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CRITICALITY SAFETY

DRAFT SAFETY GUIDE
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CONTENTS

1. INTRODUCTION

BACKGROUND

1.1. Nuclear materials containing fissionable radionuclides are required to be managed in such a way as to ensure subcriticality during normal operation and also in the case of incidents and accidents that could lead to anticipated operational occurrences or design basis accidents. This applies to large commercial facilities, e.g. fuel cycle facilities involving the supply of fresh fuel and the management of spent fuel and radioactive waste containing fissionable material, including handling, processing, use, storage, transport and disposal (operation and post-operation), and to prototype research and development facilities and also to activities such as transport of packages containing fissionable materials.

1.2. This Safety Guide establishes recommendations on how to ensure subcriticality in systems involving fissionable materials. It is intended to encompass all types of facilities and activities, except facilities that are designed to be critical, e.g. a nuclear reactor or a critical assembly.

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

OBJECTIVE

1.4. The objective of this Safety Guide is to provide guidance and recommendations on how to ensure subcriticality when dealing with fissionable material. The guidance and recommendations are applicable to both regulators and operators who are dealing with fissionable material. The Safety Guide also presents guidance and recommendations on how to fulfil the criticality related requirements established in the following IAEA Safety Requirements publications: Safety of Nuclear Fuel Cycle Facilities [1], Safety Assessment for Facilities and Activities [2], Management Systems 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.]

SCOPE

1.5. This Safety Guide establishes recommendations on how to ensure subcriticality in systems involving fissionable materials during normal operation, anticipated operational occurrences and within design basis accidents. It is intended to encompass all types of facilities and activities, except facilities that are designed to be critical, e.g. a nuclear reactor or a critical assembly, and systems that have been exempted from the criticality safety regime. Recommendations encompass approaches to and criteria for ensuring criticality safety, conducting criticality safety assessments, including the data and calculation requirements, identifying measures to ensure subcriticality, as well as the planned response to nuclear criticality accidents.

STRUCTURE

1.6. This Safety Guide covers all of the important aspects of nuclear criticality safety, from initial design, through operation to decommissioning. It consists of six sections, as well as an annex.

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

1.8. Section 3 addresses the safety measures that are important for ensuring subcriticality, especially the importance of adequately implementing the measures, the factors affecting these measures, the important roles for those involved in implementing the safety measures, as well as the implementation and reliability requirements of the safety measures.

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

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, the application of burnup credit, reprocessing, waste management and decommissioning, transport, and laboratories.

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

1.12. Section 7 provides a glossary to cover the terms used that are not in the IAEA safety glossary.

1.13. The annex includes a bibliography which identifies sources of useful background information on criticality safety relating to assessment methodology, handbooks, computational methods, training and education, management and operational experience.

2. APPROACH TO CRITICALITY SAFETY

GENERAL

2.1. Criticality safety should be achieved by ensuring that all activities involving fissionable material remain subcritical. This should be ensured for all operational states and design basis accidents. Safety measures, either technical or administrative, should be identified, implemented and maintained to ensure that the activity is conducted within specified operational limits that ensure the activity remains subcritical.

2.2. A criticality safety assessment should determine whether adequate defence in depth is provided, bearing in mind that the consequences of an unshielded criticality accident can be severe and often fatal for those in the immediate vicinity. Using the general usage of defence in depth, it should be noted that the application of the 4th level of defence in depth, which deals with beyond design basis accidents and the protection of the confinement system to limit radiological releases, may not be fully applicable to criticality safety. However, mitigation of the radiological consequences of a criticality accident, the 5th level of defence in depth, should be applied with consideration of the need for criticality detection and alarm systems and emergency arrangements.

2.3. The processes which affect the neutron multiplication factor are often complex, non-linear and contain competing effects. Also criticality safety is generally achieved through control of a limited set of macroscopic parameters such as mass, enrichment, moderator, geometry, etc. A description of the neutron multiplication properties of a system based on these parameters alone is incomplete, and a full description would require the use of microscopic properties such as fission, capture, scatter, etc. For these reasons there are many examples of apparently ‘anomalous’ behaviour in fissionable systems where the neutron multiplication factor changes in ways that seem counter-intuitive.

2.4. It is recommended that criticality safety staff should be familiar with the contents of Ref. [9], which contains a detailed description of many of the most important ‘anomalies’ that have been observed in criticality safety. Situations where criticality safety assessments may need to consider specific practices are given in Section 5.

MANAGEMENT SYSTEMS

2.5. Human error and related failures of supervisory/management systems have been a contributory cause in nearly all criticality accidents experienced to date. Design, safety assessment and the implementation of criticality safety measures should therefore be carried out under a clearly established and well controlled management system. IAEA requirements and recommendations for such a management system are detailed in Refs [3] and [10, 27 – 29], respectively.

2.6. In the context of criticality safety it is particularly important that the following items should be addressed:

- Management should clearly define personnel responsibilities for criticality safety.

- Management should provide suitably qualified and experienced criticality safety staff to serve as advisors to supervisors.

- Management should ensure that new activities and changes to existing activities undergo review and assessment, and approval at the appropriate level before they are implemented.

- Management should ensure that personnel receive training appropriate to their level of responsibility. In particular, it is important that supervisors and other personnel involved in activities with fissionable material should understand the nature of the hazard posed by criticality accidents and how the risks are controlled in the plant and within the process with the established safety measures and operating limits.

- Management should arrange internal and independent inspection of the criticality safety measures and their related operating procedures.

2.7. Inspection of existing activities and operational procedures as well as the proper control of changes in activities are particularly important for criticality safety and should be carried out and continually reviewed. The nature of the criticality hazard is such that deviations towards a less safe condition may not be intuitively obvious to operators and there will be no obvious indication that neutron multiplication is increasing. There is also a danger that conditions may ‘creep’ with time in response to factors such as ageing of the plant or due to increased production pressures, for example.

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

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

2.10. Useful information on the causes and consequences of previous criticality accidents is provided by Ref. [11]. The management system should include a means of incorporating lessons learned from incidents and accidents to ensure the continuous improvement of operational practices and assessment methodology.

SAFETY CRITERIA AND SAFETY MARGINS

2.11. The safety objective is to ensure subcriticality during operational states and design basis accidents.

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

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

- Safety criteria could be based on controlled parameters such as mass, volume, enrichment, concentration, etc.

2.13. In defining the criteria, a safety margin should be applied. This implies a value of k_{eff} somewhat less than unity or a controlled parameter value ‘below’ its critical value. In this context ‘below’ is used in the sense that the controlled parameter remains on the safe-side of the critical value.

2.14. Acceptable margins to k_{eff} and to the critical value of a controlled parameter are a function of the criticality risk and the degree of uncertainty in the estimation of k_{eff} and the critical value, including any code bias and the rate at which they vary, i.e. sensitivity, with changes to the system, particularly with respect to changes in a controlled parameter. Note that the relationship between k_{eff} and other parameters may be significantly non-linear.

2.15. All margins adopted in criticality safety assessments should be justified and documented. When appropriate, justification should be by reference to well established and documented company, national or international standards, codes of practice or guidance notes. Implementing the double contingency principle is an example of implementing a criticality safety margin.

2.16. In justifying the adequacy of a safety margin, a criticality safety assessment should demonstrate that sufficient and appropriate safety measures are in place to detect and intercept deviations from operational states and in design basis accidents before any critical value is breached. As part of that demonstration, operational limits set at values sufficiently below the critical values should be applied, so that the safety measures can act in time to terminate the fault sequence and prevent a criticality accident.

EXEMPTIONS

2.17. In some facilities or activities the amount of fissionable material may be so low that a full criticality safety assessment would not be justified. Exemption criteria should be developed, and reviewed by management and approved by the regulator as appropriate. A useful starting point is the exception criteria applied to transport packages, Ref. [6], which represents a conservative approach.

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

3. MEASURES IMPORTANT FOR ENSURING SUBCRITICALITY

GENERAL

3.1. The criticality safety measures important for ensuring sufficient subcriticality of systems processing, handling, transporting or storing fissionable materials should be based on the following hierarchy:

- Defence in depth;
- Passive safety;
- Fault tolerance.

Defence in depth

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

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

3.3. The defence in depth concept is generally applied in five levels. However, the 4th level, which deals with beyond design basis accidents and the measures necessary to control the progression of an accident, may not be fully applicable to criticality safety.

