating materials in moderator controlled areas.

(k) Moderating material that may be encountered during maintenance, decontamination, construction, and other activities.

~~5.11~~5.17 Buildings and equipment (e.g. gloveboxes) should be designed to ensure the safe retention of fissile material in the event of a credible 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.

~~5.12~~5.18 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.

5.19 Moderator-controlled areas should be clearly identified to personnel.

5.20 Penetrations into moderator controlled areas should be minimized. Systems that normally contain moderating material, as well as systems that do not normally contain moderating material, and which penetrate a moderator controlled area should be considered.

Material cross-over

5.135.21 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-

5.145.22 The different steps in the manufacturing process may create accumulations of fissile material that might 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 including ventilation systems due to the velocity of the transport medium. Periodic inspection of equipment in which fissile material could accumulate may be necessary.

5.155.23 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 the control of favourable geometry.

5.165.24 Further guidance on criticality safety for uranium fuel fabrication facilities and uranium and plutonium mixed oxide fuel fabrication facilities is provided in IAEA Safety Standards Series Nos SSG-6, Safety of Uranium Fuel Fabrication Facilities [23], and SSG-7, Safety of Uranium and Plutonium Mixed Oxide Fuel Fabrication Facilities [24], respectively.

Handling and storage of fresh fuel

5.175.25 The storage area for fresh fuel should comply with the conditions 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.under normal operation and credible abnormal conditions. 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 fissile material composition complies with the criticality limitations of the storage area.

~~5.18~~5.26 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.

~~5.19~~5.27 Drains in dry storage areas for fresh fuel should be ~~properly~~ kept clear to ensure the efficient removal of any water that may enter, so that such drains cannot constitute a possible cause of flooding.

~~5.20~~5.28 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.

~~5.21~~5.29 Further guidance for ensuring criticality safety in the handling ~~and storage~~ of fresh fuel at nuclear power plants and at research reactors, respectively, is provided in IAEA Safety Standards Series Nos NS-G-2.5, Core Management and Fuel Handling for Nuclear Power Plants [25], and in NS-G-4.3, Core Management and Fuel Handling for Research Reactors [26].

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

~~5.22~~5.30 Spent fuel operations are generally characterized by a need to handle large throughputs and to retain large inventories of fissile material in the facility. Some of the guidance provided for spent fuel (after final removal from the reactor core) may also be applied to any used fuel (irradiated fuel handled and stored at the reactor site, also before final irradiation in the reactor core). The effects of fuel irradiation and radioactive decay should be assessed for criticality safety. In determining the criticality safety measures, the following factors should be noted:

(a) Irradiation and associated radioactive decay of the fissile material nuclides during reactor operation affecting criticality safety, such as potential consequences, subcriticality margins and emergency preparedness and response.

(b) The preferred method of ensuring subcriticality during spent fuel operations is by means of geometrically favourable configuration of the fuel. Additional means, such as neutron absorbers and/or the use of a burnup credit, could be applied where subcriticality cannot be maintained by means of favourable geometrical configurations alone (see IAEA Safety Standards Series No. SSG-15 Storage of Spent Nuclear Fuel [27]).

~~(a)~~(c) 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. This affects the potential consequences of a criticality accident by reducing the direct radiation exposure while the energy release may increase radioactive contamination.

(b)(d) Much of the material will need cooling (e.g. in spent fuel ponds) for several years following its removal from the reactor. The rate of change in fuel composition can be significant during this cooling period and the subcriticality margin is affected by such cooling.

(c)(e) The nuclide, physical and chemical composition of the fissile material will have changed during irradiation in the reactor and subsequent radioactive decay.

(d)(f) The fuel assemblies will have undergone physical changes during irradiation.

(g) The optimum composition and geometry of irradiated fuel inside the reactor core is often not the optimum composition and geometry of fuel in operations outside the reactor core.

(h) The required accounting for irradiation effects does not alter the preference for geometrically safe fuel storage.

Handling accidents

5.235.31 The need for remote handling and the presence of heavy shielding necessary for radiation protection necessitates consideration of a set of credible abnormal conditions 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). The safety measures associated with prevention of such conditions include the 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.

5.32 Often such events could not lead to criticality directly but the potential for criticality in subsequent operations should be considered (e.g. transfer from a dry environment to a well-moderated environment). Observation and documentation of any potential damage to safety-related materials (fissile material, absorber materials, etc.) should be accounted for, e.g. before transfer from dry to wet handling of the fuel.

Maintaining fuel geometry

5.245.33 Where the geometry of spent fuel has to be maintained during storage and handling operations to ensure subcriticality, and this should be assessed for normal operation and for design basis accidents (or the equivalent).all credible abnormal conditions. This includes 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 might also be affected by corrosion of structural materials and by embrittlement and creep of the fuel as a result of irradiation, and the potential for these effects should also be assessed. In some operations, for example in a dry environment, the geometry is not essential for ensuring subcriticality.

5.255.34 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

5.265.35 In some storage ponds for spent fuel, one possible criticality safety measure is 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 not containing absorbers should be considered in the criticality safety assessment. Further guidance on safety of spent nuclear fuel storage is provided in SSG-15 [27].

5.275.36 Fixed absorber materials used in spent fuel pools should be designed so that high radiation fields do not lead to detrimental changes in their 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 . In existing facilities where ageing of neutron absorbers has already occurred, provision of soluble neutron absorbers for certain credible abnormal conditions, such as a drop of a fuel assembly, should be given only limited credit. In accordance with Requirement 32 of SSR-4 [1], the ageing degradation of neutron absorbers throughout the lifetime of the facility should be considered, to ensure that their physical integrity remains consistent with the assumptions used in the safety analysis.

