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CRITICALITY SAFETY FOR FACILITIES AND ACTIVITIES HANDLING FISSILE MATERIAL

DRAFT GENERAL SAFETY GUIDE GSG DS407

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1. INTRODUCTION

BACKGROUND

1.1. Nuclear criticality can theoretically be caused by most fissionable nuclides belonging to the actinide elements. Some of those nuclides are also fissile, meaning that they can be critical in a “slow” neutron energy neutron flux. Accidental criticality, outside equipment designed to be critical, without the presence of fissile nuclides is not credible. This Safety Guide thus refers to criticality safety of fissile materials but also covers mixtures of fissile and other fissionable nuclides.

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

1.3. The sub-criticality of a system depends on many parameters related to the fissile material, for example, mass, concentration, geometry, enrichment or density. It is also affected by the presence of other materials, for example, moderators, absorbers and reflectors. Ensuring sub-criticality may be realised through the control of an individual parameter or a combination of parameters, e.g. by limiting mass or by limiting both mass and moderation. The means for controlling these parameters is ensured either by engineered and/or by administrative measures.

OBJECTIVE

1.4. 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 fissile material and for planning the responses to criticality accidents. The guidance and recommendations are applicable to both regulatory bodies and operating organizations. This Safety Guide presents guidance and recommendations on how to fulfil the criticality safety 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

1.5. The criticality safety objectives are to prevent a self-sustained nuclear chain reaction and to minimise the consequences if this were it to occur. This Safety Guide encompasses all types of facilities and activities that have or use fissile materials, except systems that are: designed to be intentionally critical, e.g. a reactor core at a nuclear reactor, or a critical assembly, or are covered by other regulations, e.g. transport which is performed according to transport regulations Ref. [6]. This Safety Guide does not specifically cover any activities on defence related facilities, although many aspects will be directly applicable. If applicable the recommendations of this Safety Guide may be applied to operations that should remain sub-critical in nuclear power plants, e.g. storage and handling of fresh and spent fuel. Recommendations encompass approaches to and criteria for ensuring sub-criticality, conducting criticality safety assessments, including the use of data, identifying safety measures to ensure sub-criticality, as well as the planned response to criticality accidents.

STRUCTURE

1.6. This publication consists of six sections.

1.7. Section 2 provides an introduction to the processes which affect criticality safety and provides guidance for those involved as criticality specialists, the management systems that should be in place, safety criteria and safety margins, as well as criteria for determining exemptions to specific criticality safety measures.

1.8. Section 3 provides guidance on the safety measures for ensuring sub-criticality, especially the importance of implementing adequate safety measures, the factors affecting these safety measures and the roles and responsibilities for those involved in implementing the safety measures.

1.9. Section 4 provides guidance on conducting criticality safety assessments, the role of deterministic and probabilistic approaches and the process by which the assessment should be carried out.

1.10. 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, reprocessing, waste management and decommissioning, transport, and laboratories.

1.11. Section 6 provides guidance on 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 guidance for criticality detection and alarm systems.

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

1.13. 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. Safety measures, either engineered or administrative (i.e. based on actions of operating personnel), should be identified, implemented, maintained and periodically reviewed to ensure that the activity is conducted within specified operational limits and conditions that ensure sub-criticality (i.e. within a defined safety limit, see Para 2.5).

2.2. Criticality safety is generally achieved through control of a limited set of macroscopic parameters such as mass, concentration, moderation, geometry, isotopic composition, enrichment, density, reflection, interaction and neutron absorption. A description of the neutron multiplication of a system based on these parameters alone is incomplete, and a full description would require the use of microscopic properties such as fission, capture or scatter cross sections. For these reasons there are many examples of apparently ‘anomalous’ behaviour in fissile systems where the neutron multiplication factor (k_{eff}) changes in ways that seem counter-intuitive.

2.3. An awareness of the anomalies know to date will contribute to criticality safety. A detailed description of many of the most important ‘anomalies’ that have been observed in criticality safety is stated in Ref. [10].

SAFETY CRITERIA AND SAFETY MARGINS

2.4. Safety limits should be derived according to two types of criteria:

- Safety criteria based on the value of k_{eff} (effective neutron multiplication factor) for the system under analysis;
- Safety criteria based on the critical value of a controlled parameter(s) such as mass, volume, concentration, geometry, moderation, isotopic composition and density, and taking into account neutron production, leakage, scattering, reflection, interaction and neutron absorption. The critical value is that value of a controlled parameter that would result in the system no longer being reliably known to be sub-critical.

2.5. Safety margins should be applied to determine the safety limits. This implies a value of k_{eff} 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.

2.6. In applying safety margins to k_{eff} (relative to 1) and/or to a controlled parameter (relative to the critical value), the uncertainty in the calculation of k_{eff} (in the first criteria), or the critical value (in the second criteria), including any code bias, and sensitivity with respect to changes in a controlled parameter, should be considered. In practice, uncertainties in measurement, instruments and sensor delay should also be considered. The relationship between k_{eff} and other parameters may be significantly non-linear.

2.7. In determining operational limits and conditions sufficient and appropriate safety measures should be in place to detect and intercept deviations from normal operation before any safety limit is exceeded or design features should be in place which effectively avoids any criticality. Operational limits and conditions are often expressed in terms of process parameters, e.g. temperatures, liquid flows, acidity, fissile mass and moderator content.

EXEMPTIONS

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

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

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

MANAGEMENT SYSTEMS

2.11. Human error and related failures of supervisory/management oversight have been a feature in nearly all criticality accidents experienced to date. Consequently, the human factor interface between human and engineered systems should be considered. Design, safety assessment and the implementation of criticality safety measures should 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.

