GUIDE NO. AERB/FCF/SG-3

सत्यमेव जयते

GOVERNMENT OF INDIA

AERB SAFETY GUIDE

CRITICALITY SAFETY OF FISSILE MATERIAL HANDLING FACILITIES

ATOMIC ENERGY REGULATORY BOARD

AERB SAFETY GUIDE NO. AERB/FCF/SG-3

CRITICALITY SAFETY OF FISSILE MATERIAL HANDLING FACILITIES

Atomic Energy Regulatory Board
Mumbai-400094
India

October - 2022

FOREWORD

Activities concerning establishment and utilization of nuclear facilities and use of radioactive sources are to be carried out in India in accordance with the provisions of the Atomic Energy Act 1962 and subsequent amendments. In pursuance of the objective of ensuring safety of members of the public and occupational workers as well as protection of the environment, the Atomic Energy Regulatory Board (AERB) has been entrusted with the responsibility of laying down safety standards and enforcing rules and regulations for such activities. The Board has, therefore, undertaken a programme of developing safety codes, standards, guides and manuals for the purpose. While some of the documents cover aspects such as siting, design, construction, operation, quality assurance and decommissioning of nuclear and radiation facilities, other documents cover regulatory aspects of these facilities.

Safety codes and standards are formulated on the basis of internationally accepted safety criteria for design, construction and operation of specific equipment, structures, systems and components of nuclear and radiation facilities. Safety codes establish the objectives and set minimum requirements that shall be fulfilled to provide adequate assurance for safety. Safety guides elaborate various requirements and furnish approaches for their implementation. Safety manuals deal with specific topics and contain detailed scientific and technical information on the subject. These documents are prepared by experts in the relevant fields and are extensively reviewed by advisory committees of the Board before they are published. The documents are revised when necessary, in the light of experience and feedback from users as well as new developments in the field.

AERB safety guide on 'Criticality Safety of Fissile Material Handling Facilities' provides guidance on preventing criticality and maintaining sub-criticality in handling, processing and storage of fissile materials in nuclear and radiation facilities other than a nuclear reactor. The guide elaborates on how to ensure sub-criticality during normal operation, anticipated operational occurrences and accident conditions, from design through commissioning, operation and decommissioning. The guide covers fuel reprocessing, fuel fabrication, fresh and spent fuel storage facilities and activities that use fissile materials. It outlines criticality safety assessment methodology and specifies criteria for ensuring sub-criticality, detection of criticality and alarm systems, accident dosimetry and emergency preparedness plans. Approaches for implementation different from those set out in this guide may be acceptable, if they provide comparable assurance against undue risk to the health and safety of the occupational workers, the general public and the environment.

This guide is applicable to nuclear facilities designed and commissioned after the issue of this guide. However, for existing facilities compliance with the provisions of this guide will be examined during periodic safety review for appropriate implementation. For aspects not covered in this safety guide (such as chemical hazards, fire safety and other industrial safety aspects) applicable national and international standards, codes and guides, acceptable to AERB, may be followed.

The draft guide prepared in-house has been reviewed by experts and vetted by the Advisory Committee on Nuclear and Radiation Safety before issue. Relevant IAEA documents and other publications have been used in preparing this safety guide. Annexures and bibliography are included to provide further information on the subject. AERB acknowledges the efforts of all individuals and organisations who have prepared and reviewed the draft and helped in its finalisation.

(G. Nageswara Rao)

Chairman, AERB

DEFINITIONS

Criticality
The state of a nuclear chain reacting medium when the chain reaction is just self-sustaining (or critical), i.e. when the reactivity is zero.

Criticality Safety Index (CSI)
A number assigned to a package, overpack or freight container containing fissile material that is used to provide control over the accumulation of packages, overpacks or freight containers containing fissile material.

Defence-in-Depth
A hierarchical deployment of different levels of diverse equipment and procedures to prevent the escalation of anticipated operational occurrences and to maintain the effectiveness of physical barriers placed between a radiation source or radioactive material and workers, members of the public or the environment, in operational states and, for some barriers, in accident conditions.

Fissile Material
Uranium-233, uranium-235, plutonium or any material containing these substances or any other material that may be declared as such by notification of the Central Government.

Nuclear Facility
All nuclear fuel cycle and associated installations encompassing the activities from the front end to the back end of nuclear fuel cycle processes and also the associated industrial facilities such as heavy water plants, beryllium extraction plants, zirconium plants, etc.

Nuclear Fuel Cycle
All operations associated with the production of nuclear energy, including mining, milling, processing of uranium or thorium; enrichment of uranium; manufacture of nuclear fuel; operation of reactors; reprocessing of nuclear fuel; decommissioning; radioactive waste management and any research or development activity related to any of the foregoing.

