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CRITICALITY SAFETY FOR FACILITIES AND ACTIVITIES HANDLING FISSIONABLE MATERIAL

DRAFT GENERAL SAFETY GUIDE GSG DS407

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CONTENTS

1. INTRODUCTION

BACKGROUND

1.1. Nuclear materials containing fissionable radionuclides are required to be managed in such a way as to ensure sub-criticality during normal operation, anticipated operational occurrences and also in the case of accident conditions within design basis accidents Ref. [1]. This applies to large commercial facilities, e.g. nuclear installations, that deal with the supply of fresh fuel and the management of spent fuel and radioactive waste containing fissionable material, including handling, processing, use, storage and disposal (operation and post-operation). This also applies to prototype research and development facilities and to activities such as the transport of packages containing fissionable materials.

1.2. The sub-criticality of a system depends on many parameters related to fissionable materials, for example, mass, concentration, geometry, enrichment or density. It is also affected by parameters related to the presence of other materials, for example, moderators, absorbers (i.e. neutron poisons) and reflectors. Criticality safety may be realised through the control of an individual parameter or a combination of parameters, e.g. by limiting mass or limiting both mass and moderation. The means for controlling these parameters is ensured by engineered features of the design and by administrative measures.

OBJECTIVE

1.3. The objective of this Safety Guide is to provide guidance and recommendations on how to meet the relevant requirements for ensuring sub-criticality when dealing with fissionable material and for planning the responses to criticality accidents. The guidance and recommendations are applicable to both regulatory bodies and operating organizations who are dealing with fissionable material. The Safety Guide presents guidance and recommendations on how to fulfil the criticality related requirements established in the following IAEA Safety Requirements publications: Safety of Nuclear Fuel Cycle Facilities [1], Safety Assessment for Facilities and Activities [2], The Management System for Facilities and Activities [3], Predisposal Management of Radioactive Waste [4], Decommissioning of Facilities Using Radioactive Material [5], Regulations for the Safe Transport of Radioactive Material [6], Geological Disposal of Radioactive Waste [7] and Preparedness and Response for a Nuclear or Radiological Emergency [8]. Safety terms are defined in the IAEA Safety Glossary [9].

SCOPE

1.4. This Safety Guide makes recommendations on how to ensure sub-criticality in systems involving fissionable materials during normal operation, anticipated operational occurrences and also in the case of accident conditions within design basis accidents from initial design, commissioning, through operation and decommissioning and disposal. It encompasses all types of facilities and activities, except facilities that are designed to be intentionally critical, e.g. a reactor core at a nuclear reactor, or a critical assembly, and systems that have been exempted from complying with the criticality safety requirements, e.g. transport regulations Ref. [6] and does not cover any activities on defence related facilities. If applicable the recommendations of this guide should be applied to operations that should remain sub-critical in nuclear power plants, e.g. storage and transportation of fresh and spent fuel. Recommendations encompass approaches to and criteria for ensuring criticality safety, conducting criticality safety assessments, including the use of data, identifying measures to ensure sub-criticality, as well as the planned response to criticality accidents.

STRUCTURE

1.5. This publication consists of six sections.

1.6. Section 2 discusses the approach to criticality safety and the safety criteria to be considered. It provides an introduction to the processes which affect criticality safety and makes recommendations for those involved as criticality specialists, the management systems that should be in place, safety margins, as well as criteria for determining exemptions to criticality safety.

1.7. Section 3 addresses the safety measures for ensuring sub-criticality, especially the importance of adequately implementing the measures, the factors affecting these measures, the roles and responsibilities for those involved in implementing the safety measures, as well as the implementation and reliability of the safety measures.

1.8. Section 4 covers criticality safety assessment, the role of deterministic and probabilistic approaches and the process by which the assessment should be carried out. It also discusses the importance of carrying out the assessment in a comprehensive manner and that any codes and data should be verified and validated. Finally, it discusses the types of controls that come out of the assessment.

1.9. Section 5 identifies a number of criticality safety practices to be considered in the areas of conversion and enrichment, fuel fabrication, spent fuel operations prior to reprocessing or disposal, the application of burnup credit, reprocessing, waste management and decommissioning, transport, and laboratories.

1.10. Section 6 deals with the responses to criticality accidents, the basic responsibilities of those involved and the need to have a plan, and the various aspects of this plan. In addition, it provides recommendations for criticality detection and alarm systems.

1.11. Definitions of some technical terms are included at the end.

1.12. A bibliography identifies sources of useful background information on criticality safety relating to assessment methodology, handbooks, computational methods, training and education and operational experience.

2. APPROACH TO ENSURING CRITICALITY SAFETY

GENERAL

2.1. Criticality safety should be ensured for all operational states and accident conditions within design basis accidents. Safety measures, either engineered or administrative, should be identified, implemented, maintained and periodically reviewed to ensure that the activity is conducted within specified operational limits and conditions that ensure the activity remains sub-critical (i.e. within a defined safety limit, see Para 2.13).

2.2. One of the main outputs from a criticality safety assessment is the identification of the operational limits and conditions necessary for controlling criticality. The criticality safety assessment should also determine whether adequate defence in depth is provided, bearing in mind that the consequences of an unshielded criticality accident can be severe and even fatal for those in the immediate vicinity. A criticality is only detected when it has occurred, this emphasises the importance of safety margins in the criticality safety assessment and compliance with operating procedures to avoid this cliff edge effect.

2.3. The processes which affect the neutron multiplication factor (K_{eff}) are often complex, non-linear and contain competing effects. Also criticality safety is generally achieved through control of a limited set of macroscopic parameters such as mass, isotopic vector, enrichment, concentration, moderation, geometry, density, reflection, interaction and neutron absorption. A description of the neutron multiplication properties of a system based on these parameters alone is incomplete, and a full description would require the use of microscopic properties such as fission, capture or scatter taking into account the environment of the fissionable materials and the interaction between fissionable materials. For these reasons there are many examples of apparently ‘anomalous’ behaviour in fissionable systems where the neutron multiplication factor changes in ways that seem counter-intuitive.

2.4. A detailed description of many of the most important ‘anomalies’ that have been observed in criticality safety is stated in Ref. [10].

MANAGEMENT SYSTEMS

2.5. Human error and related failures of supervisory/management systems have been a contributory cause in nearly all criticality accidents experienced to date. Design, safety assessment and the implementation of criticality safety measures should therefore be carried out under a clearly established and well controlled management system. The IAEA requirements and recommendations for such a management system are detailed in Refs [3] and Refs [11, 19, 28 – 30], respectively.

2.6. In the context of criticality safety the following items should be addressed:

- Management[1] should establish a comprehensive criticality safety programme for maintaining sub-criticality to ensure that measures for all aspects of criticality safety

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[1] See Definitions for the term “management”

are identified, implemented, monitored, audited and documented throughout the entire lifetime of the facility or activity. Management should ensure that any corrective action plan is updated and implemented.

- To ensure correct implementation of operating procedures for ensuring sub-criticality, management should ensure that personnel involved in handling fissionable materials are involved in writing them;

- Management should clearly define and document personnel responsibilities for criticality safety;

- Management should provide suitably qualified and experienced criticality safety staff to serve as advisors to operators, supervisors and the plant management;

- Management should ensure that changes to existing facilities or activities, or the introduction of new activities, should undergo review and assessment, and approval at the appropriate level before they are implemented, and should also ensure that operators, supervisors and plant management are retrained, as appropriate, prior to the implementation of the changes;

- Management should ensure that personnel receive training and refresher training at suitable intervals, appropriate to their level of responsibility. In particular, personnel involved in activities with fissionable material should understand the nature of the hazard posed by criticality accidents and how the risks are controlled with the established safety measures and operating limits;

- Management should arrange internal and independent inspection of the criticality safety measures, including examination of emergency arrangements, e.g. emergency evacuation routes and signage. Independent inspections should be carried out by personnel independent of the operators, but not necessarily independent of the licensee/organisation.

- Management should ensure that the safety assessments and analyses are produced and periodically reviewed.

- Management should ensure that adequate resources are available in case of any mishap/accident.

2.7. The nature of the criticality hazard is such that deviations towards a less safe condition may not be intuitively obvious to operators and there will be no obvious indication that neutron multiplication is increasing. Personnel handling fissionable materials should inform their supervisors in case of difficulties. There is also a danger that conditions may ‘creep’ with time in response to factors such as ageing of the plant or due to increased production pressures, for example. Consequently, inspection of existing facilities and activities as well as the proper control of changes in facilities and activities are particularly important for ensuring criticality safety and should be carried out regularly and the results reviewed.

2.8. Most criticality accidents have had multiple causes and there is therefore often a window of opportunity for faults to be identified by operators and supervisors and for unsafe conditions to be corrected before a criticality occurs. This highlights the importance of analysis and the transferring and sharing of operating experience, operator training and of independent inspections as part of a controlled management system.

2.9. Deviation from operational procedures and unforeseen changes in operations or conditions should be reported to management and promptly investigated. The investigation should be performed to analyze the causes of the deviation and to identify corrective actions to prevent re-occurrences. The investigation should include an analysis of the operation of the organisation and human error, and a review of the safety assessment and analyses that were previously performed including the safety measures that were originally established.

2.10. Useful information on the causes and consequences of previous criticality accidents is provided by Ref. [12].

2.11. The management system should include a means of incorporating lessons learned from operating experience and incidents and accidents to ensure the continuous improvement of operational practices and assessment methodology. Guidance and recommendations for establishing an operational feedback system are contained in Ref. [33].

SAFETY CRITERIA AND SAFETY MARGINS

2.12. In ensuring criticality safety two types of criteria should be considered:

- Safety criteria based on the value of k_{eff} (the neutron multiplication factor) for the system under analysis;

- Safety criteria based on the critical value of controlled parameters such as mass, volume, concentration, geometry, moderation, taking into account reflection, interaction and neutron absorption. The critical value is that value of a controlled parameter that would result in the system no longer being sub-critical.

2.13. In applying the criteria, safety margins should be applied to set the safety limits, within which the facilities and activities are demonstrated to be safe. This implies a value of k_{eff} somewhat less than unity and/or a controlled parameter value 'below' its critical value. In this context 'below' is used in the sense that the controlled parameter remains on the safe-side of the critical value.

2.14. In determining safety margins for k_{eff} (relative to 1) or for the value of a controlled parameter (relative to the critical value), the degree of uncertainty in the estimation of k_{eff} (in the first case), or the critical value (in the second case), including any code bias and sensitivity with respect to changes in a controlled parameter, should be considered. Note that the relationship between k_{eff} and other parameters may be significantly non-linear.

2.15. All margins adopted in criticality safety assessments should be justified and documented with sufficient detail and clarity to allow an independent review of judgement. When appropriate, justification should be by reference to national regulations or international standards, codes of practice or guidance notes that are compliant with these regulations and standards.

2.16. In defining operational limits, a criticality safety assessment should demonstrate that sufficient and appropriate safety measures are in place to detect and intercept deviations from normal operation before any safety limit is exceeded or that design features are in place which effectively avoids any criticality. Operational limits are often expressed in terms of process parameters, e.g. temperatures, liquid flows and acidity.

EXEMPTIONS

2.17. In some facilities or activities the amount of fissionable material may be so low or the isotopic composition may be such, e.g. $^{235}U/U$ < or = 1%, that a full criticality safety assessment would not be justified. Exemption criteria should be developed, reviewed by management and agreed with the regulatory body as appropriate. A useful starting point is the exception criteria applied to transport packages, Ref. [6], which represents a conservative approach.