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

- Management[1] should establish a comprehensive criticality safety programme to ensure that safety measures for ensuring sub-criticality are identified, implemented, monitored, audited, documented and periodically reviewed throughout the entire lifetime of the facility or activity. Management should ensure that any required corrective action plan is set up, implemented and updated when necessary;
- For the correct implementation of operating procedures used to ensure sub-criticality, management should ensure that operating personnel, involved in the handling of fissile materials, are involved in developing the operating procedures;
- Management should clearly define and identify personnel and their responsibilities for ensuring criticality safety;
- Management should provide suitably qualified and experienced criticality safety staff;
- 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 operating personnel, including supervisors, are retrained, as appropriate, prior to the implementation of the changes;
- Management should ensure that operating personnel receive training and refresher training at suitable intervals, appropriate to their level of responsibility. In particular, operating personnel involved in activities with fissile material should understand the nature of the hazard posed by criticality accidents and how the risks are controlled with the established safety measures and operational limits and conditions;
- 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 operating personnel, but not necessarily independent of the operating organisation. The inspection data should be documented and submitted for management review and action;
- Management should ensure that criticality safety assessments and analyses are established, documented and periodically reviewed;
- Management should ensure that adequate resources are available in case of any mishap/accident;
- Management should ensure that an effective safety culture is implemented, see Ref [1].

2.13. The nature of the criticality hazard is such that deviations towards a less safe condition may not be intuitively obvious and there will be no obvious indication that neutron multiplication is

[1] See Definitions for the term “management”

increasing. Operating personnel handling fissile materials should therefore inform their supervisor in case of unexpected operational deviations.

2.14. Inspection of existing facilities and activities as well as the proper control of changes in facilities and activities are particularly important for ensuring sub-criticality and should be carried out regularly and the results reviewed. 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.

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

2.16. Deviation from operational procedures and unforeseen changes in operations or conditions should be reported and promptly investigated by the management. The investigation should be performed to analyse the causes of the deviation, lessons learned 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.

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

2.18. The management system should include a means of incorporating lessons learned from national and international 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].

3. MEASURES FOR ENSURING CRITICALITY SAFETY

GENERAL

3.1. The measures that should be taken for ensuring sub-criticality of systems handling, processing, using or storing fissile material should be based on the defence in depth concept, Refs. [1]. 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 should be 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 anticipated operational occurrences 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 primary objective should be to adopt safety measures that prevent a criticality accident. However, in line with the defence in depth principle, measures should also be taken to mitigate the consequences of such an accident.

3.3. The general defence in depth concept is normally applied in five levels (see Table 1). Using the general usage of defence in depth, described in Ref. [1], the application of the fourth level of defence in depth, which deals with beyond design basis accidents (or the equivalent) and the protection of the confinement system[2] to limit radiological releases, may not be fully applicable to criticality safety. 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 a failure occurs, it will be detected and compensated for, or corrected by appropriate measures. The aim for each level of protection is described in Ref. [1] on which the following overview of the levels is based:

TABLE 1 OVERVIEW OF DEFENCE IN DEPTH

Level	**Objective**	**Means**
1	Prevent deviations from normal operation and to prevent system failures.	Conservative design, construction, maintenance and operation in accordance with appropriate safety margins, engineering practices and quality levels.
2	Detect and intercept deviations from normal	Control, indication and alarm systems,

[2] Confinement system in Ref. [6], covering transport requirements, has a different meaning

Level	Objective	Means
	operation in order to prevent anticipated operational occurrences from escalating to accident conditions.	operating procedures to maintain plant within operational state limits.
3	Control the consequences of events within the design basis (or the equivalent) to prevent a criticality accident.	Safety measures, multiple and as far as possible independent barriers or event control procedures.
4	Address accidents in which the design basis (or the equivalent) of the system may be exceeded and to ensure that the radiological consequences of a criticality accident are kept as low as reasonably practicable.	Provision of criticality detection and alarm systems and procedures for safe evacuation and accident management. Measures designed to terminate the criticality accident, e.g. injection of neutron absorbers. Use of shielding and calculated dose contours to minimise exposure..
5	Mitigation of radiological consequences.	Use of shielding and calculated dose contours to minimise exposure. Emergency control centre and plans for on and off-site emergency response.

Passive safety

3.5. The passive safety of the facility or activity should be such that the system will remain sub-critical without the need for active engineered or operating personnel based safety measures (other than verifying that the fissile material properties are covered by the design). For example, the facility or activity might be designed such that fissile material is always restricted to containers with a favourable geometry. Special care is then needed to avoid transfer to an unfavourable geometry.

Fault tolerance

3.6. The design should take account of fault tolerance in order to complement passive safety. The double contingency principle should be the preferred means of demonstrating fault tolerance. By virtue of this principle, a criticality accident cannot occur unless at least two unlikely, independent and concurrent changes in a system's characteristics and conditions, which are essential to criticality safety, have occurred.).

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

- the two events are independent (i.e. not common mode);
- the probability of occurrence of each event is acceptably low.

3.8. The system's characteristics meet the recommendations of 2.7 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 system design should follow the fail safe principle and, as a minimum, the safety measures should fulfill the single failure criterion. Any single failure or event 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 at a rate 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 initiating event developing into a criticality accident.

SAFETY MEASURES

3.11. The safety measures for ensuring 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 initiating events relevant to criticality safety arising from credible abnormal conditions, including; human error, internal and external hazards, loss or failure of structures, systems and components needed for safety in operational states and during design basis accidents (or the equivalent).