Plant Management
The members of site personnel who have been delegated responsibility and authority by the Operating Organization for directing the safe operation of the plant.

Radiation Worker
Any person who is occupationally exposed to radiation.

Reactivity
For a nuclear chain reacting medium:

$$\varrho = 1 - 1/(k_{eff})$$

where, k_{eff} is the ratio between the number of fissions in two succeeding generations (later to earlier) of the chain reaction.

A measure of the deviation from criticality of a nuclear chain reacting medium, such that positive values correspond to a supercritical state and negative values correspond to a subcritical state.

Responsible Organisation
An organisation having overall responsibility for siting, design, construction, commissioning, operation and decommissioning of a facility.

Single Failure
A failure which results in the loss of capability of a single system or component to perform its intended safety function(s), and any consequential failure(s) which result from it.

SPECIAL DEFINITIONS

Criticality Accident
A criticality accident is an accidental release of energy as a result of unintentionally producing a criticality in a facility in which fissile material is used.

Criticality Detection and Alarm System (CDAS)
CDAS is a system capable of raising audible and visual alarm after detecting neutron or gamma radiation from a criticality accident.

Critical Concentration
Concentration of fissile material of a given isotopic composition for which a homogeneous fissile medium of a given geometrical form is just critical. Safe concentration of fissile material is derived from the above with an appropriate safety margin to ensure sub-criticality at all times.

Criticality Control Parameters
The criticality control parameter refers to the parameter used to set safe criticality limits for design and operational control to secure criticality safety of fissile material handling facilities. Criticality controls include all factors whose change influences the criticality of the system. Such factors include the shape and dimensions of the equipment containing fissile material, the concentration of the fissile material in solution, the mass and isotopic composition of fissile material, the physical and chemical properties of the fissile material, presence of neutron absorbers and neutron reflectors.

Critical Infinite Slab
For specified fissile medium and surrounding reflector, a slab of infinite lateral dimensions with finite thickness that would be just critical.

Critical Infinite Cylinder
For specified fissile medium and surrounding reflector, an infinitely long cylinder with finite diameter that would be just critical.

Critical Mass
Mass of fissile material that may be rendered critical for a specific geometry and composition of this material, taking into account the reflecting environment.

(1) **Minimum Critical Mass:** mass of fissile material below which the fissile system is sub-critical regardless of its geometry and its moderation.

(2) **Safe Mass:** mass of fissile material below which the system is subcritical with an appropriate safety margin, regardless of its geometry and moderation.

Criticality Safety
Criticality safety (CS) deals with prevention of a criticality accident and protection from the consequences of a criticality accident. It encompasses design, operating procedures, plant response to criticality accident, training, and other precautions in addition to physical protection.

Criticality Safety Assessment
Criticality safety assessment (CSA) is a comprehensive process that includes identification, evaluation, and estimation of the levels of criticality status in fissile material handling facilities from all credible states, their comparison against fissile material benchmarks or standards, and

determination of an acceptable level of criticality safety. The assessment includes the status of criticality monitoring/detection systems and emergency preparedness plan.

Criticality Safety Limit
Criticality safety limit (CSL) is the permissible upper limit on either k_{eff} or control parameters to ensure sub-criticality of the equipment/system for the design and operating condition.

Criticality Safety Margin
The criticality safety margin (CSM) on k_{eff} or control parameter is the difference between CSL and the estimated value for the equipment/system under process condition.

Double Contingency Principle
This principle requires that the process designs should, in general, incorporate sufficient factors of safety to require at least two unlikely, independent, and concurrent changes in process conditions before a criticality accident is possible.

Effective Neutron Multiplication Factor (k_{eff})
The effective neutron multiplication factor for the system is the ratio of the total number of neutrons produced by a fission chain reaction, to the total number of neutrons lost by absorption and leakage. The system is (a) critical if $k_{eff} = 1$; (b) subcritical if $k_{eff} < 1$; and (c) supercritical if $k_{eff} > 1$.

Neutron Poisoning
Reduction in the reactivity of a fissile medium by the presence of neutron-absorbing material (e.g., cadmium, boron, gadolinium etc.).

Neutron Reflector
Reflection is neutron scattering in which neutrons are directed back into fissile material from which they escaped. All materials scatter neutrons to varying extent and therefore can act as neutron reflectors such as water, steel, wood, paraffin, aluminum, polyethylene, graphite, etc.

Radiation Shielding
A barrier of appropriate thickness used to reduce radiation levels to specified values.