5.285.37 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. Where boron solutions are stored outdoors in a cold climate, the potential for boron separation due to freezing and thawing should be considered.

Changes in storage arrangements within a spent fuel facility

~~5.29~~5.38 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 made 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 absorbtion 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. [12]). These effects should be taken into account in the criticality safety assessment for such modifications.

~~5.30~~5.39 Consideration should also be given to the potential for changes in the storage arrangement due to credible abnormal conditions involving fuel movements (e.g. a flask being dropped onto the storage array).

Misloading events

~~5.31~~5.40 For ~~spent~~ fuel facilities ~~on a single reactor site where the facility~~that may handle 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 elements into the wrong storage locations should also be considered in the criticality safety assessment.

5.41 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.

~~5.32~~5.42 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

5.43 In some criticality safety assessments for operations involving spent fuel, the spent fuel has been conservatively assumed to have the ~~same~~ composition leading to greatest neutron multiplication factor (sometimes called the "peak reactivity"). For many fuel types the peak reactivity is achieved by fresh fuel. For other types there is a peak in reactivity at some higher irradiation level (burnup) for at least two reasons:

- Build-up of new fissile nuclides from fertile nuclides is more significant than depletion of initial fissile nuclides; and

- The effect of depletion of integral burnable absorber nuclides (usually gadolinium isotopes) within the fuel composition is stronger than the effect of depletion of fissile nuclides, leading to a net increase in the neutron multiplication factor.

5.44 Accounting for the maximum neutron multiplication factor due to irradiation is a requirement unless:

- The burnable absorbers, if present, are not accounted for in the criticality safety assessment, or
- It can be sufficiently demonstrated that the fuel has reached a minimum irradiation level (burnup) and that the effects of this burnup can be safely accounted for. , taking 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. 5.43–5.46.

5.335.45 Taking credit for the burnup of individual fuel assemblies will increase the potential for misloading events involving these fuel assemblies at reactor sites where fuel at different burnup levels, including fresh fuel, are handled. At other sites, screening of received fuel assemblies may result in a reduction of the potential for misloading events if burnup credit is applied (a very small fraction of fuel assemblies are typically outside the allowable range and can be accounted for individually by special measures). Without burnup credit, there may be hundreds of different fuel designs that require individual administrative controls. Protection against misloading events, as described in para. 5.38, should form one of the key considerations in the criticality safety assessment for spent fuel operations.

5.345.46 Further guidance on criticality safety at spent fuel storage facilities is provided in SSG-15 [27], and guidance on ensuring subcriticality during the handling and storage of spent fuel at nuclear power plants and research reactors is provided in NS-G-2.5 and NS-G-4.3 [25, 26].

Burnup credit

5.355.47 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:

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

(b) Verified properties of the sufficiently irradiated fuel, possibly resulting in an inherently subcritical material;

(c) Increased loading densities in spent fuel storage areas.

(d) Larger capacity transport packages (casks)

(e) Burnup credit may also be applied to assessments of emergency conditions, leading to a more appropriate response planning.

(f)

~~5.36~~5.48 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:

(a) Validation of the calculation methods used to predict the spent fuel composition based on the recommendations provided in paras. 4.22–4.37.

(b) Validation of the calculation methods used to predict k_{eff} for the spent fuel configurations based on the recommendations provided in paras. 4.22–4.37. Since calculations for burnup credit in spent fuel ~~may now~~ include many more nuclides than are present for fresh fuel calculations, any uncertainties in nuclear data and the conservatism applied should be justified.

(c) 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~~ absorbers, 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.~~

(d) 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.

(e) Justification of the inclusion or exclusion of specific nuclides such as fission products, of the in-growth of fissile nuclides and of the loss of neutron absorbers.

~~5.37~~5.49 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[13] (see Ref. [28]). 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.

~~5.38~~5.50 Further information and guidance on the application of burnup credit is available in Ref. [28].

5.51 The presence of burnable absorber (BA) and its effect on the neutron energy spectrum should be accounted for separately in the depletion calculations, and not as part of burnup credit.

Reprocessing

~~5.39~~5.52 Reprocessing facilities recover the uranium and plutonium from spent fuel by removing waste products (e.g. cladding, fission products~~,~~ and minor actinides) from the fuel ~~assemblies)~~ after it has been irradiated.

~~5.40~~5.53 Reprocessing operations can also include the treatment of fresh fuel, fertile material or low burnup fuel. Specific 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, and Th bearing fuels exhibit complicated dissolution behavior.

~~5.41~~5.54 The following issues are of particular importance and should be considered for criticality safety in reprocessing facilities:

(a) The wide range of forms of fissile material involved in reprocessing, potentially making the use of multiple control parameters necessary.

(b) Variations in neutron fluxes and spectra caused by other actinides.

~~(b)~~(c) The mobility of solutions containing fissile nuclides and the potential for their misdirection.

~~(c)~~(d) The need for chemistry control in order to prevent:

(i) Precipitation, colloid formation and increases of concentration in solution;

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

(ii) Unplanned separation and extraction of fissile nuclides.

~~(d)~~(e) The possibility for holdup 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).

~~(e)~~(f) The need for moderator control during furnace operations causing condensation in powders.

Wide range of forms of fissile material

~~5.42~~5.55 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 ~~and~~ 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

~~5.43~~5.56 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.