3.12. Taking note of the lessons learned from incidents and criticality accidents, the preventative safety measures should generally observe the following hierarchy:

- Passive engineered 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;

- Operating personnel manually initiate an active engineered safety measure (e.g. operating personnel initiate an automatic shutdown system in response to an indicator or alarm);

  or

- Operating personnel provide the safety measure (e.g. operating personnel close a shutdown valve in response to an indicator or alarm or bring the system into normal operational limits by adjusting controls).

3.13. In addition to 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 specified in 3.12, 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 safety. If sub-criticality cannot be ensured through this means, further safety measures should be considered.

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 effective neutron multiplication (k_{eff}) and/or controlled by limiting one or more parameters. The controlled parameters that may be considered for ensuring sub-criticality are as follows, but not limited to:

- Limitation on the geometry of the system to a favourable geometry;
- Limitation on the mass of fissile material within a system to the safe mass, e.g. 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(Note: consideration may be required to consider the potential for multiple over batching events);Limitation on the concentration of fissile nuclides within a solution;
- Limitation on the amount of moderating material associated with the fissile material;
- Limitation on the isotopic composition of the elements in the fissile material present in the system;
- Limitation on the density of the fissile materials;

- Limitation on the amount and form of reflecting material surrounding the fissile material;
- Ensuring the presence and form of neutron absorbers present in the system or between separate criticality safe systems;
- Minimum separation between separate criticality safe systems.

3.18. The parameter limitations exemplified in the above bullets 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. 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 criticality accident.

Factors affecting reactivity

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

- the limits on the isotopic composition of the elements in the fissile material are complied with;
- the compound to be used cannot change and become 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 fissile material. Hydrogen and carbon contained in materials such as water, oil and graphite are common moderators which are very often associated with the use of fissile material. Low-atomic mass, low-neutron absorption material (e.g. deuterium, beryllium, beryllium oxide) are less common but can be very effective moderators. 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 present outside the fissile material system will act as a neutron reflector and potentially increase the neutron multiplication factor of the system. Criticality safety assessments usually consider a light-water reflector of a thickness sufficient to approach the maximum neutron multiplication factor, known as "total or full 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 systems. Therefore, any neutron spectrum hardening, i.e. an increase in neutron energy, caused by operating conditions or accident conditions should be considered as this may result in a decrease in the effectiveness of the neutron absorption. 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 credible long term degeneration of the neutron absorbers.

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

3.24. Neutron absorbers that are homogeneously distributed in a thermal neutron system are usually more effective than if they were heterogeneously distributed (Note: heterogeneous absorbers may be easier to administratively control). In a thermal neutron system consisting of a heterogeneous arrangement of fissile material and a fixed neutron absorber (e.g. the storage of fuel assemblies) the neutron absorber may be more effective the closer it is to the fissile material. Any material (e.g. water, steel) between the absorber and the fissile 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). Demonstration of the continued presence and effectiveness of neutron absorbers throughout their operational lifetime should be considered.

3.25. Material (e.g. steam, polyethylene, concrete) located between or around fissile 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 fissile 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.

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

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

3.28. Temperature of materials may have multiple effects on reactivity resulting from density and neutron cross section changes and this should be considered in the criticality safety assessment.

ENGINEERED SAFETY MEASURES

Passive Engineered Safety Measures

3.29. Passive engineered safety is the highest ranked means of ensuring sub-criticality. It uses passive components rather than moving parts. These measures are highly preferred because they provide high reliability, cover a broad range of potential criticality accident scenarios, and require little operational support to maintain effectiveness. Human intervention is not required. Advantage may be taken of natural forces, such as gravity, rather than electrical, mechanical or hydraulic action. In addition, certain components that function with very high reliability based on irreversible action or change may be assigned to this category.

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

3.31. Certain components, such as rupture discs, check valves, safety valves, injectors and some solid state electronic devices, have characteristics which require special consideration before designation as an active or passive component. Any engineered component that is not a passive component is an active component, though it may be part of either an active engineered safety measure or an administrative safety measure.

Active Engineered Safety Measures

3.32. Active engineered safety measures use active components such as electrical, mechanical, or hydraulic hardware to ensure sub-criticality. These active components act by sensing a process variable important to criticality safety and providing automatic action to secure the system in a safe condition without human intervention. Active engineered safety measures are preferred when passive engineered safety measures are not feasible. These active components are subject to random failure, degradation and to human error occurring during operation and maintenance activities. Therefore, high quality, low failure rate components should be selected in all cases. Fail safe designs should be employed, if possible, and failures should be easily and quickly detectable. The use of redundant systems and components should be considered as a means of dealing with unavailability of function. Active engineered components require surveillance, periodic functional tests, and preventive and corrective maintenance to maintain effectiveness.

3.33. Examples of active components are neutron or gamma monitors, computer controlled fissile movement systems, weigh scales, process parameter trips (e.g. conductivity, flow, level, pressure and temperature), pumps, fans, relays and transistors. Active components that require human action in response to an engineered stimulus, (e.g. response to an alarm or a weigh scale value,) are administrative safety measures, though they contain active engineered components.

ADMINISTRATIVE SAFETY MEASURES

General considerations

3.34. When administrative safety measures are employed, particularly procedural controls, it should be demonstrated that credible deviations from such procedures have been exhaustively studied and that the combinations of deviations needed to reach a dangerous situation are understood. Human Performance/Factors specialists should be consulted to inform the management as to the robustness, or otherwise, of the procedures and to seek improvements where appropriate.