3.4. The defence in depth concept ensures that if one level fails, it will be compensated for, or corrected by, the subsequent level. The aims for each level of protection are described in detail in Ref. [12] on which the following overview of the levels is based:

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 operation in order to prevent anticipated operational occurrences from escalating into accident conditions.	Control, indication and alarm systems, systems or operating procedures to prevent or minimize damage from failures.
3	Control the consequences of faults within the design basis to prevent a criticality accident.	Engineered safety measures, multiple and as far as possible independent barriers, accident or fault control procedures.
4	Address accidents in which the design basis of the system may be exceeded and to ensure that the radiological consequences of a criticality accident are kept as low as practicable.	Provision of criticality detection and alarm systems and procedures for safe evacuation and accident management. Emergency control centre and plans for on and off-site emergency response.
5	Mitigation of radiological consequences	

Passive safety

3.5. The design of the facility or activity is such that the system will remain subcritical without the need for active engineered or operator based safety measures. This might be achieved for example, by using only very low enriched or natural uranium. Alternatively, the facility or activity might be designed such that fissionable material is always restricted to containers which are geometrically safe.

3.6. If a passively safe design cannot be achieved, then the design should be fault tolerant.

Fault tolerance

3.7. The sensitivity of the system to potential faults should be minimized.

3.8. Failures, perturbations or mal-operations of the system or mal-functions in the system should not lead to less safe conditions. However, if the change is to a less safe condition, the system should have characteristics so that key parameters deviate only slowly from their desired values so that detection, intervention and recovery is possible to prevent a criticality accident.

Safety measures and safety functions

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

3.10. Taking the physical and chemical characteristics of the fissionable material and the system into account, sufficient subcriticality can be ensured by technical, including engineered safety measures or administrative safety measures or a combination of both. Taking note of the lessons learned from incidents and criticality accidents, the safety measures should generally observe the following hierarchy:

- Passive safety measures which do not rely on control systems, active engineered safety measures or human intervention;
- Automatically initiated active engineered safety measures;
- Active engineered safety measures that need to be manually brought into action in response to the fault;
- Administrative safety measures;
- Mitigation safety measures.

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

3.12. The hierarchy of safety measures gives preference to passive safety through the use of inherently safe material or geometrical constraint. If subcriticality cannot be ensured through these means further safety measures should be considered such as controlling:

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

3.13. The design features and characteristics of the system should observe the single failure criterion. Any single failure or fault such as a component failure; a function control failure; a human error (e.g. instruction not followed); should not result in a criticality accident.

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

3.15. If a criticality accident is postulated to occur because of the simultaneous occurrence of two events, it should be shown that:

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

- the system's characteristics meet the recommendations of para 2.166 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.

TECHNICAL SAFETY MEASURES

3.16. The safety measures used can be related to the application of controlled parameters. These may be based on safe mass, safe geometry, safe concentration or controlled moderation etc.

Controlled parameters

3.17. Examples of parameter control are:

- Restriction to a certain type and chemical compound of the fissionable material (such as UF_6, UO_2F_2, $UO_2(NO_3)_2$, UO_2, etc);

- Limitation of the isotopic composition of the fissionable material present in the system;

- Limitation of the mass of fissionable material within a system to the safe mass: The safe mass should be obtained by multiplying the critical mass determined by the system conditions with a safety factor. To meet the single failure criterion the value 0.45 is sometimes applied as a safety factor so that inadvertent "double batching" of the system does not lead to criticality;

- Limitation of the geometry of the system to safe geometry: For simple geometries (sphere, cylinder, slab) the safe geometry is sometimes derived by multiplying the critical geometry determined by the system conditions with a safety factor less or equal to 0.9;

- Limitation of the concentration of fissionable material within a solution or suspension: For example a safety factor of 0.80 is sometimes applied to the critical value;

- Limitation of the amount of moderating material associated with the fissionable material;

- Limitation of the amount and restriction to a certain type of reflecting material surrounding the fissionable material;

- Ensuring the presence of neutron absorbers;

- Limitation on distance between separate criticality safe systems;

- Shielding between separate criticality safe systems.

3.18. Control of fissionable mass is sometimes combined with the control of moderation.

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

Factors affecting controlled parameters

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

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

3.21. The presence of neutron moderating materials should be considered as they can significantly reduce the critical mass of fissionable material. Water, oil, other hydrogen and carbon containing materials and graphite are common moderators which are very often associated with the use of fissionable material. The minimum critical mass for a system may be dependent on the presence of moderating material and usually changes when the system is changed.

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

3.23. Neutron absorption should be considered. Neutron absorbers are mainly effective for thermal systems. Therefore, any neutron spectrum hardening, i.e. an increase in neutron energy, caused by operating conditions (e.g. a change to plutonium containing fissionable material caused for instance by different irradiated fuel) or accident conditions should be considered as they may result in a decrease in the effectiveness of the neutron absorption. Usage of a neutron absorber should therefore require safety measures that ensure that the effectiveness of the neutron absorber is not reduced in the case for which its safety function is needed.

3.24. The distribution of neutron absorbers should also be considered. Neutron absorbers that are homogeneously distributed in a thermal fissile material system are usually more effective than if they were heterogeneously distributed (although it should be noted that heterogeneous absorbers may be easier to administratively control). In a thermal system consisting of a heterogeneous arrangement of fissionable material and a fixed neutron absorber (e.g. the storage of fuel assemblies) the neutron absorber may be more effective the closer it is to the fissionable material. Any material (e.g. water, steel) between the absorber and the fissionable material can change the effectiveness of the absorber.

3.25. It should be noted that material (e.g. steam, polyethylene, concrete) located between fissionable materials may not only act as a reflector but may also act as a moderator and can therefore increase the neutron multiplication factor of the system. Any increase in the neutron multiplication factor would be dependent on the type and density of the material positioned between the fissionable materials. Materials with low density (such as steam) can cause a significant increase in the neutron multiplication factor.

3.26. Interaction between units of fissionable material should be considered as the interaction can affect the neutron multiplication of the system. This control parameter can be used to implement criticality control, for example by specifying minimum separation distances, (or in some cases maximum distances, for example to limit interstitial moderation between fissionable units).

ADMINISTRATIVE SAFETY MEASURES

General considerations

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

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

- Determination and posting of criticality controlled areas and identification of the controlled parameters assigned to these areas: Identification, specification and, where applicable, labelling of materials (fissionable materials, moderating materials, neutron absorbing materials and neutron reflecting materials), specification and, where applicable, labelling of the controlled parameters and their associated limits on which criticality safety depend.

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

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

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

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

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

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

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

- Quality assurance, periodical inspection (e.g. checks on continued safe geometries), maintenance.

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

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

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

3.28. Before starting a new system or a new activity with fissionable material the required administrative measures should be determined, prepared and independently reviewed. Likewise, before an existing system or activity is changed the administrative measures should be revised and again independently reviewed.

3.29. Procedures for responding to criticality accidents should be prepared including the use of criticality accident alarm systems and emergency procedures (Section 6.)

Responsibility and delegation of authority

3.30. Senior persons from higher level management should be given the responsibility for implementing the criticality safety measures and for implementing appropriate quality assurance measures. Their authority and responsibility should be documented in the description of their functions and clearly reflected in the organizational diagram.

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

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

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

- criticality safety staff who are familiar with the physics of nuclear criticality and associated safety measures;
- criticality safety staff that are independent of operations management;
- the organizational means for establishing a periodical criticality safety training for the management, supervisors and operational staff to be performed by the criticality safety staff;
- the organizational means for establishing a periodical criticality safety training for the criticality safety staff;
- the organizational means for continuously reviewing and, if required, improving the criticality safety program and its effectiveness by the criticality-safety staff;
- the organizational means to establish procedures for generating and reviewing written operating procedures and for their modification.

3.34. Participation in criticality safety trainings should be documented in the personal data file of the participants.

3.35. The responsibilities of the criticality-safety staff should be, but are not limited:

- to provide documented safety assessments for fissionable material systems;
- to provide documented criticality safety guidance for the fissionable material systems' design and processes and for the development of operating procedures;
- to specify and implement the required criticality safety measures;
- to determine the location and extent of criticality controlled areas. Where applicable, to issue safety postings for these areas, labelling the materials, as well as determining the controlled parameters and their limits that apply to these areas;
- to assist and consult supervisors and to keep close contact with them to ensure familiarity with all fissionable material activities (It is recommended that the criticality safety staff should conduct regular walk-downs through the plant and inspections of the facilities, systems or 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.

3.36. The issued safety postings should be signed by a member of the criticality safety staff, the involved supervisor and the involved management person responsible for criticality safety.

3.37. The tasks of supervisors should be:

- to be aware of the controlled parameters and associated limits relevant to systems under their control;
- to supervise and document the compliance with the limits of the controlled parameters.