~~5.44~~5.57 The criticality safety assessment should give particular consideration to the impact of interruptions to normal operations (e.g. owing to corrective maintenance work) that 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.

~~5.45~~5.58 Operational experience has shown that misdirection 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.

~~5.46~~5.59 In any facility employing chemical processes, leaks are a constant hazard. Leaks may occur as a result of faulty welds, joints or 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 any 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. [29]).

Maintaining chemistry control

~~5.47~~5.60 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[14];

— Incomplete dissolution of fissile material.

~~5.48~~5.61 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.

~~5.49~~5.62 The effectiveness and reliability of these safety measures should be considered as part of

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

the criticality safety assessment. The process flowsheet[15], which is required by para. 6.153 of SSR-4 [1], 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.

~~5.50~~5.63 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.

Holdup and accumulation of material

~~5.51~~5.64 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.

~~5.52~~5.65 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~~. Particular consideration should be given to the possibility of accumulations of fissile nuclides 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.

~~5.53~~5.66 The next mechanism by which accumulation could occur is dissolution. Incomplete dissolution may occur as a result of a range of credible abnormal conditions; for example, low acidity, low temperature, short dissolution time, overloading of fuel and low acid volume. Subcriticality measures to be considered should include, but are not limited to, the following:

(a) Pre-dissolution control on the conditioning of acids;

(b) Monitoring of temperature and dissolution time;

[15] 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.

(c) Post-dissolution monitoring for gamma radiation (e.g. to detect residual undissolved fuel in hulls);

(d) Controls on material balance;

(e) Density measurements.

~~5.54~~5.67 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.

~~5.55~~5.68 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.

~~5.56~~5.69 Recommendations to trap leaks in equipment with favourable geometry and to provide monitored sumps to detect such leaks are provided in para. 5.54. However, it is possible that very slow leaks or leaks onto hot surfaces, where the material crystallizes before reaching the measuring point, may occur. Such losses 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

~~5.57~~5.70 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 be designed such that it does 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).~~[16]~~ Further guidance on criticality safety for reprocessing facilities is provided in IAEA Safety Standards Series No. SSG-42, Safety of Nuclear Fuel Reprocessing Facilities [30].

~~[16] A Safety Guide on the safety of reprocessing facilities is in preparation.~~

Waste management and decommissioning

5.585.71 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 or if the waste is compacted. Although the individual inventories of fissile material prior to processing are generally be small, significant accumulations of such material may occur in the subsequent waste collection and waste processing steps.

5.595.72 Waste management operations cover a very wide range of facilities, processes and materials. The following recommendations in paras 5.58–5.77 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')[17]. Waste management operations may be shielded or unshielded and may involve remote or manual handling operations. Waste management operations, particularly in a disposal facility, may 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). In contrast, decommissioning operations typically involve small inventories of fissile material.

5.605.73 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.

5.615.74 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, so as to avoid the need to repackage the waste to meet the criticality safety requirements and other transport requirements for the transport of radioactive material established in SSR-6 (Rev. 1) [6].

5.625.75 For the storage of waste containing fissile nuclides, consideration should be given to

[17] 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 [2631].

potential changes 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): see also IAEA Safety Standards Series No. WS-G-6.1, Storage of Radioactive Waste [32]. When a method for the prevention of settling of material is required to maintain a subcritical configuration, the method should be passive only. Such situations can arise in long term storage (or e.g. during the separation of fissile solids from aqueous mixtures).

5.635.76 Assessment of criticality safety for the period after the closure of a disposal facility presents particular challenges. These include the significant effect of geochemical and geophysical processes on the disposal facility during very long timescales, which should 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.

5.645.77 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:

(a) The nuclear, radiological, physical and chemical properties of the waste as parameters for waste classification;-

(b) Variation and uncertainty in the form and composition of the waste;

(c) The need to address the degradation of engineered barriers and the evolution of waste packages after emplacement over long timescales;

(d) Criticality safety requirements and other transport requirements to facilitate future transport of the waste.

Variation and uncertainty in -waste forms

5.655.78 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 shipments 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

5.665.79 The fissile inventory of spent fuel mainly consists of any remaining ^{233}U or/and ^{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-

5.675.80 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 in cases where 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 provided in IAEA Safety Standards Series No. SSG-47, Decommissioning of Nuclear Power Plants, Research Reactors and Other Nuclear Fuel Cycle Facilities [33].

5.685.81 Before beginning decommissioning operations, accumulations of fissile material 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 holdup. 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.

5.695.82 The approach used to ensure subcriticality in decommissioning may be similar to that used for research laboratory facilities (see paras. 5.85–5.91), 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 Requirement 10 of GSR Part 6 [5], an initial decommissioning plan for a facility is required to be developed and submitted to the regulatory body together with the application for authorization to operate the facility design and construction, and it is required to be maintained during facility operation and updated periodically or when specific circumstances warrant. When a facility approaches its permanent 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

5.705.83 Movement or transfer of radioactive material within a licensed site should be considered to be an on-site operation. 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 SSR-6 (Rev. 1) [6]. Further recommendations are provided in SSG-26 [10], TS-G-1.4 [19] and IAEA Safety Standards Series No. TS-G-1.5, Compliance Assurance for the Safe Transport of Radioactive Material [34].