2.18. The general principle should be that the maximum amounts of fissionable material involved are so far below critical values that no specific safety measures are necessary to ensure sub-criticality for operational states and design basis accidents.

2.19. Changes to the facility and/or activities should be evaluated to determine if the bases for the exemption are still met.

3. MEASURES FOR ENSURING SUB-CRITICALITY

GENERAL

3.1. The criticality safety measures that should be taken for ensuring sufficient sub-criticality of systems processing, handling, transporting or storing fissionable materials should be based on the defence in depth concept, Refs. [1] and [13]. Two vital parts of this concept are the features of passive safety and fault tolerance. For criticality safety the concept of the double contingency principle is the preferred method of demonstrating fault tolerance, Ref. [1].

Defence in depth

3.2. The facility and activity should be designed and operated such that defence in depth against incidents or accidents is achieved by provision of different levels of protection with the objective of preventing failures, or if prevention fails, ensuring detection and limiting the consequences. The consequences of an unshielded criticality event can be severe and even fatal for those in the immediate vicinity, and human intervention in case of a criticality can be difficult. Consequently, the primary objective should be to adopt safety measures that prevent a criticality event. However, in line with the defence in depth principle, measures should also be taken to mitigate the consequences of such an event. Application of the defence in depth concept should be aimed:

- to prevent deviations from normal operation and to prevent system failures;
- to ensure adequate margins which are sufficient to enable detection and actions to take place to prevent deviations from normal operation escalating to exceed the safety limit;
- to provide safety measures to prevent incidents progressing to criticality accidents;
- to provide measures for mitigating the radiological consequences of criticality accidents.

3.3. The defence in depth concept is generally applied in five levels. Using the general usage of defence in depth, described in Refs [1] and [13], it should be noted that the application of the fourth level of defence in depth, which deals with beyond design basis accidents and the protection of the confinement system to limit radiological releases, may not be fully applicable to criticality safety. Therefore the probability of the fourth level accident should be extremely unlikely. However, mitigation of the radiological consequences of a criticality accident, the fifth level of defence in depth, should be applied with consideration of the need for emergency arrangements.

3.4. The defence in depth concept ensures that if one level fails, it will be compensated for, or corrected by, the subsequent level. The aims for each level of protection are described in detail in Ref. [13] on which the following overview of the levels is based:

TABLE 1 OVERVIEW OF DEFENCE IN DEPTH

Level	**Objective**	**Means**

<table>
<tr><td>1</td><td>Prevent deviations from normal operation and to prevent system failures</td><td>Conservative design, construction, maintenance and operation in accordance with appropriate safety margins, engineering practices and quality levels.</td></tr>
<tr><td>2</td><td>Detect and intercept deviations from normal operation in order to prevent anticipated operational occurrences from escalating to exceed the safety limits.</td><td>Control, indication and alarm systems, operating procedures to prevent or minimize damage from failures.</td></tr>
<tr><td>3</td><td>Control the consequences of faults within the design basis to prevent a criticality accident.</td><td>Safety measures, multiple and as far as possible independent barriers, accident or fault control procedures.</td></tr>
<tr><td>4</td><td>Address accidents in which the design basis of the system may be exceeded and to ensure that the radiological consequences of a criticality accident are kept as low as reasonably practicable.</td><td rowspan="2">Provision of criticality detection and alarm systems and procedures for safe evacuation and accident management.

Use of shielding and calculated dose contours to minimise exposure.

Emergency control centre and plans for on and off-site emergency response.</td></tr>
<tr><td>5</td><td>Mitigation of radiological consequences</td></tr>
</table>

Passive safety

3.5. The passive design of the facility or activity is such that the system will remain sub-critical without the need for active engineered or operator based safety measures (other than verifying that the fissile material properties are covered by the design). This might be achieved by using inherently safe material, e.g. by using only very low enriched or natural uranium in specific chemical or physical forms. Alternatively, the facility or activity might be designed such that fissionable material is always restricted to containers which have geometrically sub-critical configurations.

3.6. The design should take account of fault tolerance in order to complement passive safety.

Fault tolerance

3.7. The double contingency principle is the preferred means of demonstrating fault tolerance for criticality safety. By virtue of this principle, a criticality accident cannot occur unless at least two unlikely, independent and concurrent events (e.g. failures, faults, errors, incidents, or accidents) occur resulting in changes in those system's characteristics and conditions which are essential to criticality safety. (Note; two events are regarded as concurrent when the second event falls in the time period required to remove the consequences of the first event).

3.8. According to the double contingency principle, if a criticality accident can occur because of the concurrent occurrence of two events, it should be shown that:

- the two events are strictly independent (not common mode);

- the probability of occurrence of each event is acceptably low;

- the system's characteristics meet the recommendations of 2.16 so that each event can be detected (e.g. monitored) with suitable and reliable means within a timeframe that allows the necessary countermeasures to be taken.

3.9. The sensitivity of the system to potential faults should be minimized. To achieve this, the system design should follow the fail safe principle and the safety measures should fulfill the single failure criterion. Any single failure or fault such as a component failure; a function control failure or a human error (e.g. instruction not followed); should not result in a criticality accident.

3.10. Where failures, perturbations or maloperations of the system or malfunctions in the system could lead to an unsafe condition, the system should have characteristics so that key parameters deviate only slowly from their normal operating values so that detection, intervention and recovery are viable to prevent a criticality accident. Where this is not possible, it should be justified that sufficient and appropriate additional safety measures are provided which prevent the fault developing into a criticality.

SAFETY MEASURES

Safety measures and safety functions

3.11. The safety measures for ensuring sufficient sub-criticality should be identified and their required safety functions should be defined. The identification and the substantiation of the safety functions should be based on an analysis of all fault sequences relevant to criticality safety arising from incidents and accidents, including; human error, initiating events, internal and external hazards, loss or failure of structures, systems and components needed for safety in operational states and design basis accidents.

3.12. Taking the physical and chemical characteristics of the fissionable material and the system into account, sufficient sub-criticality can be ensured by safety measures, (both engineered and administrative). Taking note of the lessons learned from incidents and criticality accidents, the preventative safety measures should generally observe the following hierarchy:

- Passive safety measures which do not rely on control systems, active engineered safety measures or human intervention;

- Automatically initiated active engineered safety measures (e.g. an automatically initiated shutdown system);

- Administrative safety measures;

    - Operator manually initiates an active engineered safety measure (e.g. operator initiates an automatic shutdown system in response to an indicator or alarm),

      or

- Operator provides the safety measure (e.g. operator closes a shutdown valve in response to an indicator or alarm).

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

3.14. Safety should be ensured by design features and characteristics of the system which are as near as possible to the top of the list above, but the hierarchy given by this list should not be interpreted to mean that the application of any measure towards the top of the list excludes provision of other measures where they can contribute to defence in depth.

3.15. The hierarchy of safety measures gives preference to passive geometry. If sub-criticality cannot be ensured through this means, further safety measures should be considered such as limiting:

- the isotopic composition of the fissionable material present in the system;
- the mass of the fissionable material present in the system
- the concentration of fissionable material in solutions;
- the amount of neutron moderating material associated with the fissionable material or present in the system;
- the amount of reflecting material present in the system.

3.16. The safety measures used should be related to the application of controlled parameters and their combinations. Examples of the controlled parameters are given below.

Controlled parameters

3.17. The sub-criticality of the system can be demonstrated by calculating the neutron multiplication (k_{eff}) and/or controlled by limiting one or more parameters. Parameters that may be controlled for ensuring criticality safety are as follows, but not limited to:

- Limitation of the isotopic composition of the fissionable material present in the system;
- Limitation of the mass of fissionable material within a system to the safe mass: To meet the single failure criterion the safe mass may be specified to be less than half the minimum critical mass (incorporating a suitable safety factor) so that inadvertent double batching of the system does not lead to criticality;
- Limitation of the geometry of the system to safe geometry;
- Safe limits such as safe mass, safe geometry can be evaluated either by multiplying the critical value determined by the system conditions with a safety factor or by calculation of the value which meets sub-critical k_{eff} criteria;

- Limitation of the concentration of fissionable material within a solution;
- Limitation of the amount of moderating material associated with the fissionable material;
- Limitation of the density of the materials;
- Limitation of the amount and restriction to a certain type of reflecting material surrounding the fissionable material;
- Ensuring the presence of neutron absorbers present in the system or between separate criticality safe systems;
- Limitation on distance between separate criticality safe systems.

3.18. Safety margins should consider the degree of uncertainty in a system's conditions, the probability and rate of changes in those conditions and the consequences of a potential criticality accident.

Factors affecting reactivity

3.19. The limitation of the isotopic composition of the fissionable material or the restriction to a certain type and chemical compound of the fissionable material or their combination, are essential safety measures in many cases. Their application would require safety measures which should ensure that:

- the isotopic composition limits are complied with;
- the compound to be used cannot be changed to a more reactive compound;
- a mixture of different types or different compounds resulting in a higher neutron multiplication factor cannot occur.

3.20. The presence of neutron moderating materials should be considered as they can significantly reduce the critical mass of fissionable material. Water, oil, other hydrogen and carbon containing materials and graphite are common moderators which are very often associated with the use of fissionable material. Low-atomic mass, low-neutron absorption material (e.g. deuterium, beryllium), sometimes known as "special moderators", are less common but very effective moderators. The minimum critical mass for a system may be dependent on the presence of moderating material and usually changes when the system is changed. Consideration should be given to substitution of a moderator for an alternative with lower or no moderating properties, e.g. in the case of oils there is the potential to swap long chain CH_2 type oils for oils containing units with (for instance) fluorine or chlorine present.

3.21. The presence of neutron reflecting material should be considered. Material that has less neutron absorbing properties and surrounds the fissionable material system will act as a neutron reflector and potentially increase the neutron multiplication factor of the system. The amount of increase will depend on the type, thickness, number and location of the reflecting material. Criticality safety assessments usually consider a light-water reflector of a thickness sufficient to approach the maximum neutron multiplication factor, known as "total reflection".

However, the availability of other reflector materials, or several reflector materials used in combination, should be considered (such as polyethylene, concrete, steel, lead, beryllium and aluminium) if they may result in a higher increase of the neutron multiplication factor than total reflection by light-water.

3.22. Neutron absorption should be considered. Neutron absorbers are mainly effective for thermal neutron and/or energy systems. Therefore, any neutron spectrum hardening, i.e. an increase in neutron energy, caused by operating conditions or accident conditions should be considered as they may result in a decrease in the effectiveness of the neutron absorption. Usage of a neutron absorber should therefore require safety measures that ensure that the effectiveness of the neutron absorber is not reduced in the case for which its safety function is needed. Consideration should be given to monitoring the potential long term degeneration of the neutron absorbers.

3.23. The geometrical distribution of neutron absorbers and potential changes in their distribution should be considered. Changes in geometrical distribution could include slumping, evaporation or compression. Neutron absorbers that are homogeneously distributed in a thermal neutron and/or energy system are usually more effective than if they were heterogeneously distributed (although it should be noted that heterogeneous absorbers may be easier to administratively control). In a thermal neutron and/or energy system consisting of a heterogeneous arrangement of fissionable material and a fixed neutron absorber (e.g. the storage of fuel assemblies) the neutron absorber may be more effective the closer it is to the fissionable material. Any material (e.g. water, steel) between the absorber and the fissionable material can change the effectiveness of the absorber. Solid, fixed neutron absorbers should be tested prior to first use in order to demonstrate the presence and uniformity of the absorber isotope (e.g. ^{10}B).