Operating procedures

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

- facilitate and document the safe and efficient conduct of operations;
- include those controls, limits and measures significant to criticality safety;
- include advice and guidance for the case of abnormal operation and accident conditions;
- include only the information required for operational and safety purposes;
- include appropriate links between procedures to avoid omissions and duplications, and where necessary, contain clear identification of entry and exit conditions;
- be simple and understood by operators;
- be periodically reviewed at predetermined intervals.

3.39. Revised procedures should be reviewed by the supervisors and the criticality safety staff and approved by the management persons responsible for criticality safety.

IMPLEMENTATION AND RELIABILITY OF SAFETY MEASURES

3.40. Maintaining sufficient subcriticality in compliance with the principles specified in para. 3.1 usually require the application of combinations of different technical and administrative safety measures. Reliance should be placed explicitly on engineered features, specific administrative controls, and/or various administrative programs such as material control and accountability, safeguards and security, on and off-site transport requirements, and non-destructive assay. Where applicable, reliance may be placed on controls already present in the facility or applied to the system of interest. The hierarchy of criticality safety measures specified in para. 3.10 should be observed.

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

- the design and arrangement of safety measures such as apparatuses, casks and other components;

- the need for measurement devices for ensuring that the system conditions and operating limits are adequately monitored and controlled (e.g. the measurement of moisture in the fissionable material powder);

- determine the need for additional administrative measures for ensuring that the system conditions and operating limits are adequately controlled.

3.42. Implementation of the safety measures includes inspections, periodic surveillances, continuous or quasi-continuous measurement. Accordingly, quality assurance measures should be developed and implemented to maintain the reliability of the safety measures. 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 requirements for the set of safety measures; and

- the ability of personnel to recognize abnormality or failure of the safety measure.

4. CRITICALITY SAFETY ASSESSMENT

GENERAL

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

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

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

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

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

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

4.7. The criticality safety assessment should include a criticality safety analysis which should evaluate criticality safety in all operational states, i.e. normal operation, anticipated operational occurrences and design basis accidents. The criticality safety analysis should identify hazard and fault scenarios and determine their consequences.

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

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

CRITICALITY SAFETY ASSESSMENT

4.10. The criticality safety assessment should analyze the hazards associated with an activity involving fissionable material and ultimately develop and document the criticality safety limits and controls (e.g. passive, active and administrative) required to prevent a criticality accident. To meet this objective a systematic approach to the assessment should be adopted as outlined below:

- Define the fissionable material system;
- Define the criticality safety assessment methodology;
- Develop computational models;
    - Verification
    - Validation
- Perform criticality safety analyses;
- Identify any unique or special requirements.

Define fissionable material system

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

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

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

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

Define criticality safety assessment methodology

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

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

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

  - What If methods;
  - Qualitative Event or Fault Trees;
  - Quantitative Probabilistic Risk Assessment methods;

- Hazard and Operability Analysis; and/or
- Fault Modes and Effects Analysis.

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

4.17. The assessment should be performed utilizing a validated methodology. The assessment should provide the documented technical basis that demonstrates subcriticality during operational states including anticipated operational occurrences and design basis accidents and should consider all single failure faults. The criticality safety assessment should identify the safety measures, including any administrative safety measures, required to ensure subcriticality, it should specify their safety functions and determine their reliability, redundancy, diversity and equipment qualification requirements.

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

- Reference to national consensus standards that present critical and/or subcritical limits;
- Reference to accepted handbooks of critical and/or subcritical limits;
- Reference to experiments with appropriate adjustments to ensure subcriticality when the uncertainties of parameters reported in the experiment documentation are considered; and/or;
- Use of validated calculation techniques.

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

Computational models

4.20. Computational models, i.e. calculation methods or computer codes, used in the criticality safety analysis should be verified and validated to ensure the quality of their predicted values and to establish their limits of applicability, bias and level of uncertainty. Verification relates to the process of determining that the controlling physical equations within the computational model have been correctly incorporated. Validation relates to the process of determining whether the overall computational model is an adequate representation of the real system being modelled and to quantify any calculation bias and uncertainty.

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

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

Verification

4.23. Verification of the computational model should be performed prior to its validation and should test the methods, mathematical or otherwise, used in the model.

Validation

4.24. After completing the verification of the computational model and prior to its use in performing a criticality safety analysis, the computational model should be validated against selected benchmarks which have representativity[1] to the activity being evaluated. The relevance of benchmarks used to perform the validation should be determined from comparisons of the benchmarks characteristics with those of the fissionable material system being evaluated.

4.25. The selection of the benchmarks should consider:

- Benchmarks that have relatively small uncertainties as compared to any arbitrary or administratively imposed margin of subcriticality;

- Benchmark characteristics (e.g. all isotopic and chemical compositions, neutron spectra and geometry, etc) should correlate to the fissionable material system and its operating parameters as identified in the criticality safety assessment, i.e. all operational states, including normal operation, anticipated operational occurrences and design basis accidents;

- Benchmarks should be reviewed to ensure that their neutronic, geometric, physical and chemical characteristics encompass the operational states of the fissionable material system to be evaluated. Examples of neutronic, geometric, physical or chemical characteristics that should be reviewed include, but not limited to:

    - Neutron-energy spectra throughout the individual benchmarks relative to the neutron-energy spectra throughout the fissionable material system that is the subject of the safety analysis;

    - Molecular compounds, mixtures, alloys and their chemical formulae;

    - Isotopic proportions (Note: Calculated isotopic proportions used in “burnup” credit should be validated);

    - Material densities;

    - Relative proportions or concentrations of materials such as the moderator-to-fissionable material or atom ratio where moderators are materials, typically of low atomic mass (i.e. < 17 amu), that is effective for decreasing the energy of

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[1] See Section 7 “Glossary” for a definition of the term “Representativity”.

neutrons scattered from the moderator. Common materials that are effective moderators include water (e.g. hydrogen, deuterium and oxygen), beryllium, beryllium oxide, graphite (e.g. carbon). In the presence of poorly absorbing materials, such as magnesium oxide, oxygen can be an effective moderator;

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

- Geometric arrangements and compositions of the fissionable materials relative to non-fissionable material such as neutron reflectors and scatterers but including materials that are effective for parasitic absorption of neutrons (e.g. common materials include cadmium, hafnium, and gadolinium but other materials, such as 240-plutonium and 238-uranium, also act as slow neutron absorbers);

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

4.26. If no benchmark experiments exist that match the system being evaluated (e.g. low-moderated powders and waste), it may be possible to interpolate from other existing benchmark data to that system. Sensitivity and uncertainty analysis should be used to assess the applicability of benchmark problems to the system being analyzed and to ensure an acceptable margin of subcriticality. An important aspect of this process should be the quality of the basic nuclear data and its uncertainties.

Criticality safety analysis

4.27. The criticality safety analysis should demonstrate that operations are subcritical under all operational states and that no incident or design basis accident can lead to a criticality. The criticality safety analysis should describe the application of the single failure criterion or the double contingency principle, which is the preferred approach in Ref. [1], for ensuring nuclear criticality safety. They are:

- Single Failure Criterion. This criterion, when applied to a fissionable material system, is such that a criticality accident cannot occur in the presence of any single fault (i.e. such as a component failure, a function control failure, a human error (e.g. instruction not followed) or an accident situation (fire for instance).

- Double Contingency Principle (the preferred approach). The double contingency principle requires that fissionable material operations should include sufficient safety factors such that a criticality accident would not be possible unless at least two unlikely and independent concurrent changes occur in process conditions (e.g. mass, enrichment and isotopic proportions, geometry, concentration, density, moderation, reflection, neutron interaction, neutron absorbers, etc.).

  If a criticality accident can occur because of the simultaneous occurrence of two faults, it should be shown that: (i) the two faults are strictly independent (not common mode); (ii) the probability of occurrence of each fault is acceptably low; and (iii) each fault can be detected (e.g. monitored) with suitable and reliable means within a time that allows countermeasures to be taken.

Unique or special requirements

4.28. Any unique or special requirements resulting from the criticality safety analysis and assessment should be specifically highlighted to ensure their visibility and to ensure that they are complied with. A statement of compliance with these requirements should be specified and incorporated in to the design or operating procedures.

5. CRITICALITY SAFETY SPECIFIC PRACTICES

GENERAL

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

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

Type of facility and operation

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

5.4. For operational convenience a certain amount of flexibility is desirable. However, working procedures, which consider criticality safety, should be developed and enforced to ensure that the activities performed in the facility remain within the approved limits and conditions identified in the criticality safety assessment.

5.5. For production facilities the effect of production pressures should not be allowed to override criticality safety considerations.