5.84 The licensing requirements for subcriticality assessment for off-site transport differ considerably from the requirements for licensing requirements for subcriticality at facilities and for activities. other than transport. The general requirement to protect against the consequences of a criticality accident, preferably by preventing criticality applies both to transport (basis for SSR-6 and as specified in para 673(a)) and to other operations. Principally due to the requirement for multilateral approval of package designs intended for transport of fissile material, the criticality safety licensing requirements for transport are more prescriptive (“how to design a subcritical package”) rather than safety-based (“what to achieve to obtain criticality safety in actual transport”). The general requirement to prevent criticality in transport does not require licensing.

5.715.85 Due to the potential for closer contact with the public and absence of the safety amenities of a facility, the criticality safety assessment for transport is more stringent and is required to be conducted solely on the basis of a deterministic approach.

5.725.86 The potential state of a sample transport package before, during and after the tests specified in SSR-6 (Rev. 1) [6] (e.g. water spray and immersion, drop and thermal tests) provides confirmation of the assumptions made for the criticality safety assessment and analysis of the design. The specified tests may not be required if the information can be concluded from reasoned arguments, calculations using validated methods or similar tests in the past. Since the tests should verify the assumptions used in the subcriticality analysis, many tests need to be considered to cover each scenario (e.g. an individual package and a package in an array configuration). Additional safety assessment (subsequent to competent authority approval) is required for the actual transport operation (see para. 5.82).

5.1. Although the requirements established in SSR-6 (Rev. 1) [6] provide a prescriptive system for package subcriticality design assessment, they are not entirely free of engineering judgement. Often, especially for estimating the potential behaviour of a real package under accident conditions, considerable engineering expertise is required. This also applies to specifications of tests to be carried out and to interpretation of test results for verification of the subcriticality assessment assumptions. The criticality safety assessment for transport requires understanding of the potential criticality accident consequences of particular transport operations, of the basis and limitations of the package design requirements, of the administrative controls before and during transport as well as of emergency preparedness and response. It should therefore be carried out only by persons with suitable knowledge and experience of the transport requirements.

5.87 The established in SSR-6 (Rev. 1) [6]. Subcriticality assessment of a package design is one component of the criticality safety assessment. The competent authority may require specific additional actions before and during transport, some of which may require specific approval.

5.735.88 The assessment of subcriticality referred to in para. 5.81 provides a safety basis for the package design, but a subcriticality assessment for the actual transport under real conditions comply with the requirements set forth in the package design approval. Reference [6]is required by Paragraph 673 of SSR-6 (Rev. 1) [6] , which 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."[18]

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

(a) Provisions to ensure that packages of fissile material remain reliably fixed to vehicles;

(b) Vehicular speeds and road conditions;

(c) Potential for transport accidents (e.g. collisions with other vehicles);

(d) Releases of fissile material out of the confinement system (e.g. into storm drains);

(e) Interaction with other fissile material that may come close in transit.

5.90 This requirement is different to the package design requirements in SSR-6. Consideration of the actual transport conditions need to be considered, which may differ from the prescriptive design requirements. Actual package contents, actual number of packages, vehicle properties, transport mode environment, human factor consideration, etc. may lead to simpler, more accurate and transparent assessments of subcriticality. Criticality safety in transport requires more than subcriticality and emergency preparedness is required specifically in SSR-6. Any case where the potential criticality accident consequences could be much more serious, than assumed as the basis by SSR-6, should be considered. That owner of the fissile material should provide any information on special controls required and should justify any actions needed to prevent such potential consequences. In general, competent authorities in all countries involved in transport of fissile material should be aware of actual transports and should act on such information where necessary and consistent with national regulations.

5.91 The criticality safety assessment of a transport package approved according to requirements of SSR-6 (Rev. 1) [6] may rely upon this approval for the use in a facility. In such a case, it should be demonstrated that all credible abnormal conditions are bound by the existing transport package safety assessment (such as a fall from a height of more than 9 m).

Research and development laboratories

5.755.92 This publication also covers those research and development of systems and productslaboratories that that handle or utilize fissile material in sufficient quantities for criticality to be credible. 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

[18] In the context of the Transport Regulations,SSR-6 (Rev. 1) [6], fissile material includes only ^{233}U, ^{235}U, ^{239}Pu and ^{241}Pu, subject to a number of exceptions [6]..

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

~~5.76~~5.93 Because of the nature of research and development ~~nature of laboratory~~ operations, laboratories can use a wide range of fissile and non-fissile materials and separated elements and nuclides, 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[19], aluminium and various metal alloys. Examples of special fissile and non-fissile nuclides sometimes encountered include ^{233}U, ^{237}Np, ^{242}Pu, ^{241}Am, ^{242m}Am, enriched boron (e.g. ^{10}B) and enriched lithium (e.g. ^{6}Li). These nuclides 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. Materials containing significant quantities and concentrations of such nuclides should therefore receive specific consideration in the criticality safety assessments and analyses. Useful references for determining the properties of some of these nuclides include Refs. [35, 36].

Overlap of operating areas and interfaces between materials

~~5.77~~5.94 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.

~~5.78~~5.95 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

~~5.79~~5.96 Frequently, activities in a specific laboratory area may be interrupted to perform a

[19] 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.

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

~~5.80~~5.97 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

~~5.81~~5.98 Particular challenges will be encountered in determining the critical mass of unusual materials, such as some of those listed in para. 5.86 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.

~~PLANNING FOR~~ Subcritical assemblies

5.99 Subcritical assemblies are generally used for research and educational purposes. Subcritical assemblies have the potential for criticality accidents but should be considered as reactor cores; consequently, criticality safety measures, as described in the previous sections, may not be sufficient.