3.24. It should be noted that material (e.g. steam, polyethylene, concrete) located between or around fissionable materials may not only act as a reflector but may also act 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 would be dependent on the type and density of the material positioned between or around the fissionable materials. Materials with low density (such as steam or foam) can cause a significant change in the neutron multiplication factor. Any materials included or omitted from the criticality safety assessment should be justified by evaluating the effect of their treatment on the neutron multiplication.

3.25. Interaction between units of fissionable material should be considered as the interaction can affect the neutron multiplication of the system. This control parameter can be used to implement criticality control, for example by specifying minimum separation distances, (or in some cases maximum distances, for example to limit interstitial moderation between fissionable units) or introducing absorbed neutron screens. Wherever possible, separation control should be via engineered separations, e.g. fixed storage racks in fissionable material stores or space frames for storage of arrays of drums containing plutonium contaminated material.

3.26. Heterogeneity of materials, e.g. swarf 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 heterogeneity or homogeneity assumed should be considered and justified.

Safety measures should be applied that ensure that heterogeneity of the materials could not result in a higher neutron multiplication factor than considered.

ADMINISTRATIVE SAFETY MEASURES

General considerations

3.27. When administrative safety measures are employed, particularly procedural controls, the operator should demonstrate that potential deviations from such procedures have been exhaustively studied and that they understand the combinations of deviations needed to reach a dangerous situation. Human Performance/Factors specialists should be consulted to inform the operator as to the robustness, or otherwise, of the procedures and to seek improvements where appropriate.

3.28. The use of administrative safety measures should include consideration of:

- Specification and control of isotopic composition, fissionable content, mass, density, concentration, chemical composition, degree of moderation and spacing of fissionable material;

- Determination and posting of criticality controlled areas and identification of the controlled parameters assigned to these areas: Identification, specification and, where applicable, labelling of materials (fissionable materials, moderating materials, neutron absorbing materials and neutron reflecting materials), specification and, where applicable, labelling of the controlled parameters and their associated limits on which criticality safety depends. A criticality controlled area is defined both by the characteristics of the fissionable materials and the controlled parameters used;

- Control of access to criticality controlled areas where fissionable materials are handled, processed or stored;

- Separation between criticality controlled areas and separation of material positions within these controlled areas;

- Movement of materials within and between criticality controlled areas, separation of moved materials to criticality controlled areas, spacing between moved and stored materials;

- Procedural controls for computer-based/paper-based accountancy record keeping systems;

- Transfer and control of fissionable materials between criticality controlled areas using different controlled parameters;

- Transfer and control of materials from areas without criticality safety control (e.g. waste water processing) to criticality controlled areas;

- Usage of neutron absorbers: Control of continued presence, distribution and effectiveness;

- Procedures for usage and control of ancillary systems and equipment (e.g. vacuum cleaners in criticality controlled areas, control of filter systems in waste air and off-gas systems);

- Quality assurance, periodical inspection (e.g. checks on continued safe geometries), maintenance and the collection and analysis of operating experience;

- Procedures in case of anticipated operational occurrences (e.g. deviations from operating procedures, unforeseen alterations in process or system conditions) relevant to criticality safety;

- Procedures for preventing, detecting, stopping and containing leakages and removing leaked materials;

- Procedures for fire fighting (e.g. use of hydrogen-free fire extinguishing materials);

- Procedures for managing and analysis of design changes;

- Procedures for safety assessment and analysis;

- Procedures for the appointment of suitably qualified and experienced criticality safety staff;

- Procedures covering the provision of personnel training;

- Ensuring that the procedures are understood by the personnel and contractors working at the facility;

- The safety functions and safety classification of the structures, systems and components important to safety.

3.29. Before starting a new facility or a new activity with fissionable material the required engineered and administrative safety measures should be determined, prepared and independently reviewed by personnel knowledgeable in criticality safety. Likewise, before an existing facility or activity is changed the engineered and administrative safety measures should be revised and again independently reviewed.

Responsibility and delegation of authority

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

3.31. These senior persons may delegate authority for the implementation of defined criticality safety measures to supervising persons. The authority and measures that can be delegated to a supervisor should be defined and documented. Similarly, the responsibilities of the supervisors and any further delegated authority should also be defined and documented in the description of their functions.

3.32. Authority for the implementation of quality assurance measures and periodical inspections and the evaluation of the results of quality controls and periodical inspection should be assigned to persons independent of the operational personnel.

3.33. In addition to these organizational requirements management should promote, in accordance with the requirements of Ref. [3], a safety culture which makes all employees aware of the importance of criticality safety and the necessity of adequately implementing the criticality safety measures. For this purpose management should provide:

- criticality safety staff that are independent of operations management;
- the organizational means for establishing a periodical criticality safety training for the management, supervisors and operational personnel to be performed by the criticality safety staff;
- the organizational means for establishing a periodical criticality safety training for the criticality safety staff;
- the organizational means for continuously reviewing and improving the criticality safety programme and its effectiveness.

3.34. Records of participation in criticality safety trainings should be maintained and used to ensure that the recommendations for routine refresher training are identified, flagged and instigated.

3.35. The responsibilities of the criticality safety staff should be at least:

- to provide documented safety assessments for fissionable material systems;
- to provide documented criticality safety guidance for the fissionable material systems' design and processes and for the development of operating procedures;
- to specify and implement the criticality safety measures;
- to determine the location and extent of criticality controlled areas. Where applicable, to issue safety postings for these areas, labelling the materials, as well as determining the controlled parameters and their limits that apply to these areas;
- to provide assistance in determining the location of criticality detection and alarm systems and developing the associated emergency arrangements and to conduct periodic audits of these arrangements;
- to assist and consult operators, supervisors and plant management and to keep close contact with them to ensure familiarity with all fissionable material activities;

- to conduct regular walkdowns through the plant and inspections of the facilities and activities;

- to provide assistance in the generation and modification of operating procedures and to review these procedures;

- to provide documented verification of compliance with the criticality safety requirements for modifications or changes in systems' design or processes;

- to provide periodical criticality safety training for operators, supervisors and plant management.

3.36. The tasks of supervisors should be:

- to be aware of the controlled parameters and associated limits relevant to systems under their control;

- to supervise and document the compliance with the limits of the controlled parameters;

- to stop work and report unsafe conditions in the event of a deviation from normal operations.

Operating procedures

3.37. Written operating procedures should be sufficiently detailed for a qualified individual to be able to perform the required activities without the need for direct supervision and should:

- facilitate and document the safe and efficient conduct of operations;

- include those controls, limits and measures significant to criticality safety;

- include advice and guidance for the case of abnormal operation and accident conditions;

- include appropriate links between procedures to avoid omissions and duplications, and where necessary, contain clear identification of entry and exit conditions;

- be simple and understood by operators;

- be periodically reviewed in conjunction with other facility documents e.g. emergency response plan and the criticality safety assessment, to incorporate updated changes and lessons learned from experience feedback, and for training at predetermined intervals;

- written operating procedures should be in the language understood at the facility.

3.38. Revised procedures should be reviewed according to the management system. As appropriate, it should include review by the supervisors and the criticality safety staff and approved by the management responsible for criticality safety.

IMPLEMENTATION AND RELIABILITY OF SAFETY MEASURES

3.39. Maintaining sufficient sub-criticality in compliance with the principles specified in 3.1 usually requires the application of combinations of different engineered and administrative safety measures. Reliance should be placed explicitly on engineered features, specific administrative controls, and/or various administrative programmes such as material control and accountability, on and off-site transport requirements, and non-destructive assay. Where applicable, reliance may be placed on controls already present in the facility or applied to the system of interest. The hierarchy of criticality safety measures specified in 3.12 should be observed.

3.40. The application of the safety measures should be used to determine:

- the design and arrangement of safety measures such as apparatuses, casks and other components;
- the need for measurement devices for ensuring that the system conditions and operating limits are adequately monitored and controlled (e.g. the measurement of moisture in the fissionable material powder);
- the need for additional administrative measures for ensuring that the system conditions and operating limits are adequately controlled.

3.41. Implementation of the safety measures should include the requirement for quality assured examination, inspection, maintenance and testing to demonstrate that the safety functions and reliabilities are met. In-service functional testing of systems, structures and components important to safety should prove the functionality of the complete system and the safety function of each component. Where administrative controls are required as part of the safety measure, these should be included in the functional test. Other factors, which influence the selection of safety measures, should be considered. These factors include:

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

4. CRITICALITY SAFETY ASSESSMENT

GENERAL

4.1. Historically most criticality assessments have been based on a deterministic approach where a set of conservative rules and requirements concerning facilities or activities involving fissionable material are applied. In this approach the reliability of safety measures in successfully minimising, detecting and intercepting deviations in controlled parameters to prevent a criticality accident are judged mainly against a set of favourable characteristics such as independence, engineered versus administrative, passive versus active etc. Such considerations may also include a qualitative judgment of the likelihood of failure on demand of these safety measures. If these rules and requirements are met then it is inferred that the risk from criticality is acceptably low. This approach has been successfully applied over a very wide range of facilities and activities.

4.2. In more recent years it has been increasingly common to complement the deterministic approach to criticality assessment with probabilistic analyses. Probabilistic studies are usually based on realistic assumptions regarding operational conditions, rather than the conservative representation typically used in deterministic assessments. Part of the probabilistic approach is to make estimates of the frequency of the initiating event(s) which trigger the deviation from normal conditions and the probabilities of failure on demand of any safety measures. These may be combined to estimate the frequency of criticality. Using this value and combining it with the consequences (often assumed to be a single fatality per criticality accident for unshielded operations), an estimate of the criticality risk can be made and compared with risk targets or criteria if any for the facility or activity.

4.3. The probabilistic approach can be used to evaluate the extent to which the overall operations are well balanced and in some cases may provide additional insights into potential weaknesses in the design or operation which may be helpful in identifying ways of reducing risk further. Difficulties in applying the probabilistic approach are sometimes encountered in criticality assessment where one or more of the safety measures may include a significant component of operator action. The reliability of this type of safety measure can be very difficult to quantify. Also, in some cases for new types of equipment, hardware and software there may be a lack of reliability data. The uncertainties in the values of risk derived by these methods should be borne in mind before using them as the basis for significant modifications to a facility or activity.

4.4. An increasing number of regulatory bodies now require that criticality assessment should form part of an integrated safety assessment for a facility or activity rather than as a ‘stand-alone’ assessment. In addition there may be increased emphasis on consideration of risks over the complete life-cycle of the facility and materials that arise, including their ultimate disposal. This leads to the need to weigh criticality risks relative to risks from other hazards such as routine dose uptake or non-nuclear risks from handling/transport activities for example. In making these types of ‘risk-informed’ judgments the levels of conservatism incorporated into estimates of risk from the different hazards should be broadly consistent. In these circumstances the more traditional deterministic approach to criticality assessment may need to be supplemented with a more realistic analysis of the type used in probabilistic assessment.

CRITICALITY SAFETY ASSESSMENT

4.5. A criticality safety assessment should be performed prior to the commencement of any new or modified activity involving fissionable material. The criticality safety assessment should be carried out during the design, construction, commissioning and operational phases of a facility or activity, during decommissioning and post-operational clean-out, during transport and during the storage of fissionable materials.

4.6. The objectives of the criticality safety assessment should be to determine whether an adequate level of safety has been achieved, to develop appropriate limits and controls, i.e. safety measures, to prevent a criticality and to demonstrate and document compliance with appropriate safety criteria and requirements as defined by the operating organization and regulatory body.