5.6. For both types of facilities the different possible errors or failures should be taken into account. In laboratory/experimental processes the majority of errors are likely to be due to human error. In production facilities human error will contribute significantly to errors but hardware and process failures should also be taken into account. Both human and hardware errors should be studied as possible initiating events for criticality accidents.

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

Life cycle issues

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

5.9. Changes due to plant ageing should be considered. The ageing effects should be monitored and their impact on criticality safety should be assessed.

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

PRACTICES ACROSS THE FUEL CYCLE

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

Conversion and enrichment

5.12. Conversion facilities refine natural uranium ores to a purified uranyl nitrate which is then typically converted to uranium hexafluoride in preparation for enrichment. Because of the isotopic composition of natural uranium (i.e. ~0.7 atom % ^{235}U) in the homogeneous processes of conversion, no criticality safety hazards are encountered. However, enrichment facilities have the potential for nuclear criticality accidents and should be protected from criticality through the application of criticality safety controls that have been discussed in the previous sections. Further guidance on criticality safety for conversion and enrichment facilities is provided in Ref. [13].

Fuel fabrication

5.13. 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 absorbent material (e.g. ^{240}Pu).

5.14. 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 and by the ^{235}U content in the composition of the uranium.

5.15. Where moderator control is employed, the criticality safety assessment should consider the following:

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

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

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

- Powders may absorb moisture. Consequently, inert and dry glovebox atmospheres should be maintained to ensure safety and quality of packaged powders. Furthermore, the application of hydrogenated materials, e.g. used as lubricants in the manufacture of pellets, should be applied with safety factors consistent with the double contingency principle. It should be noted that the criticality safety analyses for these types of material may be confounded by the limited number of experimental benchmarks to be used in validating criticality codes. Care should therefore be taken in the extrapolation of available benchmark data for these applications. Guidance for such situations is provided in para. 4.26.

5.16. 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 etc, should be monitored and controlled to avoid unsafe accumulations of moderated fissionable materials.

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

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

Material cross-over

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

Machining/grinding/cutting (residue accumulations)

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

5.21. In addition to this guidance for fuel fabrication facilities, the recommendations in sections 2 - 4 should be considered for performing criticality safety assessments and analyses. Further guidance on criticality safety for uranium and MOX fuel fabrication facilities is also provided in Refs. [14] and [15], respectively.

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 fissionable material in the facility. In contrast to criticality assessments for operations earlier in the fuel cycle, account could now be taken for the effects of fuel irradiation. In determining the criticality controls required, 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 require cooling for several years following discharge from the reactor, (in spent fuel ponds, for example);
- the isotopic, physical and chemical composition of the fissionable material will have changed during irradiation in the reactor.

5.23. These factors introduce special considerations which should be addressed in the criticality safety assessment. Some of the key considerations are summarised below. Note that the general issues relating to criticality control and assessment identified in previous sections of this report should also be addressed. The following list is provided as an overview of some of the issues with particular relevance to spent fuel operations.

Handling accidents

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

Maintaining fuel geometry

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

Loss of soluble or fixed absorbers

5.26. In some PWR spent fuel storage ponds one component of criticality control may be the inclusion of a soluble neutron absorber (e.g. boron) in the storage pond water. The potential for accidental dilution of the soluble neutron absorber by unplanned additions of un-poisoned water should be considered in the criticality safety assessment. In some facilities the presence of high radiation fields can lead to detrimental changes in the physical and chemical form of the fixed absorber materials used for criticality control. For example, Boraflex sheets (a material impregnated with boron) used in some 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. The potential for degradation of these types of criticality control measures should be included in the criticality assessment and appropriate safety measures identified. 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.

Changes in storage arrangements within a spent fuel facility

5.27. Due to its highly radioactive condition spent fuel is often stored in pond facilities for several years following discharge from the reactor core. During that time changes may be required to the storage configuration. For example, some nuclear power plants have found it necessary to re-position the spent fuel in the storage pond, i.e. to 're-rack', to increase the spent fuel ponds storage capacity. Increasing the density of fuel storage may have significant effects on the level of neutron absorbers required 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 Ref. [9]. These effects should be taken into account when assessing the criticality safety of such modifications to a facility.

Mis-loading accidents

5.28. Some spent fuel storage facilities may accept material from a range of reactor sites. To accommodate the different types of fuel the facility is usually divided into areas with distinct design features and requiring different criticality controls. In these situations, the possibility of mis-loading of spent fuel into the wrong storage location should be considered in the criticality safety assessment. Safety measures associated with this type of fault may include engineered features to preclude mis-loading (e.g. based on the physical differences in fuel assembly design) or administrative controls and checks on fuel identity.

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

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

5.30. In addition to this guidance for spent fuel operation, the recommendations in sections 2 - 4 should be considered when performing criticality safety assessments and analyses.

Burnup credit

5.31. The changes in the spent fuel composition during irradiation normally result in a reduction in spent fuel k_{eff} relative to fresh fuel and this may present several advantages as highlighted below:

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

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

- validation of the calculation methods used to predict the spent fuel composition;
- validation of the calculation methods used to predict k_{eff} for the spent fuel configurations (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 poisons, presence of burnable poisons, coolant temperature and density, fuel temperature, power history and cooling time etc. Note, the irradiation of fuel with burnable poisons could result in increased reactivity early in its life. The burn up credit analysis should take account of the depletion of the burnable poison and consider the possibility that the most reactive condition may not be for the fresh fuel;
- justification for the treatment of a large number of nuclides in the calculations;
- justification of any modelling assumptions, for example, the representation of smoothly varying changes in composition (i.e. as a result of radial and axial variations in burnup) as discrete zones of materials in the calculation model;

- ensuring that Monte Carlo calculations of spent fuel configurations are properly converged.

5.33. Generally, the limits and conditions for ensuring criticality safety based on a burnup credit assessment have been based on a conservative combination of initial enrichment and burnup. This approach is commonly known as the “Safe Loading Curve.” In such circumstances, the criticality safety assessment should include consideration of what operational requirements are necessary to ensure compliance with this curve during operations, e.g. what measurements are required to verify the initial enrichment and burnup. The criticality safety assessment should also consider the potential for mis-loading of fuel from outside the limits and conditions specified in the safe loading curve.

5.34. Established good practices for developing nuclear criticality safety assessments should be followed as described in sections 2 - 4. However, the additional complexities described above are significant and this type of assessment should only be undertaken by staff having detailed knowledge of the methodology and its application. Further information and guidance on the application of burnup credit is available in Refs [6] and [16].

Reprocessing

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

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

5.37. Several chemical processes are possible for reprocessing spent fuel. One of the most commonly used is the PUREX (Plutonium and Uranium Refining by Extraction) process. This separates the plutonium and the uranium and the products of fission (including the minor actinides) from each other by a method of solvent extraction.

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

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

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

- Maintaining chemical control during:
    - precipitation, colloid formation, concentration increases in solution, de-nitrification;
    - separation and re-concentration of fissionable material (e.g. accidental solvent extraction);
    - Process control time lags;

- Hold-up and accumulations:
    - incomplete dissolution, accumulations of fines in conditioning and vacuum vessels, chronic leaks (including leaks of liquors onto hot surfaces);
- Moderator control during furnace operations:
    - condensation in powders.

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

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

- fuel assemblies
- fuel rods
- Solutions of uranium and/or plutonium
- Plutonium oxide

5.40. Moreover, fissionable materials are handled in large quantities either as a continuous stream or in large batches. To accommodate these process conditions and to ensure an adequate safety margin, criticality control should be implemented through a number of controlled parameters, i.e. control of geometry and concentration. It is recommended that only in exceptional circumstances should soluble or fixed neutron absorbers be used, and that their use should be fully justified in the criticality safety assessment. In all cases a key consideration should be the control over the amount and type of fissionable materials entering each stage of the process.

Mobility and mis-direction of solutions

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

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

5.43. Operational experience has shown that mis-directions 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.

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

Maintaining chemical control

5.45. Particular attention should be given to chemical control during reprocessing. Some of the most important process parameters that could affect criticality include; acidity, concentration/density, purity of additives, temperature, contact area (i.e. during mixing of materials). Loss of control of any of these process parameters can lead to a range of unfavourable changes, for example:

- concentration of fissionable material (by precipitation/colloid formation/extraction);
- unplanned separation of plutonium & uranium;
- carry-over of uranium and plutonium into raffinate stream;
- incomplete dissolution.

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

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

5.47. The effectiveness and reliability of these control measures should be considered as part of the criticality safety assessment. A process flowsheet should be used to help determine the plant response and sensitivity to changes in the process, control or safety parameters. This information should be used to ensure that the safety measures are able to respond quickly enough to detect, correct or terminate unsafe conditions and prevent a criticality accident.