6 EMERGENCY PREPAREDNESS AND RESPONSE TO A CRITICALITY ACCIDENT

6.1 This Section provides recommendations on emergency preparedness and response (EPR) to a criticality accident occurring in the facilities or during the activities described in para. 1.8. It does not cover all aspects of emergency preparedness and response, however, it does highlights elements that are specific to criticality accidents. Requirements for preparedness and response to a nuclear or radiological emergency, are established in GSR Part 7 [8]. Further recommendations and guidance are provided in IAEA Safety Standard Series Nos GSG-2, Criteria for Use in Preparedness and Response for a Nuclear or Radiological Emergency [37], GS-G-2.1, Arrangements for Preparedness for a Nuclear or Radiological Emergency [38], and GSG-11, Arrangements for the Termination of a Nuclear or Radiological Emergency [39].

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 failures or events may give rise to a criticality accident. In some cases, this may give rise to exposure of persons to direct radiation (neutrons and gamma) 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

GENERAL CONSIDERATIONS FOR EMERGENCY PREPAREDNESS AND RESPONSE TO A CRITICALITY ACCIDENT

6.3 Requirement 1 of GSR Part 7 [8] states:

"The government shall ensure that an integrated and coordinated emergency management system for preparedness and response for a nuclear or radiological emergency is 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].**."**

This management system should also cover criticality events, as appropriate. Provisions are required to be in place to assign and allocate the roles and responsibilities for preparedness and response to such an emergency: see Requirement 2 of GSR Part 7 [8].

6.4 In accordance with Requirement 4 of GSR Part 7 [8], the government is required to perform a hazard assessment. This hazard assessment is required to consider criticality accidents, including those of very low probability, events not considered in the design, and combinations of events and emergencies, as described in para 4.20 of GSR Part 7 [8].

For each facility in which fissile material is handled and for which a criticality detection and alarm system is required (see para. 6.149 of SSR-4 [1]) an emergency plan, procedures and capabilities to respond to credibly criticality accidents are also required, see requirement 71 SSR-4 [1]. 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

CAUSES AND CONSEQUENCES OF A CRITICALITY ACCIDENT

6.5 plan is necessary for the facility.

6.16.6 In demonstrating the adequacy of the emergency arrangements, the potential occupational exposures and, if relevant, the dose to a member of the public exposures from external radiation exposure should be calculated. (see Para 6.150 of SSR-4 [1]).The criticality safety analysis required for emergency preparedness and response is required to consider the criticality events that have occurred at similar facilities elsewhere (GSR Part 7).

FUNCTIONAL CONSIDERATIONS FOR EMERGENCY PREPAREDNESS AND RESPONSE TO A CRITICALITY ACCIDENT

6.7 In accordance with para. 5.17 of GSR Part 7 [8], the government is required to ensure that appropriate arrangements are in place for the following:

(1) To promptly recognize and classify a criticality emergency. The operational criteria for classification are required to include emergency action levels and other observable conditions and indicators: see para. 5.16 of GSR Part 7 [8].

(2) To promptly declare the emergency class and to initiate a coordinated and pre-planned on-site response.

(3) To notify the appropriate notification point and to provide sufficient information for an effective off-site response, if needed.

(4) To initiate a coordinated and pre-planned off-site response, if needed.

As stated in para. 5.17 of GSR Part 7 [8]:

> "These arrangements shall include suitable, reliable and diverse means of warning persons on the site, of notifying the notification point … and of communication between response organizations."

6.8 Arrangements are required to be in place to mitigate the consequences of a criticality accident: see Requirement 8 of GSR Part 7 [8]. 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 excursion has occurred), portable shielding or other means of safely altering the process conditions to achieve a safe state.

6.9 Consideration should be given to limiting or terminating off-site releases by shutting down facility ventilation systems in the event of criticality accident. The possibility of an increase in hydrogen gas concentration due to radiolysis if such measures are implemented should also be considered.

6.10 In some accidents, there have been instances where ~~improper~~ incorrect actions by operating personnel have inadvertently initiated a further excursion after the initial criticality excursion. It should be ensured that operating personnel are aware 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.

~~6.2~~6.11 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 notification and evacuation of persons to a safe distance. Following this, sufficient information should be gathered to enable a planned re-entry to the facility.

6.12 The radiation dose from a criticality accident ~~may still~~can 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.

6.13 The provision of 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 effects of any penetrations through the shielding should be evaluated. When planning additional emergency shielding measures (e.g. walls), priority should be given to safe escape routes for operating personnel.

6.14 Emergency procedures are required to designate on-site 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. The emergency procedures should stress the importance of speedy evacuation and should prohibit return to the facility (re-entry) without formal authorization.

6.15 Personnel assembly points, located outside the areas to be evacuated, are required to be designated, with consideration given to the existing nuclear security requirements and the need to minimize radiation exposure.

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

6.17 Para. 5.52 of GSR Part 7 [8] states:

> "The operating organization and response organizations shall ensure that arrangements are in place for the protection of emergency workers and protection of helpers in an emergency for the range of anticipated hazardous conditions in which they might have to perform response functions."

Guidance values for restricting the exposure of emergency workers are provided in Appendix 1 of GSR Part 7 [8]. Appropriate equipment, including personal protective equipment (where appropriate) and radiation monitoring equipment, including personal dosimeters, capable of measuring the radiation emitted during a criticality accident should be provided to emergency workers. Further guidance on criticality dosimeters is provided in para. II.50 of IAEA Safety Standards Series No. GSG-7, Occupational Radiation Protection [40].