4.7. The criticality safety assessment should include a criticality safety analysis which should evaluate criticality safety in all operational states, i.e. normal operation, anticipated operational occurrences and also in the case of accident conditions within design basis accidents. The criticality safety analysis should identify hazards, both internal and external, and fault scenarios and determine their consequences.

4.8. The criticality safety assessment and analysis should be carried out by suitably qualified and experienced criticality safety staff who are knowledgeable in all aspects of criticality safety and familiar with the facility or activity concerned.

4.9. In the criticality safety assessment the criticality safety staff should consider the possibility of inappropriate (and unexpected) operator responses to incidents (i.e. off-normal conditions). For example, operators may automatically respond to leaks of fissionable solutions by catching the material in geometrically unsafe vessels.

4.10. A systematic approach to the assessment should be adopted as outlined below:

- Define the activity involving fissionable material;
  Define the methodology for criticality safety assessment;
  Perform criticality safety analyses;
    - Calculation methods
    - Verification
    - Validation
- Identify any unique or special safety measures.

Activity involving fissionable material

4.11. The limits and extent of the activity involving fissionable material should be determined. This should be achieved by providing a description of the operations being assessed and should include all relevant systems, processes and interfaces. To provide clarity and understanding, the description of the operations should include relevant drawings, illustrations and/or graphics as well as operating procedures.

4.12. Any assumptions about the operations and assumptions about any associated systems and processes that could impact the assessment should be identified and justified. These include, but are not limited to, the administrative systems, e.g. non-destructive assay, materials control and accountability and combustible material control.

4.13. If the criticality safety assessment is limited to a particular aspect of a facility or activity, then the potential for interactions with other facilities, systems, processes and activities should be described as well as references to any related criticality safety assessments.

4.14. To ensure the accuracy of the criticality safety assessment, the criticality safety staff should, whenever possible, directly observe the activity, processes and equipment if they exist and encourage operators to provide operational feedback. The overall safety case for the facility should also be reviewed and used to identify and provide information on faults that should be considered as potential initiators of criticality accidents, e.g. sprinkler activation, glove box rupture, rack collapse, movement of fissionable material during package transport and natural phenomena.

Methodology for criticality safety assessment

4.15. The first step in the assessment should be to understand and analyse the range of normal processing conditions (i.e. normal operation). The fissionable material characteristics (e.g. mass, isotopic vector, volume, enrichment, degree of fissionable material and burnable absorber depletion, degree of fission product production/in-growth and interaction) should be identified, justified and documented. Estimates of the normal range of operating parameters including conservative/bounding estimates of any anticipated variations in those parameters should be determined, justified, documented and shown to be sub-critical.

4.16. The next step in the assessment should be to identify all credible faults (i.e. incidents and accidents leading to anticipated operational occurrences and design basis accidents). These should then be analysed and documented. The following should be considered when performing the fault analysis:

(1) All potential fault scenarios should be identified. A structured, disciplined and auditable approach should be used to identify potential faults. This approach should also include a review of available lessons learned from previous incidents and accidents and also the results of any physical testing. Typical techniques available to identify fault scenarios include:

- "What-If" methods;
- Qualitative Event or Fault Trees;
- Hazard and Operability Analysis;
- Failure Modes and Effects Analysis.

(2) Input into the analysis should also be obtained from facility operations personnel and process specialists who are thoroughly familiar with the operations and potential fault conditions that could arise.

4.17. The assessment should be performed utilizing a verified and validated methodology. The assessment should provide the documented technical basis that demonstrates sub-criticality during operational states and design basis accidents in relation with the double contingency principle or the single failure approach (see Paras 3.7 - 3.10). The criticality safety assessment should identify the safety measures, including any administrative safety measures, required to ensure sub-criticality, it should specify their safety functions and determine their reliability, redundancy, diversity, separation, system requirements and equipment qualification requirements.

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

- Reference to national consensus standards;
- Reference to accepted handbooks;
- Reference to experiments with appropriate adjustments to ensure sub-criticality when the uncertainties of parameters reported in the experiment documentation are considered; and/or;
- Use of validated calculation models and techniques.

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

Criticality safety analysis

4.20. The criticality safety analysis should demonstrate that operations are sub-critical under all operational states and that no incident or design basis accident can lead to a criticality. The criticality safety analysis should describe the demonstration of the fault tolerance of the system; see Paras 3.7 to 3.10. There is a need to identify limits and conditions necessary to control criticality risks.

Calculation methods

4.21. Calculation methods, such as computer codes and nuclear data, used in the criticality safety analysis should be verified and validated to ensure the accuracy of their predicted values and to establish their limits of applicability, bias and level of uncertainty. Verification is the process of determining that a calculation method correctly implements the intended conceptual model or mathematical model, Ref. [2]. Validation relates to the process of determining whether the overall calculation method is an adequate representation of the real system being modelled and to quantify any calculation bias and uncertainty.

4.22. 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.

4.23. When computer codes are used, the type of computing platform i.e. hardware and software, along with relevant code configuration control information should be documented.

Verification

4.24. Verification of the calculation method should be performed and periodically checked and should test the methods, mathematical or otherwise, used in the model.

Validation

4.25. After completing the verification of the calculation method and prior to its use in performing a criticality safety analysis, the calculation method should be validated against selected benchmarks which are representative of the application case. The relevance of benchmarks used to perform the validation should be determined from comparisons of the benchmarks characteristics with those of the fissionable material system being evaluated.

4.26. The selection of the benchmarks should consider:

- Benchmarks that have relatively small uncertainties as compared to any arbitrary or administratively imposed margin of sub-criticality;
- Benchmark characteristics (e.g. all isotopic and chemical compositions, neutron spectra and geometry, etc) should be similar to the fissionable material system and its operating parameters as identified in the criticality safety assessment, i.e. all operational states, including normal operation, anticipated operational occurrences and design basis accidents;
- Benchmarks should be reviewed to ensure that their neutronic, geometric, physical and chemical characteristics encompass the operational states of the fissionable material system to be evaluated. Examples of neutronic, geometric, physical or chemical characteristics that should be reviewed for all materials include, but not limited to:
    - Neutron-energy spectra throughout the individual benchmarks relative to the neutron-energy spectra throughout the fissionable material system that is the subject of the safety analysis;
    - Molecular compounds, mixtures, alloys and their chemical formulae;
    - Isotopic proportions;
    - Material densities;
    - Relative proportions or concentrations of materials such as the moderator-to-fissionable material ratio. Effective moderators are materials, typically of low atomic mass. Common materials that are effective moderators include water (i.e. hydrogen, deuterium and oxygen), beryllium, beryllium oxide, graphite (i.e. carbon). In the presence of poorly absorbing materials, such as magnesium oxide, oxygen can be an effective moderator;

- Degree of homogeneity or heterogeneity, including gradients of fissionable and non-fissionable materials;

- Geometric arrangements and compositions of the fissionable materials relative to non-fissionable material such as neutron reflectors and scatterers but including materials that are effective for parasitic absorption of neutrons (e.g. common materials include cadmium, hafnium, and gadolinium but other materials, such as iron (Fe) also act as slow neutron absorbers);

- The sensitivity of any geometry simplification should be checked, i.e. elimination of pipes, ducts, etc;

- Calculation methods should be reviewed periodically to determine if relevant new benchmark data has become available for further validation.

4.27. If no benchmark experiments exist that match the system being evaluated (e.g. low-moderated powders and waste), it may be possible to interpolate or extrapolate from other existing benchmark data to that system, by making use of trends in the bias. Where the extension is large, the method should be supplemented by other calculational 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 computed results. Sensitivity and uncertainty analysis may be used to assess the applicability of benchmark problems to the system being analyzed and to ensure an acceptable margin of sub-criticality. An important aspect of this process should be the quality of the basic nuclear data and its uncertainties.

4.28. When available, the results of the calculations should be crosschecked using independent nuclear data or different computer codes.

Unique or special safety measures

4.29. Any unique or special safety measures resulting from the criticality safety analysis and assessment should be specifically highlighted to ensure their visibility and to ensure that they are complied with. A statement of compliance with these measures should be specified and incorporated into the design or operating procedures. The requirements should be treated in accordance with a quality assurance programme, see Section 3.

5. CRITICALITY SAFETY SPECIFIC SAFETY MEASURES

GENERAL

5.1. Criticality safety is a discipline that has application to many areas of the nuclear fuel cycle and throughout the life cycle of the nuclear installations, e.g. enrichment, fuel fabrication, fuel handling, transport and storage, reprocessing of spent fuel, processing of radioactive waste and its disposal.

5.2. Fuel cycle facilities may be split into two groups: facilities where a criticality hazard is not credible, e.g. mining, milling and conversion of natural uranium facilities; and those where the criticality hazards may be credible e.g. enrichment, uranium and mixed oxide fuel fabrication, fresh fuel storage (and transport), spent fuel storage (and transport), reprocessing, waste treatment facilities and disposal facilities. Facilities in this second group should be designed and operated in a manner that ensures sub-criticality in all areas and in operational states and design basis accidents. The facilities should be operated in a manner that ensures that excessive amounts of fissionable material do not accumulate above specified limits in vessels, transfer pipes, ventilation ducts, ancillary equipment and other parts of the facilities. Particular attention should be paid to: fissionable material in waste streams at the facilities; process changes or modifications which may impact on criticality prevention; fissionable material accounting and control and analytical procedures; and controls which are used to prevent the accumulation of fissionable materials in areas which are not included within the installations (equipment) design parameters.

Type of facility and operation

5.3. The scope and level of detail to be considered in the criticality safety assessment can be influenced by the type of facility and its operation. Experimental facilities tend to have lower amounts of fissionable material and flexible working procedures; thus human errors may be more prevalent. Production/utilization facilities often have large amounts of fissionable materials, high production pressures and use well-defined processes, which may depend on both human performance and the proper functioning of process equipment. The following recommendations are applicable to both experimental and production/utilization facilities, however they have varying degrees of importance for the different kinds of facilities.

5.4. For both types of facility operating procedures, which consider criticality safety, should be developed and enforced to ensure that the activities performed in the facility remain within the approved limits and conditions identified in the criticality safety assessment.

5.5. For both types of facility the effects of production pressures should not be allowed to override criticality safety considerations.

5.6. For both types of facility the different possible errors and/or failures should be taken into account. Both human and hardware/software errors should be studied as possible initiating events for criticality accidents.

5.7. For both types of facility computational errors should be taken into account. These errors can be due to calculation errors within the facility (e.g. incorrect calculation of the amount of fissionable material present) or can be due to calculation analysis errors (e.g. inherent bias and uncertainty in the calculation or computer code input), or laboratory analytical errors (e.g. isotopic errors from faulty radiochemistry procedures, insufficient or non-representative sampling).

Life cycle issues

5.8. Criticality safety should be taken into account at various stages of the life cycle of the facilities: design, commissioning, operation (including modifications), decommissioning, and disposal to ensure that the overall risk of a criticality accident is acceptably low.

5.9. Changes due to plant ageing should be considered. The ageing effects should be monitored and their impact on criticality safety should be assessed. Periodic testing of material relied upon to maintain sub-criticality should be performed to ensure the criticality safety analysis remains valid for any actual or potential material degradation.