5.48. 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

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

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

5.51. The next potential accumulation mechanism occurs during dissolution. Incomplete dissolution (in a PUREX process, for example) may occur due to a range of fault conditions, e.g. low acidity, low temperature, short dissolution time, overloading of fuel, low acid volume etc. Criticality safety measures should therefore be based on:

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

5.52. 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 required.

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

5.54. The recommendations to trap leaks in safe geometry containers and the provision of monitored sumps to detect such leaks have been discussed above. However, the possibility exists for very slow leaks or leaks onto hot surfaces, where the material crystallizes before reaching the measuring point, to occur. These types of loss of material can be very difficult to detect. Safety measures for this type of event may include periodic inspections of the areas below vessels and pipework. 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

5.55. For most furnace operations as part of the conversion process (e.g. precipitation, drying, oxidation etc), it may be practical to use safe geometry vessels (also for the furnace internal volume). However, in subsequent operations the oxide powders produced may require moderation control to allow feasible storage arrangements. It is important that 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).

5.56. In addition to this guidance for reprocessing, the recommendations in sections 2 - 4 should be considered for performing criticality safety assessments and analyses.

Waste management and decommissioning

5.57. 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 spent fuel as well as other types of waste arising from operations involving fissionable material (e.g. 'Legacy Waste'[2]). The operations may be shielded or un-shielded and may involve remote or manual handling operations. Generally, this type of operation would be expected to involve large inventories (particularly in a disposal facility) of fissionable material from a wide range of sources. In the case of Legacy Waste there may also be considerable variability and uncertainty in the material properties (e.g. in the physical form and chemical composition of the non-fissionable and fissionable components of the waste material). In contrast, decommissioning operations may typically involve small inventories of fissionable material.

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

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

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

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

5.61. The recommendations relating to criticality assessment identified in sections 2 - 4 should be addressed. The following is provided as an overview of some of the issues with particular relevance to waste management operations. Methodologies and standards in this

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[2] See Section 7 “Glossary” for a definition of the term “Legacy Waste”.

area are currently in a state of development. It is therefore recommended that a state-of -the-art review should be made prior to carrying out this type of assessment.

Variability and uncertainty in waste form

5.62. 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 numbers of packages produced, resulting in more handling and transport moves and higher storage volumes, each of this carrying their own risks (from hazards such as radiological doses to operators, road/rail accidents, increased construction risks etc.). Consideration should therefore be given to the balance of risk between the criticality hazard and these other hazards. This may be achieved through the use of risk-informed assessment methods, where both the likelihood and consequences of a potential hazard are considered. Note that this approach may also be applied to assessment of post-closure criticality safety.

Degradation of engineered features over long time scales

5.63. Some reduction in the fissile inventory of nuclear waste will occur over the long time scales associated with post-closure assessment due to radioactive decay (of ^{239}Pu for example). However the half-life of ^{235}U (a daughter product of ^{239}Pu decay) is such that this fissionable isotope will persist (along with the potential for a criticality event) for millions of years. Over that time scale, significant degradation of engineered features of the waste packaging may occur, along with relocation and accumulation of fissionable and non-fissionable components. A full description of this evolution of package contents requires consideration of the geo-chemical processes involved, which are subject to significant uncertainties. As a result it is difficult to provide deterministic evidence that a post-closure criticality event cannot occur. Assessment of post-closure criticality safety may be based on risk-informed methods, where the aim should be to establish that the combination of the likelihood and the consequences (i.e. the risk) of a criticality are acceptably low. Note that in this context the consequences of criticality are the resulting increases in doses to the public through any increased release of radioactive material from the disposal facility to the surface environment.

Validation issues

5.64. The analysis of degraded waste scenarios and the quantification of the consequences of post-closure criticality may involve extending existing calculation tools beyond their current proven range of applicability. Realistic models of degraded scenarios are unlikely to closely resemble available benchmark experiments. Extrapolation of calculation bias from existing benchmarks should take into account the representativity of the benchmarks and of the quality and uncertainties in the relevant basic nuclear data used.

Decommissioning

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

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

Transport

5.67. Safe transport of radioactive material, including consideration of the criticality hazard, is detailed in Refs. [6], [17], [18] and [19], which constitute IAEA safety requirements and recommendations on the subject.

5.68. It is noted that the requirements for transport criticality safety assessments differ considerably from the requirements for facility criticality safety assessments. Due to the potential for closer contact with the public, the transport criticality safety assessment is stringent and based on a fully deterministic system, which does not allow risk-informed judgements.

5.69. Transport packages containing radioactive material for transport outside of a nuclear site and in the public domain should be licensed by the competent authority of all the countries through which the package travels.

5.70. Transport packages should be shown to be safe for both normal and accident conditions of transport.

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

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

5.73. Fissile material should be transported so as to maintain sub-criticality during normal and accident conditions of transport. In particular, the following contingencies should be considered:

- water in-leakage or out-leakage from the transport package;
- damage to the package, including the loss of built-in neutron absorbers or moderators;

- rearrangement of the contents within the transport package;
- reduction of spaces within or between packages;
- packages becoming immersed in water or buried in snow;
- temperature changes.

Exceptions

5.74. Some packages containing fissile material could be excepted from the transport requirements. These exceptions are detailed in Ref. [6]. These may be applicable to particular types of fissionable material in waste.

Laboratory

5.75. This type of facility is defined as being dedicated to the research and development of systems and products that utilize fissionable materials. These facilities are generally characterized by the requirement for high flexibility in their operations and processes, but typically have low inventories of fissionable materials and can include both hands-on and/or remote handling operations.

Access to wide range of fissionable and non-fissionable materials

5.76. Due to the research and development nature of the laboratory operations, these laboratories can use a wide range of fissionable and non-fissionable materials and separated isotopes, typically including low-, intermediate-, and high-enriched uranium, plutonium that is high in ^{240}Pu content (e.g. >15 $^{w}/_{o}$), plutonium that is low in ^{240}Pu content (e.g. <5$^{w}/_{o}$), graphite, boron, gadolinium, hafnium, heavy water, zirconium, poreformer, aluminium and various metal alloys. Examples of special fissionable and non-fissionable 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, etc.), 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 these materials include Refs. [20] and [21].

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

Overlap of operating areas and material interfaces

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

5.79. 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 control area or the movement of moderators into an area is restricted and subjected to a criticality safety analysis before the movement is approved.

Inadvertent consolidation of fissionable materials

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

Specialized education and training of personnel

5.81. Because of the diverse characteristics of materials and laboratory operations, laboratory personnel and management should be sensitized (i.e. educated and trained) about the seemingly anomalous characteristics of typical and special fissionable and non-fissionable materials under differing degrees of neutron moderation.

Additional information:

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

6. PLANNED RESPONSE TO NUCLEAR CRITICALITY ACCIDENTS

CAUSES AND CONSEQUENCES OF A NUCLEAR CRITICALITY ACCIDENT

6.1. Priority should always be given to the prevention of criticality accidents through the provision of “defence in depth”. However, in the event of failures leading to a criticality accident, a means of minimising the consequences of the criticality should be provided. The consequences should be minimised by alerting personnel to the threat of high radiation intensity and providing a procedure for their safe evacuation.

6.2. The radiation doses from criticality accidents may be significant, even for personnel located at some distance from the accident, and so a mechanism for identifying appropriate evacuation and control areas should be developed. Alarms should be provided and appropriate evacuation routes and assembly areas defined.

6.3. In demonstrating the adequacy of the emergency arrangements the expected external dose should be calculated. Of the 22 world-wide criticality accidents that have occurred in process facilities; 20 have occurred in solutions, one involved a slurry and one occurred with metal ingots Ref. [11]. In these events, the key physical phenomena affecting the fission yield were:

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

6.4. Guidance for the estimation of fission yield magnitudes may be found in Ref. [22].

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

6.6. An analysis of the 22 process accidents identified a common theme in terms of the reactivity excursion mechanism; the majority being due to increase in concentration, movement of fissionable material/reflector by gravity or flow through pipework. A detailed description of the dynamic behaviour of criticality accidents can be found in Ref. [11].

BASIC RESPONSIBILITIES

6.7. Despite all the precautions that are taken in the design and operation of nuclear fuel cycle facilities, there remains a possibility that a failure (i.e. mechanical or operational errors) or an incident may give rise to a criticality accident. In some cases, this may give rise to exposure or the release of radioactive materials within the facility and/or into the environment, which may necessitate emergency response actions. Such emergencies may include transport accidents. Adequate preparations should be established and maintained at local and national levels and, where agreed between States, at the international level to respond to nuclear or radiological emergencies.