3.35. The use of administrative safety measures should include, but not be limited to, consideration of:

- Specification and control of isotopic composition of the elements in the fissile material, fissile nuclide content, mass, density, concentration, chemical composition, degree of moderation and spacing of fissile 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 (e.g. fissile 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 sub-criticality depends. A criticality controlled area is defined both by the characteristics of the fissile materials and the controlled parameters used;
- Control of access to criticality controlled areas where fissile 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 record keeping systems (accountancy);
- Movement and control of fissile material between criticality controlled areas using different fissile materials and/or controlled parameters;

- Movement and control of materials from areas without criticality safety control (e.g. waste water processing) to criticality controlled areas or vice versa (e.g. effluent waste streams from controlled to uncontrolled processes);
- 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, periodic inspection (e.g. control on continued favourable geometries), maintenance and the collection and analysis of operating experience;
- Procedures in case of anticipated operational occurrences (e.g. deviations from operating procedures, credible alterations in process or system conditions) relevant to ensuring sub-criticality;
- 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 operating personnel training;
- Ensuring that the procedures are understood by the operating personnel and contractors working at the facility;
- The safety functions and safety classification of the structures, systems and components important to safety (e.g. this is applicable to the design, procurement, administrative oversight of operations, and the maintenance, inspection, testing and examination).

3.36. Before starting a new facility or a new activity with fissile material the engineered and administrative safety measures should be determined, prepared and independently reviewed by operating 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.

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 ensuring sub-criticality;
- 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 the operating personnel;
- 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.

3.38. 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 ensuring sub-criticality.

Responsibility and delegation of authority

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

3.40. Management 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.

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

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

- criticality safety staff that are independent of operational personnel;
- the organizational means for establishing periodic criticality safety training to improve the safety awareness and behaviour for the management, supervisors and operating personnel to be performed by the criticality safety staff;
- the organizational means for establishing a periodic criticality safety training for the criticality safety staff;
- The organizational means to undertake periodic reviews of criticality safety assessments;

- the organizational means for continuously reviewing and improving the criticality safety programme and its effectiveness.

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

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

- to provide documented criticality safety assessments for fissile material systems;
- 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 operating personnel to provide operational feedback;
- to provide documented criticality safety guidance for the fissile material systems' design and processes and for the development of operating procedures;
- to specify the criticality limits and conditions and required safety measures and support their implementation;
- to determine the location and extent of criticality controlled 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 operating personnel, supervisors and management and to keep close contact with them to ensure familiarity with all fissile material activities;
- to conduct regular walkdowns through the facility 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 ensure that periodic criticality safety training is provided for operating personnel, supervisors and management.

3.45. The responsibilities of supervisors should include:

- 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;

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

3.46. The responsibilities of operating personnel and other personnel should be to:

- to cooperate and comply with management training, instructions and procedures.

IMPLEMENTATION AND RELIABILITY OF SAFETY MEASURES

3.47. Ensuring sub-criticality in compliance with the principles specified in 3.1 usually requires the application of combinations of different engineered and administrative safety measures. Where applicable, reliance may be placed on safety measures already present in the facility or applied to the system of interest. However, the hierarchy of criticality safety measures specified in 3.12 should be observed.

3.48. Criticality safety considerations should determine:

- the design and arrangement of safety measures;
- the need for instrumentation for ensuring that the operational limits and conditions are adequately monitored and controlled (e.g. the measurement of moisture in the fissile material dioxide powder);
- the need for additional administrative measures for ensuring that the operational limits and conditions are adequately controlled.

3.49. Safety measures should include the requirement for quality assured examination, in-service inspection and testing, and maintenance to demonstrate that the safety functions and reliabilities are met. Where administrative controls are required as part of the safety measure, these should be included in the functional test.

3.50. 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 operating personnel to recognize abnormality or failure of the safety measure;
- the ability of operating personnel to manage abnormal situations;
- operating experience.

3.51. 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 items relied upon to ensure sub-criticality should be performed to ensure the criticality safety analysis remains valid for any actual or potential material degradation.

4. CRITICALITY SAFETY ASSESSMENT

GENERAL

4.1. Criticality safety assessments have been based on a deterministic approach where a set of conservative rules and requirements concerning facilities or activities involving fissile 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.

4.2. It is also common to complement the deterministic approach to criticality safety assessment with a probabilistic approach. The probabilistic approach is based on realistic assumptions regarding operational conditions and experiences, rather than the conservative representation typically used in the deterministic approach. The probabilistic approach provides estimates of the frequency of the initiating event(s) which trigger a deviation from normal conditions and the probabilities of failure on demand of any safety measures. The frequency of the initiating event and the probabilities of failure can be combined to estimate the frequency of criticality. Using this value and the consequences (sometimes 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 is 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 safety assessment where one or more of the safety measures may include a significant component of operating personnel 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.

CRITICALITY SAFETY ASSESSMENT

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

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

4.6. The criticality safety assessment should include a criticality safety analysis which should evaluate sub-criticality in all operational states, i.e. normal operation, anticipated operational occurrences and also during design basis accidents (or the equivalent). The criticality safety analysis should identify hazards, both internal and external and determine their consequences.

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

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 relevant aspects of criticality safety and familiar with the facility or activity concerned, and should also include input from operating personnel.

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

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

- Define fissile material, its constituents, chemical and physical forms, nuclear and chemical properties etc.;
- Define activity involving the fissile material;
- Methodology for criticality safety assessment;
- Verification and validation of the calculation methods and nuclear date;
- Perform criticality safety analyses.

Define fissile material

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

Define activity involving the fissile material

4.12. The operational limits and conditions of the activity involving the fissile 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.

4.13. Any assumptions about the operations and any associated systems, processes and interfaces 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.

4.14. 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.