5.10. The impact of design changes on criticality safety, made at any part of the life cycle, should be assessed.

5.11. In addition to the factors discussed above, criticality safety assessments should be periodically reviewed.

SPECIFIC SAFETY MEASURES THROUGHOUT THE FUEL CYCLE

5.12. The remainder of this section provides guidance on specific issues that should be taken into account to ensure criticality safety in each of the main fuel cycle areas.

Conversion and enrichment

5.13. Conversion facilities refine natural uranium ores to a purified uranyl nitrate which is then typically converted to uranium hexafluoride in preparation for enrichment. Because of the isotopic composition of natural uranium (i.e. ~0.7 atom % ^{235}U) in the homogeneous processes of conversion, no criticality safety hazards are encountered. However, enrichment facilities have the potential for criticality accidents and should be protected from criticality hazards through the application of criticality safety measures that have been discussed in the previous sections. Further guidance on criticality safety for conversion and enrichment facilities is provided in Ref. [14].

Fuel fabrication

5.14. These facilities process powders, solutions and metals of uranium and/or plutonium which may have variable content in either fissile material (e.g. in ^{235}U enrichment) or in absorber material (e.g. ^{240}Pu).

5.15. These facilities can be characterised depending on the ^{235}U content for uranium fuel fabrication or for facilities mixing powders of uranium and plutonium (i.e. MOX fuel fabrication) by the Pu content in the mixture (principally, ^{239}Pu, ^{240}Pu and ^{241}Pu), and by the ^{235}U content in the composition of the uranium.

5.16. Typical control parameters used during fuel fabrication include, moderator, geometry and mass. Where moderator control is employed, the criticality safety assessment should consider the following:

- Buildings containing fissionable material should be protected from inundations of water from internal sources (e.g. use of fire fighting systems, leaks or failure of pipework) or ingress from external sources (e.g. rainfall and flooding);

- For fire fighting, procedures should be provided to ensure the safe use of extinguishants (e.g. control on volumes of materials and types and densities of materials to be used such as CO_2, water, graphite and sand);

- The storage of fissionable material should be designed to prevent its rearrangement in events such as fire fighting with high pressure water jets;

- Powders may absorb moisture. The maximum powder moisture content reached in contact with humid air should be taken into account in the criticality safety analysis. If necessary, inert and dry glovebox atmospheres should be maintained to ensure safety and quality of packaged powders. Furthermore, the application of hydrogenated materials, e.g. used as lubricants in the manufacture of pellets, should be applied with safety factors consistent with the double contingency principle. It should be noted that the criticality safety analyses for these types of material may be confounded by the limited number of experimental benchmarks to be used in validating criticality codes. Care should therefore be taken in the extrapolation of available benchmark data for these applications. Guidance for such situations is provided in 4.27.

5.17. The introduction and removal of moderating material, e.g. equipment or cleaning material, within moderation controlled environments such as gloveboxes, packaging areas or criticality controlled areas, should be monitored and controlled to avoid unsafe accumulations of moderated fissionable materials.

5.18. In the case of earthquakes, and other external hazards, buildings and equipment (e.g. gloveboxes) should be designed to ensure the safe location of the fissionable material. Similarly, for multiple separated systems relying on distance or shielding, they should be suitably fixed in place to maintain the appropriate distance and ensure the integrity of the shielding.

5.19. The production and collection of waste throughout the process should be identified and evaluated to ensure the quantities of fissionable materials for each waste container remain within specified limits.

Material cross-over

5.20. Production operations may be intermittent. To ensure adequate control during and between production campaigns, the fundamental fissionable 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 ensure that the containers and work stations remain sub-critical.

Machining/grinding/cutting (residue accumulations)

5.21. The different steps in the manufacturing process may create accumulations of fissionable material that may or may not be readily visible. A method for the periodic cleaning and accountancy checks of the facility and work stations should be defined which allows the identification and recovery of the fissionable material. For potential accumulations of fissionable materials that are not readily visible, a method for estimating and tracking of these residues should be developed to ensure that the work stations remain sub-critical. The methods to be used could be based on quantification using spectral measurements, e.g. gamma spectrometry or by a structured evaluation, estimating the volume, taking into account the contents and the densities of the material. These methods should take into account operating experiences, successive interventions, and recording of information.

5.22. Machining, grinding and cutting should ideally be undertaken without the use of coolants. However, it may not be possible to eliminate these entirely from the process or replace them with non-moderating coolants, hence the collection of residues and/or coolant is likely to require control of other parameters, particularly the use of safe geometry.

5.23. It is noted that commercial fuel production relies heavily on limiting moderators as a primary control parameter, however, the implementation of the defence in depth principle should lead to consideration of control by other parameters in preference to multiple defences against moderator ingress to a system. In many cases it is possible to include passive safety engineering such as safe geometry or fixed neutron absorbers, for example, for fuel pin/rod storage.

5.24. In addition to this guidance for fuel fabrication facilities, the recommendations in Sections 2-4 should be considered for performing criticality safety assessments and analyses. Further guidance on criticality safety for uranium and MOX fuel fabrication facilities is also provided in Refs. [15] and [16], respectively.

Handling and storage of fresh fuel

5.25. On completion of manufacture of the fresh fuel assemblies, a fresh nuclear fuel handling programme should be established with the objective of preventing a criticality when the fresh fuel is handled, stored or transported.

5.26. The principal elements of any fresh fuel handling programme should include inspection and storage of nuclear fuel. A well structured programme should adopt a methodical approach that is controlled by engineering practices and administrative procedures. The purposes of this programme should be to delineate physical boundaries within which the fresh nuclear fuel is to be stored and which are subject to practices for material control and constraints on the criticality configuration.

5.27. The storage area for fresh fuel should meet the sub-criticality requirements specified in the design and should be kept sub-critical at all times, even in the event of internal or external flooding or any other event considered in the design. Physical 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 arising. It should be verified that the fuel's enrichment is commensurate with the design limitations of the storage area.

5.28. 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 that they have not lost their effectiveness or been displaced.

5.29. Drains in dry storage areas for fresh fuel should be properly kept clear for the efficient removal of any water that may enter and they should not constitute a possible cause of flooding.

5.30. Fire risks in the fuel storage area should be minimized by preventing the accumulation of combustible material in the storage area. Instructions for fire fighting and fire fighting equipment suitable for use in case of fires involving fuel should be readily available. There should be set procedures for controlling the transfer of moderating material into the fresh fuel storage area to ensure that sub-criticality will always be maintained, even if fire extinguishing materials are used.

5.31. Further guidance for ensuring criticality safety during handling and storage of fresh fuel at nuclear power plants is provided in Ref. [32].

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

5.32. These operations are generally characterised by a requirement to handle large throughputs and retain large inventories of fissionable material in the facility. In contrast to criticality assessments for operations earlier in the fuel cycle, account may now be taken for the effects of fuel irradiation. In determining the criticality safety measures, the following factors should be noted:

- the material is now highly radioactive and will generally need to be handled remotely in shielded facilities or shielded packages;
- much of the material will need cooling for several years following discharge from the reactor, (in spent fuel ponds, for example);
- the isotopic, physical and chemical composition of the fissionable material will have changed during irradiation in the reactor and subsequent cooling;
- the fuel assemblies will have undergone physical changes during irradiation and those changes should be accounted for in the criticality safety analysis.

5.33. These factors introduce special considerations which should be addressed in the criticality safety assessment. Some of the key considerations are summarised below.

Handling accidents

5.34. The need for remote handling and the presence of heavy shielding necessary for radiation protection, introduce a set of accident conditions with the potential to damage fuel elements (e.g. leading to loss of geometry control) or to damage other structures (e.g. leading to loss of fixed absorbers). Safety measures associated with these events should include robust design of supporting structures, engineered or administrative limits on the range of movements of fuel elements and other objects in the vicinity of fuel elements, and regular testing/maintenance of handling equipment.

Maintaining fuel geometry

5.35. Maintaining spent fuel geometry during storage and handing operations is necessary to ensure criticality safety and should be assessed for all operational states and design basis accidents. This recommendation should also apply to the handling and storage of any degraded fuel, e.g. fuel with failed cladding, which has been stored in canisters. The potential for dispersion of fuel due to degradation of fuel cladding or due to fuel cladding and fuel assembly structural failures should be assessed and included in the criticality safety assessment. Note that control over fuel geometry may also be affected by corrosion of structural materials and by embrittlement of the fuel as a result of irradiation.

5.36. For stored fuel there is sometimes a requirement to remove fuel pins/rods for post-irradiation examination work which can change the moderation state of the fuel element potentially increasing its reactivity. Controls should be identified and implemented to ensure that the potential impacts of such changes are considered in the criticality safety assessment.

Loss of soluble or fixed absorbers

5.37. In some spent fuel storage ponds one component of criticality control may be the inclusion of a soluble neutron absorber (e.g. boron) in the storage pond water, further guidance is provided in Ref. [31]. In this case, the potential for accidental dilution of the soluble neutron absorber by unplanned additions of un-poisoned water should be considered in the criticality safety assessment. In some facilities the presence of high radiation fields can lead to detrimental changes in the physical and chemical form of the fixed absorber materials used for criticality control. For example, Boraflex sheets (a material composed of boron carbide, silica and polydimethyl siloxane polymer) used in some PWR and BWR spent fuel storage ponds have been found to shrink as a result of exposure to radiation creating gaps in the material and reducing the effectiveness of the neutron absorbers. In line with the recommended preference for engineered safety measures, the presence of a soluble neutron absorber in the storage pond water should not be taken into account in the criticality safety demonstration for normal operation. For certain accident conditions such as a drop of a fuel assembly, limited credit for soluble boron may be allowed in view of the double contingency principle.

5.38. The potential for degradation of these types of criticality safety measures should be included in the criticality assessment. Safety measures associated with these types of event may include restrictions on the volumes of fresh water available to cause dilution, periodic sampling of the soluble neutron absorber levels and periodic inspection/surveillance of fixed absorber materials. Sampling of soluble boron in the pond water should be representative and the level of boron should be demonstrated to be homogenous across the pond. Where soluble boron is used for criticality control, 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.

Changes in storage arrangements within a spent fuel facility

5.39. Due to its highly radioactive condition spent fuel is often stored in pond facilities for several years following discharge from the reactor core. During that time changes may be required to the storage configuration. For example, some nuclear power plants have found it necessary to re-position the spent fuel in the storage pond, i.e. to 're-rack', to increase the spent fuel ponds storage capacity. Increasing the density of fuel storage may have significant effects on the level of neutron absorbers needed to ensure sub-criticality. A reduction in the amount of interstitial water between spent fuel assemblies in a storage rack may also tend to reduce the effectiveness of fixed absorbers, see Ref. [10]. These effects should be taken into account when assessing the criticality safety of such modifications to a facility.

Misloading accidents

5.40. Some spent fuel storage facilities may 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 criticality controls. In these situations, the possibility of misloading of spent fuel into the wrong storage location should also be considered in the criticality safety assessment. Safety measures associated with this type of fault may preferably include engineered features to preclude misloading (e.g. based on the physical differences in fuel assembly design) or otherwise administrative controls and checks on fuel identity.

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

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

5.42. It has often been the practice to base criticality safety assessments of spent fuel operations on a conservative assumption using fresh fuel compositions. Alternatively, it may be possible to account for changes in k_{eff} as a result of changes in the spent fuel composition due to irradiation. This approach is commonly known as “burnup credit”. The application of burnup credit is covered in more detail later in this section. Taking credit for the burn-up of individual fuel assemblies will increase the potential for misloading accidents. Consequently, protection against misloading accidents, mentioned above, should form one of the key considerations in the criticality safety assessment for the spent fuel operations.