Medical considerations

6.18 Arrangements for managing the medical response in the event of a criticality accident are required to be in place, in accordance with Requirement 12 of GSR Part 7 [8]. This includes the pre-designation of medical facilities with a trained and multidisciplinary healthcare team, to provide specialized treatment for individuals exposed to a criticality event. Recommendations on medical follow up are provided in GSG-11 [39]

6.19 Relevant medical personnel are required to be made aware of the clinical symptoms of radiation exposure due to a criticality accident: see para. 5.63 of GSR Part 7 [8], which provides a classification for radiation emergencies at facilities. For some classified emergencies, means of appropriate identification (diagnosis), early medical management (treatment), prognosis, long-term medical follow-up and counselling are required. Access to these arrangements should also be provided for other facilities and activities having a criticality hazard and with a lower emergency classification. The provision of mental health and psychosocial support of individuals exposed to criticality accidents is also recommended.

6.20 The data and information to be gathered for the medical management of affected individuals should include basic contact details, information on the circumstances under which the criticality accident occurred, and any relevant medical history (e.g. previous illnesses, co-morbidities, habits). Further information on medical management of radiation injuries is provided in Ref. [41].

6.21 Trained multidisciplinary healthcare staff may be needed to provide an appropriate medical response to a criticality accident. This may include medical teams from different disciplines (e.g. haematology, neurology, radiopathology, gastroenterology, emergency); equipped medical facilities (e.g.

isolation reverse room, surgical room, intensive care units); dose assessment professionals (e.g. internal and biological dosimetry); other healthcare professionals to adequately support the medical response (e.g. medical and health physicists).

6.22 Emergency medical actions should prioritize the treatment of life threatening conditions. Appropriate medical attention to those individuals who have been significantly exposed is required to cover the triage, medical treatment, longer term medical follow-up and counselling aimed at detecting radiation induced health effects early and treating them effectively.

6.23 The medical consequences of a criticality accident could exceed the response capabilities of the State. In such cases, arrangements for international assistance are required to be in place (especially regarding medical treatment and dose assessment), in accordance with Requirement 17 of GSR Part 7 [8].

6.24 Reconstructing the doses received will be critical to the medical response. Paragraph 5.102 of GSR Part 7 [8] states:

> "Arrangements shall be made to document, protect and preserve, in an emergency response, to the extent practicable, data and information important for an analysis of the nuclear or radiological emergency and the emergency response. "

These arrangements should include comprehensive interviews on the circumstances of the criticality accident and the emergency response to be conducted with those involved.

Dose estimation

6.25 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.

6.26 The initial determination of the dose from a criticality accident should consider, at least, the following:

(a) The location of the criticality accident;

(b) The power of the criticality accident (i.e. the number of fissions that have occurred);

(c) As appropriate, 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);

(d) Estimations of the dose received by those likely to be affected (i.e. operating personnel).

6.27 It is possible that a clear picture of the location and cause of the accident may not emerge for several hours. Additional information may come from several sources (e.g. radiation monitors, eyewitness accounts, facility records). The following information should be used to refine the dose reconstruction:

(a) Details of the items of equipment involved;

(b) The radiological, physical and chemical properties of the fissile material, including quantities;

(c) The reactivity insertion mechanism that caused the system to achieve criticality;

(d) Feedback and quenching mechanisms[20] present (such as venting);

(e) An estimation of any radioactive release (see Ref. [42]).

INFRASTRUCTURAL CONSIDERATIONS FOR EMERGENCY PREPAREDNESS AND RESPONSE TO A CRITICALITY ACCIDENT

6.28 Requirements 20 and 24 of GSR Part 7 [8] state:

> **"The government shall ensure that authorities for preparedness and response for a nuclear or radiological emergency are clearly established."**
>
> **"The government shall ensure that adequate logistical support and facilities are provided to enable emergency response functions to be performed effectively in a nuclear or radiological emergency"**

The authorities for preparedness and response to a criticality accident may be very similar or identical to those established for other types of nuclear or radiological emergencies.

6.29 Each response organization is required to prepare a specific emergency plan or plans for coordinating and performing their assigned functions: see para. 6.17 of GSR Part 7 [8]. In addition, the appropriate responsible authorities are required to ensure that a 'concept of operations' for the response to a criticality accident is developed at the preparedness stage: see para. 6.18 of GSR Part 7 [8].

6.30 In accordance with Requirement 25 of GSR Part 7 [8], training, drills and exercises are required to be provided for personnel involved in the emergency response to a criticality accident, to ensure that such personnel are able to perform their assigned response functions effectively.

6.31 Criticality accidents may require knowledge, skills and abilities beyond those needed for other nuclear and radiological emergencies. References [13, 43, 44] provide detailed descriptions of the dynamic behaviour of criticality accidents that have occurred in the past. Training exercises for criticality emergencies should be provided and could be based on these references. Training in criticality emergencies should be provided to both workers and designated response staff.

[20] 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 [1713].

CAUSES AND STABILISATION OF A CRITICALITY ACCIDENT

6.36.32 Of the 22 criticality accidents in fuel processing facilities reported in Ref. [13], all but one involved fissile material in solutions or slurries (i.e. mixtures of enriched uranium or plutonium compounds with water or organic chemicals). 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:

(a) The volume of the fissile region (particularly for systems with fissile nuclides in solution).