Methodology for criticality safety assessment

4.15. The assessment should identify all credible initiating events, i.e. incidents leading to anticipated operational occurrences and design basis accidents (or the equivalent). These should then be analysed and documented. The following should be considered when performing the analysis:

(1) All credible scenarios should be identified. A structured, disciplined and auditable approach should be used to identify credible initiating events. This approach should also include a review of available lessons learned from previous incidents and accidents and also the results of any physical testing. Techniques available to identify the scenarios include, but not limited to:

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

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

4.16. The assessment should be performed using a verified and validated methodology. The assessment should provide the documented technical basis that demonstrates sub-criticality during operational states and during design basis accidents (or the equivalent) in accordance with the double contingency principle or the single failure approach (see Para's 3.7 - 3.10). The criticality safety assessment should identify the safety measures required to ensure sub-criticality, it should specify their safety functions including their reliability, redundancy, diversity and independence requirements and also any equipment qualification requirements.

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

- Reference to national and international 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;
- Use of validated calculation models and techniques.

4.18. The applicability of reference data to the fissile 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.

Verification and validation

4.19. Calculation methods, such as computer codes and nuclear data, used in the criticality safety analysis to calculate k_{eff}, should be verified to ensure the accuracy of their derived values and to establish their limits of applicability, 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].

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

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

4.22. After completing the verification of the calculation method and prior to its use in performing a criticality safety analysis, it should be validated. Validation relates to the process of determining whether the overall calculation method adequately reflects the real system being modelled and enables the quantification of any calculation bias and uncertainty. The calculation method should be validated against selected benchmarks which are representative of the system being evaluated. The relevance of benchmarks used to perform the validation should be determined from comparisons of the benchmarks characteristics with those of the fissile material system being evaluated.

4.23. 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;
- Benchmarks should be reviewed to ensure that their neutronic, geometric, physical and chemical characteristics encompass the characteristics of the fissile material system to be evaluated. Examples of neutronic, geometric, physical or chemical characteristics that should be reviewed for all materials include, but are not limited to:
    - Molecular compounds, mixtures, alloys and their chemical formulae;
    - Isotopic proportions;
    - Material densities;
    - Relative proportions or concentrations of materials such as the moderator-to-fissile nuclide ratio. Effective moderators are materials, typically of low atomic mass. Common materials that can be 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, uniformity and non-uniformity, including gradients of fissile and non-fissile materials (e.g. spent fuel rods, settling of fissile materials such as waste, etc.);
    - Geometric arrangements and compositions of the fissile materials relative to non-fissile material such as neutron reflectors and scatterers but including materials contributing to 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 reviewed, 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.

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

Criticality safety analysis

4.25. The overall safety case for the facility should also be reviewed and used to identify and provide information on initiating events that should be considered as credible initiators of criticality accidents, e.g. sprinkler activation, glove box rupture, ventilation filter material build-up, rack collapse, movement of fissile material during package transport and natural phenomena.

4.26. 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.

4.27. If no benchmark experiments exist that encompass 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 analysed and to ensure an acceptable margin of sub-criticality. An important aspect of this process is the quality of the basic nuclear data and its uncertainties.

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

5. CRITICALITY SAFETY SPECIFIC PRACTICES

GENERAL

5.1. Criticality safety is a discipline that has application to many areas of the nuclear fuel cycle, 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, spent fuel storage, 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 operational states and during design basis accidents (or the equivalent).

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

SPECIFIC PRACTICES

5.4. 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

5.5. Conversion facilities typically purify natural uranium ore concentrate and convert it to the chemical forms required for the manufacture of nuclear fuel, i.e. uranium metal, uranium oxide, or uranium hexafluoride in preparation for enrichment.

5.6. 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.

5.7. Conversion facilities can also be used for enrichment of regenerated uranium, which has a higher enrichment than natural uranium and in some conditions can lead to criticality.

5.8. 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

5.9. 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. Gadolinium).

5.10. 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 of its isotopic composition (principally ^{239}Pu, ^{240}Pu and ^{241}Pu) and by the ^{235}U content in the uranium.

5.11. A typical controlled parameter used during fuel fabrication is moderation. Where moderator control is employed, the criticality safety assessment should consider the following:

- Buildings containing fissile 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);
- In order to prevent water leakage and unexpected changes of criticality safety control conditions, air rather than water should be used for heating or cooling in some facilities for fissile material storage or processing. If not practical, limiting the amount of water that can leak should be considered.
- For fire fighting, procedures should be provided to ensure the safe use of extinguishants (e.g. control on materials and densities of materials to be used such as CO_2, water, foam, dry powders and sand);
- The storage of fissile material should be designed to prevent its 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. 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;
- 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 fissile materials.

5.12. 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 fissile material. Similarly, for multiple separated systems relying on distance or neutron absorbers, they should be suitably fixed in place to maintain the appropriate distance and ensure the integrity of the shielding.

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

Machining/grinding/cutting (residue accumulations)

5.14. The different steps in the manufacturing process may create accumulations of fissile material that may or may not be readily visible. A method for the periodic cleaning and accountancy control of the facility and work stations should be defined which allows the identification and recovery of the fissile material. For credible accumulations of fissile materials that are not readily visible, a method for estimating and tracking of these residues should be developed to ensure that the work stations and ventilation systems 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. Consideration should be given for process and ventilation entrainment of fissile materials due to the velocity of the transport medium. Periodic inspection of equipment that may accumulate fissile materials may be required.

5.15. Machining, grinding and cutting should ideally be undertaken without the use of coolants. However, for safety reasons, 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 favourable geometry.

5.16. 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

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

5.18. 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.

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

5.20. 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.