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

EMERGENCY PREPAREDNESS AND RESPONSE

6.9. It is acknowledged that in some operations with fissionable materials the risk of a criticality accident, while very small, cannot be eliminated. In such an event a means of alerting personnel to the threat of high radiation intensity, using a criticality accident alarm system and a procedure for their safe evacuation should be provided.

6.10. Each installation where criticality accident alarm systems are installed should have an emergency preparedness plan, program, and capabilities to respond to credible criticality accidents.

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

Emergency response plan

6.12. In general the emergency response plan should:

- Define responsibilities of the management team and the technical staff, including the criteria for notifying the relevant local or national authorities;
- Provide an evaluation of the potential criticality accident locations and the accident characteristics;
- Identify appropriate equipment, including protective clothing and radiation detection and monitoring equipment;
- Consider treatment and appropriate medical care;

- Detail the actions to be taken on evacuation and the evacuation routes;
- Describe requirements and activities associated with re-entry, rescue and stabilisation;
- Discuss training, exercises and evacuation drills.

Responsibilities

6.13. Prepared emergency procedures should be approved by management.

6.14. Management should ensure that staff with relevant expertise are provided.

6.15. Organisations (including Emergency Services), on- and off-site, that are expected to provide assistance during emergencies should be 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.

6.16. 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.

6.17. During an Emergency response the criticality safety staff should be able to advise and assist the nominated emergency co-ordinator in responding to the criticality accident.

6.18. Criticality safety staff should be competent to conduct a radiological dose assessment appropriate for a criticality accident.

Pre-Accident Evaluation

6.19. Potential criticality accident locations should be identified and include appropriate facility descriptions. The predicted accident characteristics should be evaluated and documented in sufficient detail to assist emergency planning. This evaluation may be based on professional judgment or a more detailed analysis. The evaluation should include the estimated fission yield. The likelihood of recurrence of criticality should also be considered.

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

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

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

"During-Accident" Evaluation

6.22. 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
- The physical and chemical properties of the fissionable material
- The reactivity insertion mechanism that took the system super-critical

6.23. 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 subcritical condition.

6.24. In developing these options the criticality safety staff should be directly involved in the emergency response team and should seek advice from other known specialists as required. A directory of such experts should be available with the emergency response plan. Once the information listed above is available useful comparisons can be made with details available from other criticality accidents Refs. [11], [23] and [24]. 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 shutdown the excursion. In some cases termination may be achieved by reversing the reactivity insertion mechanism that initiated the accident.

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

Instrumentation and Equipment

6.26. 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.

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

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

Evacuation

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

6.30. 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. Facility changes should not unnecessarily impede or otherwise lengthen evacuation time and should be subjected to assessment and approval before being implemented.

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

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

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

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

Re-entry, Rescue and Stabilisation

6.35. An assessment of the state of the facility should be completed by nominated, suitably qualified and experienced criticality safety staff, to determine the actions to be taken on the site to limit the extent of radioactive release and spread of contamination.

6.36. 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.

6.37. 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.

6.38. Re-entry during the emergency should only be made by personnel trained in emergency response and re-entry. Re-entry should be performed by more than one person.

6.39. Re-entry should only be made if radiological surveys indicate that the radiation levels are acceptable.

6.40. If the system remains critical and is causing significant releases of radioactive material, an early re-entry effort to disable the system should be considered.

6.41. The criticality safety staff should determine if the system is subcritical and advise management of methods to ensure stabilisation.

6.42. 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

6.43. 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.

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

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

Training and exercises

6.46. Refs. [11], [23] and [24] provide detailed descriptions of the dynamic behaviour of criticality accidents that have occurred in the past and could be used to develop training exercises.

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

CRITICALITY ACCIDENT ALARM AND DETECTION SYSTEMS

6.48. Criticality accident 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.

6.49. Exceptions to this requirement are:

- *Shielded Facilities* where either the potential for a criticality accident is not foreseeable, or 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)

- *Where a documented analysis* concludes that no foreseeable set of circumstances can initiate a criticality accident or where the provision of criticality accident alarm systems offers no reduction in total risk, i.e. the overall risk to personnel from all hazards, including industrial is not reduced.

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

6.50. The principles of the procedures to be adopted in a transport emergency should be based upon Ref. [25].

6.51. Thus, relevant national or international organisations should establish emergency procedures, as outlined above and that these procedures should be followed in the event of a transport accident involving radioactive material.

Performance and testing requirements for criticality detection and alarm systems

Limitations and general requirements

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

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

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

Detection and Dependability

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

Alarm

6.56. The alarm signal should:

- Be unique, i.e. immediately recognisable as a criticality accident alarm,
- be audible in all areas to be evacuated,
- sound as soon as the accident is detected,
- continue until evacuation is complete,
- be supplemented with visual signals in areas with high background noise.

6.57. The alarm trip point should be set low enough to detect the minimum accident of concern, that is defined as the smallest accident a criticality alarm system is required to detect, but sufficiently high to minimise the probability of alarm from sources other than criticality.

Dependability

6.58. 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.

6.59. Criticality accident 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.

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

6.61. Uninterruptible power supplies should be available for criticality detection and alarm systems or else portable instruments should be available to compensate during such interruptions.

Design criteria

6.62. The design of the Criticality Detection and Alarm Systems should be as simple as is consistent with the objectives of ensuring reliable activation of the alarm and avoiding false alarms.

Detection criterion

6.63. Criticality alarm systems should be designed to detect promptly the minimum accident of concern. Ref. [26] recommends that in typical unshielded process areas, the minimum accident of concern may be assumed to deliver an absorbed neutron and gamma dose in free air of 0.2Gy at a distance of 2 m from the reacting material within 60s (consideration of past accidents shows that if a criticality accident should occur, the radiation intensity may be expected to exceed this value). The ability to attain these conditions is somewhat system dependent e.g. excursions in un-moderated systems will probably occur much more rapidly.

Instrument response

6.64. In the design of radiation detectors, it may be assumed that the minimum duration of the radiation transient is 1ms. Ref. [26] recommends that systems should be designed to respond to radiation transients of this duration.

Trip point

6.65. In order to minimize false alarms, the trip point may be set as high as necessary provided the detection criterion specified above is met. Indications should be provided to show which detection channels have been tripped.

Positioning the detectors

6.66. The location and spacing of detectors should be chosen to avoid 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.

Testing

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

6.68. Instrument response to radiation should be checked periodically. (Ref. [26] recommends at least once a month).

6.69. Each audible signal generator should be tested periodically (Ref. [26] recommends at least once every three months). 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.

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

6.71. The facility management should be given advance notice of any periods during which the system will be taken out of service.

6.72. Records of the tests should be maintained in accordance with approved quality assurance plans as part of the overall management system.

7. GLOSSARY[3]

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

Control – is an engineered feature (active or passive) or administrative process that establishes constraints on the range of values that process parameters can assume with a given reliability (i.e. failure frequency) thereby providing a barrier to a criticality accident. The preferred hierarchy is a) passive engineered controls, b) active engineered controls, and c) administrative controls.

Depletion – is the change in the concentration of one or more specified nuclides in a material of one of its constituents.

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

Heavy water – is water that contains a higher proportion than normal of the isotope deuterium, as deuterium oxide, D_2O or ^2H_2O.

Initial enrichment – is the enrichment of fuel prior to irradiation in a reactor.

Irradiated material – is material that has been exposed to a reactor flux.

ISOCS™ – is the *In Situ* Object Counting System for gamma spectroscopy used in nuclear materials accountability.

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

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

Loading curve – is the curve joining pairs of initial enrichment and burnup that have been demonstrated to be safely subcritical.

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

Pore former – is an additive that is used in the blending of nuclear fuel oxides for the purpose of creating randomly distributed closed pores in the blended oxide prior to pelletizing

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[3] A Glossary is included only during the development of the Safety Guide to aid discussion. It is intended to either include the final list of definitions as footnotes in the final document or add to the IAEA Safety Glossary.

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.

Pyroelectric (Electrolytic dissolution, Electro deposition, Electro reduction, Electrolytic decomposition), **Chemical** (Precipitation, crystallization, sorption, complexation, solvent extraction), and **Crystallization** – are separation processes used within the nuclear fuel cycle.

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

Representativity (*ck*) – is the correlation coefficient index, denoted as *ck*, which is a measure of similarity between two systems in terms of their related uncertainties which are based upon the coupling of neutron cross section reaction sensitivity data from both systems with the neutron cross-section covariance data.

Subcriticality – is the state of a nuclear chain reacting medium when the chain reaction is less than self-sustaining (or *critical*), i.e. when the *reactivity* is negative.