(b) The reactivity insertion mechanism and reactivity insertion rate.-

(c) Parameters relating to reactivity feedback mechanisms, for example:

— Doppler feedback[21];

— 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.

Special consideration should be given to plutonium solutions as positive temperature reactivity feedback can occur [45, 46]. Guidance on estimating the magnitude of the fission yield can be found in Refs. [47, 48].

6.46.33 Typically, criticality accidents in solution systems have been characterized by one or several fission excursion spikes[22], particularly at the start of the transient, followed by a 'quasi-steady state' or plateau phase in which fission rates fluctuate much more slowly.

6.56.34 An assessment of the 22 criticality accidents reported in Ref. [13] 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

[21] 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.

[22] A fission excursion spike is the initial power pulse of a nuclear criticality excursion, limited by quenching mechanisms and mechanical damage [1713].

found in Ref. [17].

EMERGENCY PREPAREDNESS AND RESPONSE

6.1. 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.

6.2. evacuation of persons to a safe distance. 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.

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

6.4. 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

6.5. 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*~~

~~6.6. 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).~~

~~6.7. Management should ensure that personnel with relevant expertise are available during an emergency.~~

~~6.8. 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.~~

~~6.9. 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.~~

~~6.10. Management, in consultation with relevant staff for criticality safety, should specify the conditions and criteria under which an emergency is declared, and should specify the persons with the authority to declare such an emergency.~~

~~6.11. During an emergency response, the relevant staff for criticality safety should be available to advise and assist the nominated emergency coordinator in responding to the criticality accident.~~

~~6.12. 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*~~

~~6.13. 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.

6.14. 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.

6.15. 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;

(a) 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).

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

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

Initial evaluation of the criticality accident

6.18. 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:

(a) The location of the event, including details of the items of equipment involved;

(b)(a) The radiological, physical and chemical properties of the fissile material, including quantities;

(c)(a) The reactivity insertion mechanism that caused the system to achieve criticality;

- Feedback and quenching mechanisms[23] present (such as venting).

6.19. On the basis of this information, the relevant staff for criticality safety should make a reasonable prediction as to the likely evolution of the system with time and should advise the emergency response team on possible options for terminating the criticality and returning the system to a safe subcritical state.

6.20. 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.

6.61.1 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

6.21. 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.

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

6.23. 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

6.24. 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.

6.71.1 The emergency procedures should stress the importance of speedy evacuation and should prohibit

[23] 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 [1713].

return to the facility (re-entry) without formal authorization.

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

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

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

Re-entry, rescue and stabilization

6.28. An assessment of the state of the facility should be conducted by nominated, suitably qualified and experienced staff relevant 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.

6.29. 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.

6.30. 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.

6.86.35 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. (monitoring both gamma and neutron radiation).

6.96.36 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.

6.106.37 The emergency response plan should describe the provisions for declaring the termination of an emergency, and the emergency procedures should describe the procedures for re-entry and the membership of re-entry teams. The operating organization should take the primary responsibility for the termination of an emergency due to a criticality accident: see also Requirement 18 of GSR Part 7 [8] and the recommendations provided in GSG-11 [39]. Lines of authority and communication should be included in the emergency procedures.

Medical care

6.31. 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.

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

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

Training and exercises

6.34. 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.

6.35. Relevant 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.

6.38 If the emergency plan specifies the use of special material to shut-down or stabilize the system, such as a neutron absorber, a sufficient quantity of the material should be available. The potential for corrective actions to make the situation worse (see para 6.8) and the hazards to emergency workers should be assessed before attempting corrective action.

CRITICALITY DETECTION AND ALARM SYSTEMS

6.116.39 The need for a criticality detection and alarm system should be evaluated for all facilities and activities involving, or potentially involving, the risk of criticality. In determining this evaluation, consideration should be given to all processes, including those in which neutron moderators or reflectors more effective than water may be present.

6.126.40 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.

6.136.41 When installed, the criticality detection and alarm system is required to provide effective means of minimizing the total dose received by personnel from a criticality accident and to initiate mitigating actions.

6.146.42 Justification of any exceptions to the need to provide a criticality detection and alarm system should be provided and could be based upon the following cases:

(a) 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. The transportation of fissile materials does not require criticality detection and alarm systems for these reasons.

(b) 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.

(c) In credible abnormal conditions during transport, such as immersion of packages under water where the water provides shielding.

(c)(d) Licensed or certified transport packages for fissile material awaiting shipment or during shipment or awaiting unpacking.

6.156.43 Where the potential for criticality exists but no criticality alarm system is employed, another 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

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

Detection

6.176.45 In areas in which criticality alarm coverage is necessary, means are required to be provided to detect excessive radiation doses or dose rates and to trigger an alarm for the evacuation of personnel.

Alarm

6.186.46 The alarm signal should meet the following criteria:

(a) It should be unique (i.e. it should be immediately recognizable to personnel as a criticality alarm);

(b) 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;

(c) Systems to manually reset the alarm signal, with limited access, should be provided outside areas that require evacuation;

(d) The alarm signal should be audible in all areas to be evacuated;

(e) It should continue to alarm for a time sufficient to allow a complete evacuation;

(f) It should be supplemented with visual signals in areas with high background noise.

Dependability

~~6.19~~6.47 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.

~~6.20~~6.48 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.

~~6.21~~6.49 Warning signals indicating a malfunction but not actuating the alarm should also be provided.

Design criteria

~~6.22~~6.50 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.

~~6.23~~6.51 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.