5.21. 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)

5.22. These operations are generally characterised by a requirement to handle large throughputs and retain large inventories of fissile 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 fissile material will have changed during irradiation in the reactor and subsequent radioactive decay;
- the fuel assemblies will have undergone physical changes during irradiation.

Handling accidents

5.23. The need for remote handling and the presence of heavy shielding necessary for radiation protection introduce a set of design basis accidents 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

5.24. Maintaining spent fuel geometry during storage and handling operations is necessary to ensure sub-criticality and should be assessed for all operational states and during design basis accidents (or the equivalent). This recommendation should also apply to the handling and storage of any degraded fuel, e.g. fuel with failed cladding, 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. Control over fuel geometry may also be affected by corrosion of structural materials and by embrittlement of the fuel as a result of irradiation.

5.25. For stored fuel there is sometimes a requirement to remove or repair fuel pins/rods which can change the moderation ratio of the fuel element potentially increasing its reactivity. Criticality safety assessments should be performed to consider the impact of those operations.

Loss of soluble or fixed absorbers

5.26. In some spent fuel storage ponds one component of criticality safety 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.

5.27. 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 safety 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. For certain accident conditions such as a drop of a fuel assembly, limited credit for soluble neutron absorbers may be allowed.

5.28. 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 homogeneous across the pond. Where soluble boron is used for criticality safety 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

5.29. 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.

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

Misloading accidents

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

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

5.32. Usually, fresh fuel composition is assumed in criticality safety assessments for operations involving spent fuel. Alternatively, it may be possible to account of reductions in k_{eff} as a result of changes in the spent fuel composition due to irradiation. This approach is commonly known as "burnup credit". It is an option, as opposed to the peak k_{eff} approach, for which an assessment is required whenever k_{eff} may increase due to irradiation. The application of burnup credit is covered in more detail later in this section.

5.33. 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.

5.34. Further guidance on criticality safety at spent fuel storage facilities is provided in Ref. [31] and for ensuring sub-criticality during handling and storage of spent fuel at nuclear power plants, in Ref. [32].

Burnup credit

5.35. The changes in the spent fuel composition during irradiation eventually result in a reduction in spent fuel k_{eff} relative to the peak k_{eff} approach, for which an assessment is required whenever k_{eff} may increase due to irradiation. The application of burnup credit may present several advantages as below:

- increased flexibility of operations and simplification of administrative requirements (e.g. accepting a wider range of allowable fuel types);
- verified properties of the irradiated fuel may result in an inherently sub-critical material.
- improved efficiency (e.g. increased loading densities in spent fuel storage).

5.36. On the other hand the application of burnup credit may significantly increase the complexity, uncertainty and difficulty in demonstrating an adequate sub-critical margin. The criticality safety assessment and supporting analysis should determine reliably the system k_{eff} accounting for the changes to the fuel composition during irradiation and radioactive decay after irradiation. Spatial variations in the spent fuel composition should be taken into account in calculating k_{eff} for the relevant spent fuel configuration. The increase in complexity presents several challenges for the criticality safety assessment. In 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 4.19 to 4.24;
- validation of the calculation methods used to predict k_{eff} for the spent fuel configurations using the guidelines presented in Para 4.19 to 4.24 (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. For fuel assemblies with burnable poisons, the assessment 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;
- Justification of inclusion or exclusion of specific isotopes, e.g. fission products, in growth of fissile nuclides, loss of neutron absorbers.

5.37. Generally, the operational limits and conditions for ensuring sub-criticality in spent fuel storage based on a burnup credit assessment have been based on a conservative combination of initial enrichment and burnup history (in which burnup is an important parameter). This approach is commonly known as the “Safe Loading Curve” Ref [17]. In such circumstances, the criticality safety assessment should determine the operational measures 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.

5.38. Further information and guidance on the application of burnup credit is available in Ref [17].

Reprocessing

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

5.40. Reprocessing operations can also include the treatment of fresh fuel or low burnup fuel or materials for scrap recovery. Consideration should be given to specific criticality safety measures for the control of the dissolution phase as these materials can be more difficult to dissolve. In addition, MOX fuels tend to be more difficult to dissolve than UO_2 fuels.

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

- Reprocessing involves a wide range of forms of fissile material and the use of multiple controlled parameters may be necessary;
- The mobility and potential for misdirection of solutions containing fissile nuclides;
- Maintaining chemistry control in order to prevent:
  - precipitation, colloid formation, concentration increases in solution;
  - unplanned separation and extraction of fissile nuclides;
- 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 fissile materials and need for multiple controlled parameters

5.42. The forms of fissile materials are diverse and could 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 and plutonium oxalate;
- uranium or plutonium metals;
- other compositions (e.g. materials containing minor actinides).

Mobility and misdirection of solutions

5.43. Many of the fissile materials are in a liquid form and due to the existence of many connections between equipment the criticality safety assessment should consider the possibility for misdirection of the fissile 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 misdirection to systems of unfavourable geometry.

5.44. 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 fissile material. The possibility of ad hoc external connections to approved pipework and vessels should also be considered.

5.45. 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.

5.46. 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, favourable geometry drains, drip trays, recovery pans and vessels etc, should be provided to ensure that fissile materials that could leak are safely contained. Consideration should also be given to the provision of monitored favourable geometry sumps for the detection of leaks. It should not be assumed that leaks will be detected in sumps as they may evaporate and form solid accumulations over time. Consideration should be made for inspection to prevent long-term build-up, especially in unmanned areas, Ref. [37].