5.43. In addition to this guidance for spent fuel operation, the recommendations in Sections 2-4 should be considered when performing criticality safety assessments and analyses. Further guidance on criticality safety at spent fuel storage facilities is provided in Ref. [31] and for ensuring criticality safety during handling and storage of spent fuel at nuclear power plants, in Ref. [32].

Burnup credit

5.44. The changes in the spent fuel composition during irradiation normally result in a reduction in spent fuel k_{eff} relative to fresh fuel and the application of burnup credit may present several advantages as below:

- increased flexibility of operations (e.g. accepting a wider range of allowable fuel types);
- improved efficiency (e.g. increased loading densities);
- removal of other less favourable types of control (e.g. reduction in use of soluble absorbers).

5.45. On the other hand the application of burnup credit significantly increases the complexity, uncertainty and difficulty in demonstrating an adequate criticality safety margin. The criticality analysis and supporting calculations now need to determine the changes to the fuel composition during irradiation and cooling time after irradiation. Spatial variations in the spent fuel composition (resulting from variations in conditions in the reactor during burnup) should be accounted for in calculating k_{eff} for the relevant spent fuel configuration. The increase in complexity presents several challenges to the production of a suitable criticality assessment. In demonstrating the adequacy of a criticality safety assessment based on burnup credit, the following should be addressed:

- validation of the calculation methods used to predict the spent fuel composition using the guidelines presented in Para 4.21 to 4.28;
- validation of the calculation methods used to predict k_{eff} for the spent fuel configurations using the guidelines presented in Para 4.21 to 4.28 (noting that this may now include many more isotopes than present for fresh fuel calculations);
- identification and demonstration of a suitably conservative representation of the irradiation conditions, for example, amount of burnup, presence of soluble absorbers, presence of burnable poisons, coolant temperature and density, fuel temperature, power history and cooling time etc. Note, the irradiation of fuel with burnable poisons will typically result in increased reactivity early in its life. The burnup credit analysis should take account of the depletion of the burnable poison and consider the possibility that the most reactive condition may not be for the fresh fuel;
- justification of any modelling assumptions, for example, the representation of smoothly varying changes in composition (i.e. as a result of radial and axial variations in burnup) as discrete zones of materials in the calculation model;
- ensuring that Monte Carlo calculations of spent fuel configurations are properly converged.

5.46. Generally, the limits and conditions for ensuring criticality safety based on a burnup credit assessment have been based on a conservative combination of initial enrichment and burnup. This approach is commonly known as the "Safe Loading Curve" Ref [17]. In such circumstances, the criticality safety assessment should include consideration of what operational measures are necessary to ensure compliance with this curve during operations, e.g. what measurements are required 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.

5.47. Established good practices for developing criticality safety assessments should be followed as described in Sections 2-4. However, the additional complexities described above are significant and this type of assessment should only be undertaken by personnel having detailed knowledge of the methodology and its application. Further information and guidance on the application of burnup credit is available in Ref [17].

Reprocessing

5.48. Spent fuel reprocessing involves operations to separate and treat materials formed during the irradiation of fuel in nuclear power reactors and research reactors.

5.49. Reprocessing operations could also include the treatment of fresh fuel or low burnup fuel or materials for scrap recovery. Consideration should be given to supplementary criticality precautions for the control of the dissolution phase as these materials can be more difficult to dissolve.

5.50. Several chemical processes are possible for reprocessing spent fuel. In addition to general considerations for reprocessing, each process may have unique aspects, which must be considered.

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

- Reprocessing involves a wide range of forms of fissionable material and the use of multiple controlled parameters may be necessary;

- The mobility and potential for misdirection of solutions containing fissionable material;

- Maintaining chemical control in order to prevent:

    - precipitation, colloid formation, concentration increases in solution;
    - unplanned separation and extraction of fissionable material;

- Hold-up and accumulations;

    - incomplete dissolution, accumulations of fines in conditioning and vacuum vessels, chronic leaks (including leaks of liquors onto hot surfaces);

- Moderator control during furnace operations:

    - condensation in powders.

Wide range of forms of fissionable materials and need for multiple controlled parameters

5.52. The forms of fissionable materials are diverse and include:

- fuel assemblies;

- fuel rods;

- sheared fuel;

- fines or swarf;

- solutions of uranium and/or plutonium;

- oxides of uranium, plutonium or mixed uranium and plutonium;

- plutonium oxalate or mixed uranium/plutonium oxalate;

- uranium or plutonium metals;
- other compositions (e.g. minor actinides).

5.53. Moreover, fissionable materials are handled in large quantities either as a continuous stream or in large batches. To accommodate these process conditions and to ensure an adequate safety margin, criticality control should be implemented through a number of controlled parameters, e.g. control of geometry and concentration. The use of soluble neutron absorbers should, if possible, be limited, and their use should be fully justified in the criticality safety assessment. Periodic testing of material relied upon to maintain sub-criticality should be performed to ensure the criticality safety analysis remains valid for any actual or potential material degradation. In all cases, a key consideration should be the control over the amount and type of fissionable materials entering each stage of the process.

Mobility and misdirection of solutions

5.54. Many of the fissionable materials are in a mobile liquid form and due to the existence of many connections between equipment the criticality safety assessment should consider the possibility for misdirection of the fissionable material. The assessment should identify the safety measures necessary to avoid this possibility. Misdirection can lead to uncontrolled chemical phenomena (e.g. concentration or precipitation of plutonium or dilution of neutron absorbers in solution) or to a change in the safe geometry.

5.55. The criticality safety assessment should give particular attention to the impact of interruptions to normal operations, (e.g. due to corrective maintenance work), which have the potential to create unplanned changes to the flow of fissionable material. The possibility of operational personnel employing ad hoc external connections to approved pipework and vessels should also be considered.

5.56. Operational experience has shown that misdirections due to unexpected pressure differentials in the system have occurred, (e.g. due to sparging operations during clean-up). The criticality safety assessment should include consideration of these effects.

5.57. In any chemical plant leaks are a constant hazard. These may be caused by faulty welds, joints, seals etc. Ageing of the plant may also contribute to leaks through corrosion, vibration and erosion effects. In general, safe geometry drains, drip trays, recovery pans and vessels etc, should be provided to ensure that fissionable materials that could leak are safely contained. Consideration should also be given to the provision of monitored safe geometry sumps for the detection of leaks.

Maintaining chemical control

5.58. Particular attention should be given to chemical control during reprocessing. Some of the most important process parameters that could affect criticality include; acidity, concentration/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 can lead to a range of unfavourable changes, for example:

- concentration of fissionable material (by precipitation/colloid formation/extraction);
- unplanned separation of plutonium and uranium;

- carry-over of uranium and plutonium into the raffinate stream;

- incomplete dissolution.

5.59. The potential for these changes to affect criticality control 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 fissionable material concentration (e.g. in-line neutron monitoring, chemical sampling);

- monitoring of flow rates and temperature;

- testing of acidity, quality control of additives.

5.60. The effectiveness and reliability of these control measures should be considered as part of the criticality safety assessment. A process flowsheet should be used to help determine the plant response and sensitivity to changes in the process, control 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 and prevent a criticality accident. The process control time lags should be considered in maintaining chemical control.

5.61. Particular attention should be paid to the control of re-start operations following interruptions to normal process conditions. Some changes in chemical condition may occur during the period of shutdown (e.g. changes in valence state of plutonium leading to reduction in acidity, resulting in possible colloid formation) and these effects should be accounted for in re-establishing a safe operating condition.

Hold-up and accumulation

5.62. In a reprocessing facility there are many potential accumulation sites and many potential mechanisms (physical and chemical) for diverting fissionable material from the intended process flow. In addition, due to the high through-put of material, these losses may be hard to detect based solely on material accountancy. Several diverting mechanisms have already been discussed above (e.g. loss of chemical control, leaks, and misdirection). Other mechanisms that should be considered are discussed below.

5.63. The start of the reprocessing operation usually involves mechanical operations, such as shearing/sawing of the fuel to facilitate dissolution. These operations are usually made in a dry environment, so the risk of criticality is low. However, particular attention should be paid to the possibility of fissionable material accumulations in swarf, fines and other debris, becoming moderated through entrainment in subsequent wet chemistry conditions. For this reason, regular checks and housekeeping should be implemented.

5.64. The next potential accumulation mechanism occurs during dissolution. Incomplete dissolution may occur due to a range of fault conditions, e.g. low acidity, low temperature, short dissolution time, overloading of fuel and low acid volume. Criticality safety measures to be considered should include:

- pre-dissolution checks on conditioning of acid;

- monitoring of temperature and dissolution time;
- post dissolution gamma monitoring (e.g. to detect residual fission products in hulls);
- density measurements.

5.65. The effectiveness, reliability and accuracy of these measures should be considered as part of the criticality safety assessment. In particular, the possibility of non-representative sampling should be considered. Similarly, the potential settling of fines in the bottom of vessels throughout the subsequent processes should also be considered. In these cases neutron monitoring of the lower part of the vessels and periodic emptying and flushing of those vessels may be necessary.

5.66. The potential for fissionable material to remain attached to cladding following dissolution should be considered. For example, in some cases residual plutonium has been bonded to the inside surface of cladding as a result of polymerization.

5.67. The recommendations to trap leaks in safe geometry containers and the provision of monitored sumps to detect such leaks have been discussed above. However, the possibility exists for very slow leaks or leaks onto hot surfaces, where the material crystallizes before reaching the measuring point, to occur. These types of loss of material can be very difficult to detect. Safety measures for this type of event may include periodic inspections of the areas below vessels and pipework and the review of operational records to identify chronic process loss. The criticality safety assessment should consider the timescales over which unsafe accumulations could occur so that suitable inspection frequencies can be defined.

Moderator control during furnace operations

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

5.69. In addition to this guidance for reprocessing, the recommendations in Sections 2-4 should be considered for performing criticality safety assessments and analyses. Further guidance on criticality safety at reprocessing facilities is provided in Ref [36].

Waste management and decommissioning

5.70. The collection and storage of unconditioned waste before waste treatment should be subject to the same considerations as the processes from which such waste was produced. Additionally special considerations may be necessary if such waste streams are mixed with other radioactive and/or non radioactive waste streams of different origin which is frequently the case in research centres. Although in the individual laboratories the inventory of fissile material may generally be small, significant accumulation of such material may occur during the subsequent waste collection and waste treatment procedures.

5.71. Waste management operations cover a very wide range of facilities, processes and materials. The following guidance applies to packaging, interim storage and disposal operations. The guidance is intended to cover the long-term management and disposal of waste arising from operations involving fissionable material (e.g. 'Legacy Waste'[2]). The operations may be shielded or un-shielded and may involve remote or manual handling operations. Generally, this type of operation would be expected to involve large inventories (particularly in a disposal facility) of fissionable material from a wide range of sources. In the case of Legacy Waste there may also be considerable variability and uncertainty in the material properties (e.g. in the physical form and chemical composition of the non-fissionable and fissionable components of the waste material). In contrast, decommissioning operations may typically involve small inventories of fissionable material.

5.72. It should be noted that wastes are commonly wrapped with vinyl, more moderated than water. Moreover, vinyl wraps with fissionable materials are sometimes placed together so that repartition of the fissionable material is heterogeneous.

5.73. Criticality control of waste operations should be based on the application of appropriate limits on the waste package contents. Other controls may include the design of the packages and the arrangements for handling, storing and disposing of many packages within a single facility. Where practicable, package limits should be applicable to all operations along the waste management route, including disposal, so that subsequent re-packing, with its associated hazards may be avoided.