REFERENCES

1. INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Nuclear Fuel Cycle Facilities, IAEA Safety Standards Series No. NS-R-5, IAEA, Vienna (2008).

2. INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Assessment for Facilities and Activities, IAEA Safety Standards Series No. GSR Part 4, IAEA, Vienna (2009).

3. INTERNATIONAL ATOMIC ENERGY AGENCY, The Management Systems for Facilities and Activities, IAEA Safety Standards Series No. GS-R-3, IAEA, Vienna (2006).

4. INTERNATIONAL ATOMIC ENERGY AGENCY, Predisposal Management of Radioactive Waste, IAEA Safety Standards Series No. GSR Part 5, IAEA, Vienna (2009).

5. INTERNATIONAL ATOMIC ENERGY AGENCY, Decommissioning of Facilities using Radioactive Materials, IAEA Safety Standards Series No. WS-R-5, IAEA, Vienna (2006).

6. INTERNATIONAL ATOMIC ENERGY AGENCY, Regulations for the Safe Transport of Radioactive Materials, IAEA Safety Standards Series No. TS-R-1, IAEA, Vienna (2009).

7. INTERNATIONAL ATOMIC ENERGY AGENCY, Geological Disposal of Radioactive Waste, IAEA Safety Standards Series No. WS-R-4, IAEA, Vienna (2006).

8. INTERNATIONAL ATOMIC ENERGY AGENCY, Preparedness and Response for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GS-R-2, IAEA, Vienna (2002).

9. US DoE, PNL-SA-4868 Rev 6, Anomalies of Criticality, E.D. Clayton, July 2009.

10. INTERNATIONAL ATOMIC ENERGY AGENCY, Application of the Management System for Facilities and Activities, IAEA Safety Standard Series No. GS-G-3.1, IAEA, Vienna (2006).

11. Los Alamos National Laboratory, LA 13638, A Review of Criticality Accidents, 2000 revision.

12. INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Nuclear Power Plants: Design, IAEA Safety Standards Series No. NS-R-1, IAEA, Vienna (2000).

13. INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Conversion Facilities and Uranium Enrichment Facilities, IAEA Safety Standards Series No. SSG-5, IAEA, Vienna (to be published).

14. INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Uranium Fuel Fabrication Facilities, IAEA Safety Standards Series No. SSG-6, IAEA, Vienna (to be

published).

15. INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Uranium and Plutonium Mixed Oxide Fuel Fabrication Facilities, IAEA Safety Standards Series No. SSG-7, IAEA, Vienna (to be published).

16. ANSI/ANS-8.27-2008, “Burnup Credit for LWR Fuel,” American Nuclear Society, La Grange Park, Illinois, USA.

17. INTERNATIONAL ATOMIC ENERGY AGENCY, Compliance Assurance for the Safe Transport of Radioactive Material, IAEA Safety Standards Series No. TS-G-1.5, IAEA, Vienna (2009).

18. INTERNATIONAL ATOMIC ENERGY AGENCY, The Management System for the Safe Transport of Radioactive Material, IAEA Safety Standards Series No. TS-G-1.4, IAEA, Vienna (2009).

19. INTERNATIONAL ATOMIC ENERGY AGENCY, Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material, IAEA Safety Standards Series No. TS-G-1.1 (Rev.1), IAEA, Vienna (2008).

20. C. Lavarenne, D. Mennerdahl, C. Dean, Evaluation of Nuclear Criticality Safety Data and Limits for Actinides in Transport, Institut de Radioprotection et de Sureté Nucléaire (IRSN), C4/TMR2001/200-1, 21 May 2003.

21. ANSI/ANS-8.15-1981, “Nuclear Criticality Control of Special Actinide Elements,” American Nuclear Society, La Grange Park, Illinois, USA.

22. ISO 27467:2009, Nuclear Criticality Safety – Analysis of a Postulated Criticality Accident, International Standards Organization.

23. Hopper, C.M.; Broadhead, B.L. “An Updated Nuclear Criticality Slide Rule: Functional Slide Rule.” NUREG/CR 6504, VOL. 2(ORNL/TM 13322/V2), Oak Ridge National Laboratory, Oak Ridge, Tennessee, September 1998.

24. Thomas P. McLaughlin, “Process Criticality Accident Likelihoods, Magnitudes and Emergency Planning—A Focus on Solution Accidents.” Proceedings of the Seventh International Conference on Nuclear Criticality Safety (ICNC 2003), October 20-24, Tokai-mura, Ibaraki, Japan, JAERI-Conf 2003-019, Japan Atomic Energy Research Institute (2003).

25. INTERNATIONAL ATOMIC ENERGY AGENCY, Planning and Preparing for Emergency Response to Transport Accidents Involving Radioactive Material, IAEA Safety Standards Series No. TS-G-1.2, IAEA, Vienna (2002).

26. ISO 7753:1987, Nuclear Energy – Performance and Testing requirements for Criticality detection and Alarm Systems, International Standards Organization.

27. INTERNATIONAL ATOMIC ENERGY AGENCY, The Management System for the Processing, Handling and Storage of radioactive Waste, IAEA Safety Standard Series

No. GS-G-3.3, IAEA, Vienna (2008)

28. INTERNATIONAL ATOMIC ENERGY AGENCY, The Management System for the Disposal of radioactive Waste, IAEA Safety Standard Series No. GS-G-3.4, IAEA, Vienna (2008)

29. INTERNATIONAL ATOMIC ENERGY AGENCY, The Management System for Nuclear Installations, IAEA Safety Standard Series No. GS-G-3.5, IAEA, Vienna (2009)

Annex I

Bibliography

Assessment Methodology

- ISO 27467, Nuclear criticality safety — Analysis of a postulated criticality accident
- ANSI/ANS-8.9-1987;R1995;W2005 (R=Reaffirmed, W=Withdrawn): Nuclear Criticality Safety Guide for Pipe Intersections Containing Aqueous Solutions of Enriched Uranyl Nitrate

Standards

ISO Standards

- ISO 1709, Nuclear energy — Fissile materials — Principles of criticality safety in storing, handling and processing
- ISO 27467, Nuclear criticality safety — Analysis of a postulated criticality accident
- ISO 14943, Nuclear fuel technology — Administrative criteria related to nuclear criticality safety
- CEI/IEC 860, Warning equipment for criticality accidents
- ISO 7753, Nuclear energy — Performance and testing requirements for criticality detection and alarm systems

ANSI/ANS Standards

- ANSI/ANS-8.1-1998; R2007 (R = Reaffirmed): Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors
- ANSI/ANS-8.3-1997;R2003 (R=Reaffirmed): Criticality Accident Alarm System
- ANSI/ANS-8.5-1996;R2002;R2007 (R=Reaffirmed): Use of Borosilicate-Glass Raschig Rings as a Neutron Absorber in Solutions of Fissile Material
- ANSI/ANS-8.6-1983;R1988;R1995;R2001 (R=Reaffirmed): Safety in Conducting Subcritical Neutron-Multiplication Measurements In Situ
- ANSI/ANS-8.7-1998: Guide for Nuclear Criticality Safety in the Storage of Fissile Materials
- ANSI/ANS-8.9-1987;R1995;W2005 (R=Reaffirmed, W=Withdrawn): Nuclear Criticality Safety Guide for Pipe Intersections Containing Aqueous Solutions of Enriched Uranyl Nitrate
- ANSI/ANS-8.10-1983;R1988;R1999;R2005 (R=Reaffirmed): Criteria for Nuclear Criticality Safety Controls in Operations With Shielding and Confinement
- ANSI/ANS-8.12-1987;R2002 (R=Reaffirmed): Nuclear Criticality Control and Safety of Plutonium-Uranium Fuel Mixtures Outside Reactors
- ANSI/ANS-8.14-2004: Use of Soluble Neutron Absorbers in Nuclear Facilities Outside Reactors
- ANSI/ANS-8.15-1981;R1987;R1995;R2005 (R=Reaffirmed): Nuclear Criticality Control of Special Actinide Elements
- ANSI/ANS-8.17-2004: Criticality Safety Criteria for the Handling, Storage, and Transportation of LWR Fuel Outside Reactors