Maintaining chemistry control

5.47. Particular attention should be given to chemistry 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:

- increased concentration of fissile nuclides (by precipitation/colloid formation/extraction);
- unplanned separation of plutonium and uranium;
- carry-over of uranium and plutonium into the raffinate stream;
- incomplete dissolution.

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

- monitoring of fissile nuclide concentration (e.g. in-line neutron monitoring, chemical sampling);
- monitoring of flow rates and temperature;
- testing of acidity, quality control of additives.

5.49. The effectiveness and reliability of these safety 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 chemistry control.

5.50. 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

5.51. In a reprocessing facility there are many credible accumulation sites and many potential mechanisms (physical and chemical) for diverting fissile 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.

5.52. 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 fissile nuclide accumulations in swarf, fines and other debris, becoming moderated through entrainment in subsequent wet chemistry conditions. For this reason, regular inspections and housekeeping should be implemented. See also Para 3.20.

5.53. 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, but not be limited to:

- pre-dissolution control on conditioning of acid;
- monitoring of temperature and dissolution time;
- post dissolution gamma monitoring (e.g. to detect residual un-dissolved fuel in hulls);
- material balance controls;

- density measurements.

5.54. 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.

5.55. The potential for fissile nuclides 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.

5.56. The recommendations to trap leaks in favourable geometry containers and the provision of monitored sumps to detect such leaks have been discussed above, Para 5.47. 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

5.57. For most furnace operations as part of the conversion process (e.g. precipitation, drying and oxidation), it may be practical to use favourable 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).

5.58. Further guidance on criticality safety at reprocessing facilities is provided in Ref [36].

Waste management and decommissioning

5.59. 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 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.

5.60. 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 fissile material (e.g. 'Legacy Waste'[3]). 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 fissile 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-fissile and fissile components of the waste material). In contrast, decommissioning operations may typically involve small inventories of fissile material.

5.61. Wastes are commonly wrapped in materials that can act as more effective moderators than water, e.g. polyethylene, PVC.

5.62. Criticality safety control of waste operations should be based on the application of appropriate limits on the waste package contents. Other criticality safety 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 operations at a disposal facility, so that subsequent re-packing, with its associated hazards may be avoided.

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

5.64. 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 fissile nuclides (as well as possible removal of absorbers from fissile material). In addition, a previously dry environment may be replaced by a water-saturated situation. (Note: Consideration of the consequences of a criticality post-closure is much different to that for say fuel stores or reprocessing plant where immediate deaths may be possible. Disruption of protection barriers and effects on transport mechanisms are likely to be more significant than the immediate effects of direct radiation from a criticality in a disposal facility post-closure).

5.65. 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 safety should include consideration of:

[3] See Definitions for the term "legacy waste".

- 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.

Variability and uncertainty in waste form

5.66. 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 operating personnel, 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 assessment. If an integrated 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

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

5.68. Assessment of post-closure criticality safety should establish that the combination of the likelihood and the consequences (i.e. the risk) of a criticality accident are acceptably low. In the post-closure phase, package degradation will inevitably happen and that the potential for relocation and criticality should be considered.

Decommissioning

5.69. Before beginning decommissioning operations, accumulations of fissile materials should be identified in order to assess the recovery of these materials. The potential for sites with unaccounted accumulations of fissile material (e.g. active lathe sumps) needs to be recognised and considered. A method for estimating and tracking accumulations of fissile materials that are not readily visible should be developed to ensure that the work stations remain sub-critical during decommissioning operations. These methods should take into account operating experiences, successive interventions, and recording of information. 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.

5.70. The approach to ensuring sub-criticality may be similar to that used for research laboratory facilities described below, where setting a low limit on allowable fissile material 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 fissile 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.

Transport

5.71. Transport within a licensed site should be considered as other onsite operations. Safe transport of radioactive material offsite (i.e. public domain), including consideration of the criticality hazard, is detailed in Refs. [6, 18-20], which constitute IAEA safety requirements and recommendations on the subject.

5.72. The requirements for offsite transport criticality safety assessments differ considerably from the requirements for facility and activity criticality safety assessments. Principally 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.

5.73. The state of the transport package before, during and 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 of the design. Additional safety assessment is required for the actual transport, see 5.76.

5.74. 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 persons with suitable knowledge and experience of the transport requirements.

5.75. The package design assessment referred to above in 5.74 provides a safety basis but the final safety assessment can only be made at the time of transport, accounting for real fissile materials, real packaging, real loading, labelling, etc. and real transport conditions. It is stated in the IAEA transport regulations Ref [6], that "Fissile material shall be transported so as to ensure 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.

5.76. Hazards to be considered for onsite transport should include, but not be limited to:

- Fissile material packages should be reliably fixed to vehicles;
- Vehicular speeds and road conditions;
- Potential for transport accidents (e.g. collisions with other vehicles);
- Material releases out of containment (e.g. into storm drains).

In laboratories

5.77. This type of facility is defined as being dedicated to the research and development of systems and products that utilize fissile materials. These facilities are generally characterized by the need for high flexibility in their operations and processes, but typically have low inventories of fissile 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 fissile and non-fissile materials

5.78. Due to the research and development nature of laboratory operations, these laboratories can use a wide range of fissile and non-fissile materials and separated isotopes, typically including low-, intermediate-, and high-enriched uranium, plutonium that is high in ^{241}Pu content (e.g. >15 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 fissile and non-fissile materials sometimes encountered include ^{233}U, ^{237}Np, ^{242}Pu, ^{241}Am, ^{242m}Am, enriched boron (e.g. ^{10}B) and enriched lithium (e.g. ^{6}Li). These 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].