5.74. For the storage of waste containing fissile material, consideration should be given to the possible consequences of a change in the configuration of the waste, the introduction of a moderator or the removal of material (such as neutron absorbers), as a consequence of an internal or external event (e.g. movement of the waste, precipitation of solid phases from liquid waste, loss of containment of the waste or a seismic event), Ref. [35].

5.75. Assessment of post-closure criticality safety in a disposal facility presents particular challenges. Among these are the very long time scales which need to be considered. Following closure of a disposal facility engineered barriers provided by the package design and the form of the waste will tend to degrade allowing the possibility of separation, relocation and accumulation of fissionable material (as well as possible removal of absorbers from fissionable material). In addition, a previously dry environment may be replaced by a water-saturated situation.

5.76. Criticality safety assessment for waste management operations should consider the specific details of the individual facilities and processes involved. The special characteristics of waste management operations with respect to criticality assessment should include consideration of:

- variability and uncertainty in the form and composition of the waste;
- the need to address the degradation of engineered features and evolution of waste packages over long time scales.

[2] See Definitions for the term “legacy waste”.

5.77. The following is provided as an overview of some of the issues with particular relevance to waste management operations. Methodologies and standards in this area are currently in a state of development. A state-of -the-art review should be made prior to carrying out this type of assessment.

Variability and uncertainty in waste form

5.78. This is a particular challenge for some types of Legacy Waste where the accuracy and completeness of historical records may be limited. If traditional deterministic methods are applied, where bounding values are applied to all individual material parameters, the resulting package limits may prove to be very restrictive. This might then lead to an increase in the number of packages produced, resulting in more handling and transport moves and higher storage volumes, each of these carrying their own risks (from hazards such as radiological doses to operators, road/rail accidents, increased construction risks etc.). This involves a specific consideration about the optimization of the margins to be used in the criticality safety analysis. If a global risk approach is used, consideration should be given to the balance of risk between the criticality hazard and these other hazards.

Degradation of engineered features over long time scales

5.79. The fissile inventory of spent fuel mainly consists of the remaining ^{235}U and the plutonium isotopes, ^{239}Pu and ^{241}Pu. Overall, due to radioactive decay, some reduction in the fissile inventory of nuclear waste will occur over the long time scales associated with post-closure of a disposal facility. Over that time scale, significant degradation of engineered features of the waste packaging may occur, along with relocation and accumulation of fissionable and non-fissionable components. A full description of this evolution of package contents requires consideration of the geo-chemical processes involved, which are subject to significant uncertainties.

5.80. If the criticality safety design of disposal waste packages is based on the assumption that the empty spaces of the package will eventually be filled with groundwater and no burnup credit is adopted, the safety margin to criticality will be high. Consequently, future degradation of the engineered structures in the waste package with the potential for relocation of the fissile components would not necessarily lead to a criticality accident. However, if burnup credit is adopted, the safety margin to criticality will be less and consequently more sophisticated analyses and controls in waste packaging will be required. Notwithstanding the very low likelihood of a criticality, assessments of criticality in a disposal waste package should be performed to show that the consequences of such an accident are acceptably low. Assessment of post-closure criticality safety should establish that the combination of the likelihood and the consequences (i.e. the risk) of a criticality are acceptably low. Note that in this context the consequences of criticality are the resulting increases in doses to the public through any increased release of radioactive material from the disposal facility to the surface environment.

Decommissioning

5.81. To account for criticality safety during decommissioning a graded approach should be applied to consider the type of facility and therefore the fissile inventory present. Generally this Safety Guide should be applied as long as fissile material in relevant amounts is handled, so that criticality safety needs to be considered. Additional guidance and recommendations on the decommissioning of nuclear fuel cycle facilities are given in Ref. [34].

5.82. Before beginning decommissioning operations, accumulations of fissionable materials should be identified in order to assess the recovery of these materials. A method for estimating and tracking accumulations of fissionable materials that are not readily visible should be developed to ensure that the work stations remain sub-critical during decommissioning operations. The methods to be used could be based on quantification using spectral measurements (e.g. gamma spectrometry) or by a structured evaluation, estimating the volume, taking into account the contents and the densities of the material. These methods should take into account operating experiences, successive interventions, and recording of information.

5.83. The approach to criticality safety may be similar to that used for research laboratory facilities described below, where setting a low limit on allowable fissionable mass provides the basis for allowing other parameters (e.g. geometry, concentration, moderation, absorbers) to take any value. In line with general requirements on decommissioning of facilities established in Ref. [5], the initial decommissioning plan for a facility should be developed and maintained throughout the lifetime of the facility. In facilities handling significant amounts of fissionable material this plan should be supported by criticality safety assessments looking ahead to ensure that practices during the operating lifetime of the facility do not create avoidable problems during decommissioning.

5.84. In addition to this guidance for waste management and decommissioning, the recommendations in Sections 2-4 should be considered for performing criticality safety assessments and analyses.

During transport

5.85. Safe transport of radioactive material, including consideration of the criticality hazard, is detailed in Refs. [6, 18-20], which constitute IAEA safety requirements and recommendations on the subject.

5.86. It is noted that the requirements for transport criticality safety assessments differ considerably from the requirements for facility and activity criticality safety assessments. Due to the potential for closer contact with the public, the transport criticality safety assessment is more stringent and based on a solely deterministic system.

5.87. The state of the transport package after the tests specified in Ref. [6] (e.g. water spray and immersion, drops and thermal tests) provides the basis for the criticality safety assessment and analysis.

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

5.89. It is stated in the IAEA transport regulations Ref [6], that “Fissile material shall be transported so as to maintain sub-criticality during normal and accident conditions of transport; in particular, the following contingencies shall be considered:

- leakage of water into or out of packages;
- loss of efficiency of built-in neutron absorbers or moderators;
- rearrangement of the contents either within the package or as a result of loss from the package ;
- reduction of spaces within or between packages;
- packages becoming immersed in water or buried in snow;
- temperature changes”

In laboratories

5.90. This type of facility is defined as being dedicated to the research and development of systems and products that utilize fissionable materials. These facilities are generally characterized by the need for high flexibility in their operations and processes, but typically have low inventories of fissionable materials and can include both hands-on and/or remote handling operations. The general assumption of low fissile inventories may not be applicable to those laboratories which are used for fuel examinations or experiments as well as their respective waste treatment facilities.

Access to wide range of fissionable and non-fissionable materials

5.91. Due to the research and development nature of the laboratory operations, these laboratories can use a wide range of fissionable and non-fissionable materials and separated isotopes, typically including low-, intermediate-, and high-enriched uranium, plutonium that is high in ^{241}Pu content (e.g. >15 w/o), plutonium that is low in ^{240}Pu content (e.g. <5w/o), graphite, boron, gadolinium, hafnium, heavy water, zirconium, pore former, aluminium and various metal alloys. Examples of special fissionable and non-fissionable materials sometimes encountered include ^{233}U, ^{237}Np, ^{242}Pu, ^{241}Am, ^{242}Am, enriched boron (e.g. ^{10}B) and enriched lithium (e.g. ^{6}Li). These materials have diverse energy dependent nuclear reaction properties (e.g. neutron-fission, neutron-absorption, neutron-scattering, gamma-neutron, gamma-fission), which can result in non-linear, and seemingly incongruent variations of critical mass and should therefore receive specific consideration in the criticality safety assessments and analyses. Useful references for determining the properties of some of these materials include Refs [21] and [22].

5.92. The criticality assessment should consider the potential for combinations of these materials, as combinations of these materials can significantly alter the sub-criticality and safety of an intended laboratory process.

Overlap of operating areas and material interfaces

5.93. Due to the significant flexibility in operations, controls on the location and movement of fissionable material within the laboratory are important to ensuring criticality safety, any associated limits and conditions should be identified in the criticality safety assessment. The criticality safety assessment should define criticality controlled areas and identify their limiting content and boundaries.

5.94. Particular attention should therefore be given to the potential for an overlap of these controlled areas and the material interfaces between them. 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 subjected to a criticality safety analysis before the movement is approved.

Inadvertent consolidation of fissionable materials

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

Specialized education and training of personnel

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

Additional information:

5.97. In addition to this guidance for laboratories, the recommendations in Sections 2-4 should be considered for performing criticality safety analyses and assessments. Particular challenges will be encountered in determining safe sub-critical masses of the materials cited in Para 5.91as there are frequently no criticality experiment benchmarks to validate criticality computations with these materials.

6. PLANNED RESPONSE TO CRITICALITY ACCIDENTS

GENERAL

6.1. This section mainly deals with emergency response in stationary nuclear installations. Guidance on planning and preparing for an emergency response to a transport accident involving fissionable material can be found in Ref. [26].

6.2. Priority should always be given to the prevention of criticality accidents through the provision of "defence in depth". Despite all the precautions that are taken in the handling and use of fissionable material there remains a possibility, while very small, that a failure (i.e., instrumentation and controls, electrical, mechanical or operational errors) or an incident may give rise to a criticality accident. In some cases, this may give rise to exposure or the release of radioactive materials within the facility and/or into the environment, which may necessitate emergency response actions. Such emergencies may include transport accidents. Adequate preparations should be established and maintained at local and national levels and, where agreed between States, at the international level to respond to nuclear or radiological emergencies.

6.3. The requirements for developing an adequate emergency response to a nuclear or radiological emergency are provided in Ref. [8].

CAUSES AND CONSEQUENCES OF A CRITICALITY ACCIDENT

6.4. In demonstrating the adequacy of the emergency arrangements the expected external dose should be calculated. Of the 22 world-wide criticality accidents that have been reported in process facilities; 20 have occurred in solutions, one involved a slurry and one occurred with metal ingots, shown in Ref. [12]. In these events, the key physical phenomena affecting the fission yield were:

- Volume of fissionable region (particularly for solution systems);
- Reactivity insertion mechanism and rate;
- Reactivity feedback mechanisms, e.g.
  - Doppler feedback;
  - Duration time and time constant of reaction;
  - Degree of confinement;
  - Neutron spectral shifts;
  - Voiding;
  - Density changes.

6.5. Guidance for the estimation of fission yield magnitudes may be found in Ref. [23].

6.6. Typically criticality accidents in solution systems were characterised by one or several fission excursion spikes, particularly at the start of the transient, followed by a 'quasi-steady state' or plateau phase where fission rates fluctuate much more slowly.

6.7. An analysis of the 22 process accidents identified a common theme in terms of the reactivity excursion mechanism; the majority being due to increase in concentration, movement of fissionable material/reflector by gravity or flow through pipework. A detailed description of the dynamic behaviour of these process based criticality accidents can be found in Ref. [12].

EMERGENCY PREPAREDNESS AND RESPONSE

6.8. Each installation where criticality alarm systems (see Paras 6.48 & 6.49) are installed should have an emergency response plan, programme, and capabilities to respond to credible criticality accidents.

6.9. Experience of criticality accidents shows that the main risk is to operators in the immediate vicinity of the event. Generally, radiation doses to personnel more than a few tens of metres away are not life-threatening. On the other hand it is common for some types of systems, particularly solutions, to display oscillatory behaviour with multiple bursts of radiation continuing over hours or even days. Bearing this in mind the key principle in emergency planning should be prompt evacuation to a safe distance followed by a period of information gathering ahead of initiating a planned re-entry.