~~6.24~~6.52 Uninterruptible power supplies should be available for the criticality detection and alarm system.

Trip point

~~6.25~~6.53 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

~~6.26~~6.54 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.

6.276.55 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 detect the minimum accident of concern should be subject to prior evaluation.

Testing

6.286.56 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.

6.296.57 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.

6.306.58 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.

6.316.59 Relevant personnel 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.

6.326.60 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.

6.336.61 Further guidance on criticality detection and alarm systems is provided in Ref. [49].

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Hand Calculation Methods

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Training and Education

TRAINING AND EDUCATION

US Department of Energy Nuclear Criticality Safety Program Nuclear Criticality Safety Engineer Training (http://ncsp.llnl.gov/trainingMain.html), (http://ncsp.llnl.gov/training..php)

- Module 1: Introductory Nuclear Criticality Physics (PDF)
- Module 2: Neutron Interactions (PDF)
- Module 3: The Fission Chain Reaction (PDF)
- Module 4: Neutron Scattering and Moderation (PDF)
- Module 5: Criticality Safety Limits (PDF)
- Module 6: Introduction to Diffusion Theory (PDF)
- Module 7: Introduction to the Monte Carlo Method (PDF)
- Module 8: Hand Calculation Methods – Part I (PDF)
- Module 9: Hand Calculation Methods – Part 2
- Module 10: Criticality Safety in Material Processing Operations – Part 1 (PDF)

- ~~Module 11: Criticality Safety in Material Processing Operations - Part 2 (PDF)~~
- ~~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)~~
- ~~Module 15: Fundamentals of Criticality Safety for Non-material Handlers (web based interactive training course)~~

Nuclear Criticality Safety Engineer Training (NCSET) modules:

— Module 1: Introductory Nuclear Criticality Physics (PDF)

— Module 2: Neutron Interactions (PDF)

— Module 3: The Fission Chain Reaction (PDF)

— Module 4: Neutron Scattering and Moderation (PDF)

— Module 5: Criticality Safety Limits (PDF)

— Module 6: Introduction to Diffusion Theory (PDF)

— Module 7: Introduction to the Monte Carlo Method (PDF)

— Module 8: Hand Calculation Methods - Part I (PDF)

— Module 9: Hand Calculation Methods - Part 2

— Module 10: Criticality Safety in Material Processing Operations — Part 1 (PDF)

— Module 11: Criticality Safety in Material Processing Operations — Part 2 (PDF)

— 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)

— Module 15: Fundamentals of Criticality Safety for Non-material Handlers (web based interactive training course)

— Module 16: Burnup Credit for Criticality Safety Analysis of Commercial Spent Nuclear Fuel (PDF)

US Department of Energy Nuclear Criticality Safety Program Oak Ridge Critical Experiment Facility History Videos

- ~~Chapter 1: Early History of Criticality Experiments http://ncsp.llnl.gov/flv/ORCEF1chapter1.html~~
- ~~Chapter 2: Purposes of Early Critical Experiment Campaigns http://ncsp.llnl.gov/flv/ORCEF1chapter2.html~~

- Chapter 3: Early ORCEF Line Organizations and Facilities http://ncsp.llnl.gov/flv/ORCEF1chapter3.html
- Chapter 4: Facility Description http://ncsp.llnl.gov/flv/ORCEF1chapter4.html
- Chapter 5: Characteristic Experimental Programs http://ncsp.llnl.gov/flv/ORCEF1chapter5.html
- Chapter 6: Polonium-Beryllium Neutron Source Experience http://ncsp.llnl.gov/flv/ORCEF1chapter6.html
- Chapter 7: Operational Safety Experiments and Analysis http://ncsp.llnl.gov/flv/ORCEF1chapter7.html
- Chapter 8: Additional ORCEF Experimentalists http://ncsp.llnl.gov/flv/ORCEF1chapter8.html
- Chapter 9: Solution Sphere Experiment http://ncsp.llnl.gov/flv/ORCEF1chapter9.html
- Chapter 10: Sponsor and Credit http://ncsp.llnl.gov/flv/ORCEF1chapter10.html

Operational Experience and Accidents and Incidents

— Chapter 1: Early History of Criticality Experiments https://ncsp.llnl.gov/videos/ORCEF1Chapter1.mp4

— Chapter 2: Purposes of Early Critical Experiment Campaigns https://ncsp.llnl.gov/videos/ORCEF1Chapter2.mp4

— Chapter 3: Early ORCEF Line Organizations and Facilities https://ncsp.llnl.gov/videos/ORCEF1Chapter3.mp4

— Chapter 4: Facility Description https://ncsp.llnl.gov/videos/ORCEF1Chapter4.mp4

— Chapter 5: Characteristic Experimental Programs https://ncsp.llnl.gov/videos/ORCEF1Chapter5.mp4

— Chapter 6: Polonium-Beryllium Neutron Source Experience https://ncsp.llnl.gov/videos/ORCEF1Chapter6.mp4

— Chapter 7: Operational Safety Experiments and Analysis https://ncsp.llnl.gov/videos/ORCEF1Chapter7.mp4

— Chapter 8: Additional ORCEF Experimentalists https://ncsp.llnl.gov/videos/ORCEF1Chapter8.mp4

— Chapter 9: Solution Sphere Experiment https://ncsp.llnl.gov/videos/ORCEF1Chapter9.mp4

— Chapter 10: Sponsor and Credit https://ncsp.llnl.gov/videos/ORCEF1Chapter10.mp4

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