Overlap of operating areas and material interfaces

5.79. Due to the significant flexibility in operations, criticality safety controls on the location and movement of fissile material within the laboratory are important to ensuring sub-criticality, 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.

5.80. 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 assessment before the movement is approved.

Inadvertent consolidation of fissile materials

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

Specialized education and training of operating personnel

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

Additional information:

5.83. Particular challenges will be encountered in determining safe sub-critical masses of the unusual materials, like some of those cited in Para 5.78and other exotic trans-plutonium materials (e.g. ^{243}Cm, ^{245}Cm) because 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 fissile 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 fissile 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. 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.

6.5. Of the 22 world-wide criticality accidents that have been reported all but one involved fissile material in solutions or slurries Ref. [12]. In these events, the key physical phenomena affecting the fission yield were:

- Volume of fissile 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;
    - Temperature;

- Density changes.

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

6.7. 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.

6.8. An assessment 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 fissile material 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

6.9. Each installation where criticality alarm systems are installed should have an emergency response plan, programme, and capabilities to respond to credible criticality accidents. In some circumstances where a criticality alarm system is not installed (e.g. shielded facilities), analyses should still be conducted to determine if the installation needs an emergency response plan.

6.10. Experience shows that the main risk during a criticality accident is to operating personnel in the immediate vicinity of the event. Generally, radiation doses to operating personnel more than a few tens of metres away are not life-threatening. 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.

6.11. The radiation doses from criticality accidents may be significant, even for operating 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 should be provided and appropriate safe evacuation routes and assembly areas defined.

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

6.13. 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

6.14. 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 credible criticality accident location and the expected or possible accident characteristics;
- Identify appropriate equipment, including protective clothing and radiation detection and monitoring equipment;
- Include the prior provision of individual personal dosimeters;
- Consider treatment and appropriate medical care and their availability;
- 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

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

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

6.17. 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.

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

6.19. 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.

6.20. 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.

6.21. The operating organisation should be able to conduct or have external experts to conduct a radiological dose assessment appropriate for a criticality accident.

Evaluation of credible accidents

6.22. Credible 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.

6.23. Consideration should be given during the design, operation and periodic review stages to identifying measures to mitigate the consequences of a criticality accident, e.g. for intervention in order to stop the criticality. Possible approaches include installation of isolation valves, remote control systems, e.g. the availability of neutron absorbers and the means of injecting them into the materials where the criticality has occurred, portable shielding or other means of safely altering the process conditions to achieve a safe state.

6.24. The process of calculating the dose from a criticality accident is subject to various uncertainties. The final dose estimate will therefore also include uncertainty. The acceptable level of uncertainty (or the level of confidence that the dose is not greater than predicted) will be a decisive factor in determining the method/assumptions used to produce the estimate. The methodology is complex and specialised and should follow the basic steps below:

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

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

"During-accident" evaluation

6.26. 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 fissile material including quantities;
- The reactivity insertion mechanism that took the system super-critical;
- Feedback and quenching mechanisms (venting etc).

6.27. 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.

6.28. 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.

6.29. In some accidents there have been instances where ill-planned actions of operating personnel 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

6.30. 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.

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

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

Evacuation

6.33. 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.

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

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

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

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

Re-entry, rescue and stabilisation

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

6.39. 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.

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

6.41. 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.

6.42. 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.

6.43. 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. 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 may be present.

6.50. 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.

6.51. 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.

6.52. Exceptions to this recommendation are:

- *Where a documented assessment* concludes that no credible 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 operating 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 fissile material awaiting or during shipment or awaiting unpacking (certain conditions should be met e.g. the potential for neutron interaction with other fissile materials in adjoining areas should be negligible).

Performance and testing of criticality detection and alarm systems

Limitations and general recommendations

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

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;
- alarm as soon as the accident is detected and continue even if the radiation falls below the alarm point until manually reset;
- manual resets, with limited access, should be provided outside areas that require evacuation;
- be audible in all areas to be evacuated;
- 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. The performance of the detectors should be carefully considered to avoid issues such as potential omission or overload of signals.

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

Trip point

6.62. 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

6.63. 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.

6.64. 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

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

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[4]

Burnup Credit

Accounting methodology for an overall reduction in reactivity associated with the irradiation of fuel in a reactor and with cooling time.

Credible

The attribute of being believable on the basis of commonly acceptable engineering judgement.

Criticality controlled area

An area authorised to contain significant quantities of fissile material.

Doppler feedback

A phenomenon whereby the thermal motion of fissile and non-fissile material nuclei changes the “relative” energy between the nuclei and interacting neutrons thereby causing an effective broadening of neutron reaction cross sections of the materials. Depending upon the enrichment or composition of the materials, this phenomenon can increase or decrease the neutron multiplication of a system.

Fault tolerance

To ensure safety, the design should be tolerant of failure occurring anywhere within the safety systems provided to secure each safety function.

Favourable geometry

A system, whose dimensions and shape are such that a nuclear criticality event cannot occur so long as the selected control parameters (e.g. fissile material concentration, enrichment) are maintained within specified limits.

Fissile nuclides and fissile material

[4] 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.

Fissile nuclides include those nuclides such as ^{233}U, ^{235}U, ^{239}Pu and ^{241}Pu, which are able to support a self-sustaining nuclear chain reaction with neutrons of all energies, but predominantly with slow neutrons. Fissile material refers to a material containing any of the fissile nuclides.

Initial enrichment

Enrichment of fuel prior to irradiation in a reactor.

Legacy Waste

Radioactive waste that may contain fissile materials that have remained from historic fissile material facilities and processes. Legacy waste may need to be treated before storage and/or disposal.

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.

Sub-critical

k_{eff} less than 1.0000

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