- ANSI/ANS-8.19-2005: Administrative Practices for Nuclear Criticality Safety
- ANSI/ANS-8.20-1991;R1999;R2005 (R=Reaffirmed): Nuclear Criticality Safety Training
- ANSI/ANS-8.21-1995;R2001 (R=Reaffirmed): Use of Fixed Neutron Absorbers in Nuclear Facilities Outside Reactors
- ANSI/ANS-8.22-1997;R2006 (R=Reaffirmed): Nuclear Criticality Safety Based on Limiting and Controlling Moderators
- ANSI/ANS-8.23-2007: Nuclear Criticality Accident Emergency Planning and Response
- ANSI/ANS-8.24-2007: Validation of Neutron Transport Methods for Nuclear Criticality Safety Calculations
- ANSI/ANS-8.27-2007 Burnup Credit for LWR Fuel
- ANSI/ANS-8.26-2007: Criticality Safety Engineer Training and Qualification Program

Government standards

- DOE-STD-1173-2003, Criticality Safety Functional Area Qualification Standard
- DOE-STD-1135-99, Guidance for Nuclear Criticality Safety Engineer Training and Qualification
- DOE-STD-1158-2002, Self-Assessment Standard for DOE Contractor Criticality Safety Programs
- DOE-STD-3007-2007, Guidelines for Preparing Criticality Safety Evaluations at Department of Energy Nonreactor Nuclear Facilities
- DOE-STD-3009-06, Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Documented Safety Analyses
- 10 CFR Part 60, Disposal of High-Level Radioactive Wastes in Geologic Repositories
- 10 CFR 61, Licensing Requirements for Land Disposal of Radioactive Waste
- 10 CFR Part 70, Domestic Licensing of Special Nuclear Material
- 10 CFR Part 71, Packaging and Transportations of Radioactive Material
- 10 CFR Part 72, Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater than Class C Waste

Handbooks & Guides

- ARH-600 Handbook
- NRC Reg Guide 3.71, Nuclear Criticality Safety Standards for Fuels and Material Facilities
- DOE-STD-3011-94, Guidance for Preparation of DOE Order 5480.22 (TSR) and DOE Order 5480.23 (SAR) Implementation Plans
- 10 CFR 830, Nuclear Safety Management
- DOE G 421.1-2, Implementation Guide for use in Developing Documented Safety Analyses to meet Subpart B of 10 CFR 830
- DOE G 423.1-1, Implementation Guide for use in Developing Technical Safety Requirements

- DOE G 424.1-1, Implementation Guide for use in Addressing Unreviewed Safety Question Requirements LA-10860-MS, Critical Dimensions of Systems Containing U235, Pu239, and U233, 1986.
- NCSD Education Committee Criticality Accidents - White Paper, April 2005
- SCALE Primer, a self-extracting compressed file for SCALE Primer
- ORNL/TM-2008/069, KENO-VI Primer: A Primer for Criticality Calculations with SCALE/KENO-VI Using GeeWiz, September 2008
- ORNL/TM-2009/027, TSUNAMI Primer: A Primer for Sensitivity/Uncertainty Calculations with SCALE, January 2009
- TID-7016-Rev.1, The Nuclear Safety Guide, June 1978.
- NRC: Standard Review Plan for Dry Cask Storage Systems (NUREG-1536, Initial Report) http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1536/final/index.html
- NRC: A Prioritization of Generic Safety Issues (NUREG-0933) - NUREG-0933 - NMSS-0021: UNLIKELY EVENTS Feb-23-2007 06:59: http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr0933/appendices/nmss0021.html
- NRC: A Prioritization of Generic Safety Issues (NUREG-0933) - NMSS-0007: CRITICALITY BENCHMARKS GREATER THAN 5% ENRICHMENT (REV. 2) Aug-26-2008 14:32 http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr0933/appendices/nmss0007r2.html
- NRC: A Prioritization of Generic Safety Issues (NUREG-0933) - NMSS-0006: CRITICALITY IN LOW-LEVEL WASTE Feb-23-2007 http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr0933/appendices/nmss0006.html

Hand Methods

- LA-14244-M, Hand Calculation Methods for Criticality Safety - A Primer, by Douglas G. Bowen and Robert D. Busch.

Computational Methods

- *SCALE (Standardized Computer Analyses for Licensing Evaluation),* Modular Code System for Performing Criticality and Shielding Analyses for Licensing Evaluation with ORIGEN-ARP, ORNL/TM-2005/39 Version 6.0, Vol. I-III, January 2009, RSICC Code Package C00-750, Radiation Safety Information Computational Center, Post Office Box 2008, 1 Bethel Valley Road, Oak Ridge, Tennessee 37831-6171.
- *MCNP (Monte Carlo N-Particle)* Transport Code System Including MCNP5 1.51 and MCNPX 2.6.0 and Data Libraries, RSICC Code Package C00-740, Radiation Safety Information Computational Center, Post Office Box 2008, 1 Bethel Valley Road, Oak Ridge, Tennessee 37831-6171.
- *VIM*, Continuous Energy Neutron and Photon Transport Code System, April 2009 Release. RSICC Code Package C00-754, Radiation Safety Information Computational Center, Post Office Box 2008, 1 Bethel Valley Road, Oak Ridge, Tennessee 37831-6171.
- COG, Multiparticle Monte Carlo Code System for Shielding and Criticality Use. RSICC Code Package C00-724, Radiation Safety Information Computational Center, Post Office Box 2008, 1 Bethel Valley Road, Oak Ridge, Tennessee 37831-6171.

Training & Education

- U.S. Department of Energy Nuclear Criticality Safety Program Nuclear Criticality Safety Engineer Training (http://ncsp.llnl.gov/trainingMain.html)
    - Module 1: Introductory Nuclear Criticality Physics (PDF)
    - Module 2: Neutron Interactions (PDF)
    - Module 3: The Fission Chain Reaction (PDF)
    - Module 4: Neutron Scattering and Moderation (PDF)
    - Module 5: Criticality Safety Limits (PDF)
    - Module 6: Introduction to Diffusion Theory (PDF)
    - Module 7: Introduction to the Monte Carlo Method (PDF)
    - Module 8: Hand Calculation Methods - Part I (PDF)
    - Module 9: Hand Calculation Methods - Part 2
    - Module 10: Criticality Safety in Material Processing Operations - Part 1 (PDF)
    - Module 11: Criticality Safety in Material Processing Operations - Part 2 (PDF)
    - Module 12: Preparation of Nuclear Criticality Safety Evaluations (PDF)
    - Module 13: Measurement and Development of Cross Section Sets (PDF)
    - Module 14: A Review of Criticality Accidents by Thomas McLaughlin (video presentation taped Dec. 10, 1999;
    - Module 15: Fundamentals of Criticality Safety for Non-material Handlers (web-based interactive training course)
- U.S. Department of Energy Nuclear Criticality Safety Program Oak Ridge Critical Experiment Facility History Videos
    - Chapter 1: Early History of Criticality Experiments
    - Chapter 2: Purposes of Early Critical Experiment Campaigns
    - Chapter 3: Early ORCEF Line Organizations & Facilities
    - Chapter 4: Facility Description
    - Chapter 5: Characteristic Experimental Programs
    - Chapter 6: Polonium - Beryllium Neutron Source Experience
    - Chapter 7: Operational Safety Experiments & Analysis
    - Chapter 8: Additional ORCEF Experimentalists
    - Chapter 9: Solution Sphere Experiment
    - Chapter 10: Sponsor & Credit

Management

- DOE Order 420.1A, Facility Safety
- DOE Order 420.1B, Facility Safety
- DOE Policy 450.4, Safety Management System Policy
- DOE Guide 450.4, Integrated Safety Management System Guide
- DOE-STD-3007-93, CN1 Guidelines for Preparing Criticality Safety Evaluation at Department of Energy Non-Reactor Nuclear Facilities
- DOE-STD-3009-94, CN2 Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Safety Analysis Reports
- DOE-STD-1186-2004, Specific Administrative Controls
- DOE-STD-1134-99, Review Guide for Criticality Safety Evaluations
- DOE-STD-1135-99, Guidance for Nuclear Criticality Safety Engineer Training and Qualification
- DOE-STD-1158-2002, Self-Assessment Standard for DOE Contractor Criticality Safety Programs

Operational experiences/accidents and incidents

- LA-13638, A Review of Criticality Accidents, 2000 Revision
- DOE/NCT-04, A Review of Criticality Accidents, March 1989.

CONTRIBUTORS TO DRAFTING

Cousin. R	IRSN, France
De Vita. A	AREVA/Melox, France
Dunn. L	AECL, Canada
Farrington, L	WNTI, United kingdom
Gulliford, J	Nexiasolutions, United Kingdom
Galet, C	IRSN, France
Hopper, C	ORNL, United States of America
Irish, D	AECL, Canada
Jones, G	International Atomic Energy Agency
Neuber, J	AREVA NP GmbH, Germany
Warnecke, E	International Atomic Energy Agency
Winfield, D	International Atomic Energy Agency