6.10. The radiation doses from criticality accidents may be significant, even for personnel located at some distance from the accident, and so a mechanism for identifying appropriate evacuation and control areas should be developed. Criticality alarm systems (see paras 6.48 & 6.49) should be provided and appropriate safe evacuation routes and assembly areas defined.

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

6.12. The provision of shielding should also be considered in minimising the consequences of a criticality accident. In employing shielding as a protection measure, the implications on dose of penetrations through the shielding should be evaluated.

Emergency response plan

6.13. In general the emergency response plan should:

- Define responsibilities of the management team and the technical personnel, including the criteria for notifying the relevant local and national authorities;

- Provide an evaluation of the potential criticality accident locations and the accident characteristics;

- Identify appropriate equipment, including protective clothing and radiation detection and monitoring equipment;
- Include a requirement for individual personal dosimeters to be issued;
- Consider treatment and appropriate medical care;
- Detail the actions to be taken on evacuation and the evacuation routes and the use of control areas;
- Describe arrangements and activities associated with re-entry, rescue and stabilisation;
- Discuss training, exercises and evacuation drills.

Responsibilities

6.14. Prepared emergency procedures should be established and approved according to the management system.

6.15. Management should ensure that personnel with relevant expertise are provided.

6.16. Management should ensure that organisations (including Emergency Services), on- and off-site, that are expected to provide assistance during emergencies are informed of conditions that might be encountered and offered training as appropriate. These organisations should be assisted by technical experts in preparing suitable emergency response procedures.

6.17. Management should conduct emergency exercises to ensure that workers are well aware of the emergency procedures and an awareness program for local residents.

6.18. Management, in consultation with criticality safety staff, should identify the conditions and criteria under which an emergency should be declared, and list the persons empowered to declare it.

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

6.20. The licensee should be able to conduct or have external experts to conduct a radiological dose assessment appropriate for a criticality accident.

Evaluation of potential accidents

6.21. Potential criticality accident locations should be identified and documented with appropriate facility descriptions. The predicted accident characteristics should be evaluated and documented in sufficient detail to assist emergency planning. The evaluation should include an estimate of the fission yield and the likelihood of recurrence of the criticality. Consideration should be given at the design stage to identifying measures for intervention in order to stop the criticality (e.g. the availability of neutron absorbers and the means of injecting them into the materials where the criticality has occurred).

6.22. The process of calculating the dose from an unplanned criticality incident 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/assumptions used to produce the estimate. The methodology is complex and specialised and should follow the basic steps below:

- Decide on the incident size (number of fissions);
- Decide on the incident location;
- Calculate the effect of any shielding (including the source of the criticality itself) between the incident and those likely to be affected, i.e. workforce;
- Calculate the dose received by those likely to be affected, i.e. workforce.

6.23. An emergency response plan, consistent with the documented accident evaluation, should then be established and maintained.

"During-accident" evaluation

6.24. Information on the event will come from a number of sources (e.g. radiation monitors, eye-witness accounts and plant 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 pieces of information will be:

- The location of the event, including involved equipment details;
- The physical and chemical properties of the fissionable material including quantities;
- The reactivity insertion mechanism that took the system super-critical;
- Feedback and quenching mechanisms (venting etc).

6.25. Based on this information the criticality safety staff 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 sub-critical condition.

6.26. In developing these options the criticality safety staff should be directly involved in the emergency response team and should seek advice from other known experts as necessary. A directory of such experts should be available with the emergency response plan. Once the information listed above is available useful comparisons can be made with details available from other criticality accidents, see Refs [12, 24 and 25]. This will help with predictions of the likely evolution of the current event and may also provide information as to potential methods to terminate and shut the excursion down. In some cases termination may be achieved by reversing the reactivity insertion mechanism that initiated the accident.

6.27. In some accidents there have been instances where ill-planned actions of operators after the initial accident have inadvertently initiated a further excursion. It should be borne in mind that following the initial fission spike(s) the system may have returned to a state at or very close to critical but at low fission rate. This typically occurs in solution systems where inherent negative reactivity feedback effects will tend to balance out the excess reactivity inserted during the initial stages. In this condition very small additions of reactivity may then be sufficient to initiate further fission spikes.

Instrumentation and equipment

6.28. Based on 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 as well as personal monitoring devices.

6.29. Emergency equipment (and an inventory of such) should be kept in readiness at specified locations.

6.30. Appropriate monitoring equipment, to determine if further evacuation is needed and to identify exposed individuals, should be provided at personnel assembly stations.

Evacuation

6.31. When an evacuation is initiated all personnel within the immediate evacuation zone should evacuate without hesitation and not return to the area until given permission to do so.

6.32. Emergency procedures should designate evacuation routes which should be clearly identified. Evacuation should follow the quickest and most direct routes practicable with consideration for reducing radiation exposure. Any changes to the facility should not unnecessarily impede or otherwise lengthen evacuation times.

6.33. The procedures should stress the importance of speedy evacuation and prohibit the return to the facility without formal authorisation.

6.34. Personnel assembly locations, outside the areas to be evacuated, should be designated with consideration for potential radiation exposure.

6.35. Means should be developed for ascertaining that all personnel have been evacuated from the area of the accident.

6.36. The procedure should describe the means for alerting response personnel, the public and the Authorities.

Re-entry, rescue and stabilisation

6.37. An assessment of the state of the facility should be conducted by nominated, suitably qualified and experienced criticality safety staff with the support from operators, to determine the actions to be taken on the site to limit the extent of radioactive release and spread of contamination.

6.38. The procedure should identify the criteria and radiological conditions on and off the site which would lead to evacuation of potentially affected neighbouring areas and a list of persons empowered to declare the evacuation.

6.39. 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 stations.

6.40. Re-entry during the emergency should only be made by personnel trained in emergency response and re-entry. Persons performing re-entry should be provided with personal dosimetry.

6.41. Re-entry should only be made if radiological surveys indicate that the radiation levels are acceptable. Radiation monitoring with an alarm capability should be performed during re-entry.

6.42. The criticality safety staff should determine if the system is sub-critical and advise management of methods to ensure stabilisation.

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

Medical care and treatment

6.44. Arrangements should be made in advance for the care and treatment of injured and exposed persons. The possibility of personnel contamination by radioactive materials should be considered.

6.45. Planning should also include a programme for personnel dosimetry and for the prompt identification of exposed individuals.

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

Training and exercises

6.47. Refs [12, 24 and 25] provide detailed descriptions of the dynamic behaviour of criticality accidents that have occurred in the past and could be used to develop training exercises.

6.48. Criticality safety staff should familiarise themselves with publications on criticality accidents to ensure that learning from past experience is factored into accident analyses and the emergency response plan.

CRITICALITY DETECTION AND ALARM SYSTEMS

6.49. Criticality alarm systems should be provided to mitigate, by means of quick detection and immediate evacuation alarm, the risk incurred, and the total dose received, by personnel from a criticality accident.

6.50. Exceptions to this recommendation are:

- *Where a documented analysis* concludes that no foreseeable set of circumstances can initiate a criticality accident or where the provision of criticality alarm systems offers no reduction in the risk from a criticality accident, or results in an increase in total risk, i.e., the overall risk to personnel from all hazards, including industrial, is increased.

- *Shielded facilities* in which the potential for a criticality accident is foreseeable but the resulting dose is less than the acceptable level at the outer surface. Examples of facilities which might comply are hot cells and underground stores (closed repositories)

- *Licensed/certified transport packages* for fissionable material awaiting or during shipment or awaiting unpacking (certain conditions should be met e.g. the potential for neutron interaction with other fissionable materials in adjoining areas should be negligible)

Performance and testing of criticality detection and alarm systems

Limitations and general recommendations

6.51. The guidance provided here is principally concerned with gamma-radiation rate-sensing systems. Specific detection criteria can be met with rate and/or integrating systems and systems detecting neutron or gamma radiation, and analogous considerations apply.

6.52. The need for criticality alarm systems should be evaluated for all activities involving more than a minimum critical mass. In determining these limiting masses consideration should be given to all processes in which neutron moderators or reflectors more effective than water are present.

6.53. In the above context, individual areas may be considered unrelated where the boundaries are such that there can be no inadvertent interchange of material between areas and neutron coupling is negligible.

Detection

6.54. In areas in which criticality alarm coverage is necessary, a means should be provided to detect excessive radiation dose or dose rate and to signal personnel evacuation.

Alarm

6.55. The alarm signal should:

- be unique, i.e. immediately recognisable as a criticality alarm;

- sound as soon as the accident is detected;

- be audible in all areas to be evacuated;

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- continue until evacuation is complete;
- be supplemented with visual signals in areas with high background noise.

Dependability

6.56. Consideration should be given to avoiding false alarms, for example by using concurrent response of two or more detector channels to trigger the alarm. In the evaluation consideration should be given to other hazards that may result from false alarms.

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

6.58. Warning of a malfunction without activation of the alarm should be provided.

Design criteria

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

6.60. Uninterruptible power supplies should be available for criticality detection and alarm systems.

Trip point

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

Positioning the detectors

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

6.63. In decommissioning facilities it is common practice to establish interim storage areas for items such as waste drums or to position modular containment systems around plant/equipment items requiring size reduction. The implications on the siting of such areas on the continuing ability of the criticality detectors to "see" the minimum incident of concern should need prior evaluation.

Testing

6.64. The entire alarm system should be tested periodically. Testing periods should be determined from experience and kept under review.

6.65. Instrument response to radiation should be checked periodically.

6.66. Each audible signal generator should be tested periodically. Field trials should establish 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 an audible test.

6.67. Where tests reveal inadequate performance, management should be notified immediately and agreed corrective action should be taken without delay.

6.68. The facility management should be given advance notice of testing the subsystems of the alarm system and any periods during which the system will be taken out of service. Operating rules should define the compensatory measures to be taken into account when the system is out of service.

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

6.70. Further guidance on criticality detection and alarm systems is provided in Ref. [27].

DEFINITIONS[3]

Burnup Credit

accounting for an overall reduction in reactivity associated with the irradiation of fuel in a reactor and with cooling time. Burnup credit is a criticality safety control that includes both analysis and implementation.

Depletion

the isotopic change in the concentration of one or more specified nuclides in a material of one of its constituents.

Doppler feedback

a phenomenon whereby the thermal motion of fissionable and non-fissionable 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 neutron multiplication of a system.

Initial enrichment

enrichment of fuel prior to irradiation in a reactor.

Irradiated material

material that has been exposed to radiation.

k_{eff}

the ratio of neutron production to neutron losses of a fission chain reaction – see also, neutron multiplication factor.

Legacy Waste

low-level and mixed low-level radioactive waste that may contain fissionable materials that have remained from historic fissionable material facilities and processes. Legacy waste may need to be treated before storage and/or disposal.

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[3] Definitions are included only during the development of the draft Safety Guide to aid drafting. It is intended to include the definitions, if necessary at all, as footnotes in the final draft.

Loading curve

the curve joining pairs of initial enrichment and burnup that have been demonstrated to be safely sub-critical.

Management

the person who, or group of people which, directs, controls and assesses an organization at the highest level.

Neutron multiplication factor

the ratio of neutron production to neutron losses of a fission chain reaction – see also, k_{eff}.

Pore former

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 free of flaws that have improved strength. Pore former has a neutron moderating effect.

Process flow sheet

depicts a chemical or operational engineering process that describes materials, rates, volumes, concentrations, enrichments, and masses required to attain intended results/products.

Raffinate

a liquid stream that remains after the extraction with the immiscible liquid to remove solutes from the original liquor.

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