ABBREVIATIONS

ALARA	As Low As Reasonably Achievable
ALARP	As Low As Reasonably Practicable
AOO	Anticipated Operational Occurrences
BSC	Benchmark Selection Criteria
DBA	Design Basis Accident
DCP	Double Contingency Principle
DID	Defence-In-Depth
CCA	Criticality Controlled Area
CS	Criticality Safety
CSA	Criticality Safety Assessment
CSI	Criticality Safety Index
CSL	Criticality Safety Limit
CSM	Criticality Safety Margin
FCF	Fuel Cycle Facility
OLC	Operational Limits and Conditions
EPR	Emergency Preparedness and Response
MOX	Mixed oxide
SFSB	Spent Fuel Storage Bay
AFR	Away From Reactor
WMP	Waste Management Plant
RO	Responsible Organisation
PM	Plant Management
HAZOP	Hazard and Operability Study

CONTENTS

1. INTRODUCTION

1.1 General

1.1.1 Criticality Safety (CS) is an important aspect of nuclear safety. The CS is the main concern for a facility using fissile material(s) such as plutonium, uranium, mixed (plutonium-uranium) carbide or Mixed (plutonium-uranium) Oxide (MOX). Closed fuel cycle in a nuclear power program requires facilities to process fissile material and fabricate them into fuel element and fuel assembly/bundle, to extract the fissile material from the spent fuel, to manage the waste containing fissile material, if any and to transport and store fissile materials. All these facilities handle different types of fissile materials in various forms such as solution, powder, pellet, metal, fuel pin, sheared fuel pins, pin magazine, fuel assembly etc. Process parameters such as composition, concentration or enrichment of fissile isotopes, fissile mass, geometry of the equipment, configuration of fissile system, and associated control mechanisms may vary from system to system. Front end and back end Fuel Cycle Facilities (FCF) involve handling of significant amount of fissile materials and hence are susceptible to have criticality risk due to inadvertent accumulation of fissile materials beyond permissible limit.

1.1.2 A criticality accident or event is characterized by the release of energy as a result of accidentally producing a self-sustaining or divergent fission chain reaction. The hazard is due to the accompanying radiation which can deliver lethal radiation doses to workers in the neighborhood of the criticality accident. To protect the radiation workers from the radiation hazards and consequences of a criticality accident, it is necessary to prevent such an accident during handling, processing, storage and transportation of fissile materials.

1.1.3 This document provides regulatory guidance to ensure criticality safety by providing appropriate criticality control mechanisms in the design by means of safety assessment methodology, criticality monitoring and alarm system and emergency preparedness plan for handling accidents in fissile material handling facilities.

1.2 Objective

The objective of this safety guide is to provide guidance on preventing criticality or maintaining sub-criticality in handling, processing, storage and transport of fissile materials in nuclear and radiation facilities other than a nuclear reactor. The major objectives of the document are:

a) To lay down criticality safety principles to be followed at various stages of design, commissioning, operation, decommissioning of fissile material handling facilities to protect workers, public and the environment.

b) To provide guidance for ensuring sub-criticality of the fissile material handling systems.

c) To provide guidance and specify the requirements for criticality monitoring system, criticality alarm system, effective emergency planning and response to a criticality accident.

1.3 Scope

This document provides guidance to ensure sub-criticality in systems involving fissile material(s) during normal operation, anticipated operational occurrences and accident conditions. It is applicable to fuel reprocessing facilities, fuel fabrication plant, fresh fuel storage building, spent fuel storage bay (SFSB/SFB), away from reactor facility (AFR) and waste management plant (WMP). The guidance also apply to research and development facilities and activities that use fissile material and to the transport of packages containing fissile material.

This document does not specifically cover nuclear reactor, critical facility/assembly, though many aspects may be applicable. Chemical hazards, fire safety and other industrial safety aspects are not addressed in this guide.

2. GOALS AND PRINCIPLES

2.1 Goals

2.1.1 The main goal of the CS is to prevent criticality accident in fissile material handling, processing, storage and transport systems. The criticality safety can be achieved by providing engineered and administrative control measures to ensure adequate Criticality Safety Margin (CSM) while deriving Operational Limits and Conditions (OLC) of a process. These include provision of criticality accident protection mechanism, monitoring instrumentation, criticality accident alarm system and effective emergency response plan.

2.2 Principles

2.2.1 The basic principle of criticality safety is to prevent criticality for all situations that are technically conceivable[1]. Criticality safety may be enhanced by adopting the principles described in sections 2.3 to 2.6.

2.3 Criticality Control Area

2.3.1 An area handling a fissile material higher than its exempted quantity (given in section 4.3 & Annexure-I) should be demarcated as Criticality Control Area (CCA) with clearly defined boundaries and criticality controls.

2.3.2 Each CCA should be posted with a CCA identification sign which, where appropriate, should appear near entrance and exit of each CCA. Each CCA identification sign should contain information on authorized person(s) responsible for fissile material handling in that area.

2.3.3 In some CCAs there might be a restriction on using water to fight a fire, since water is a moderator. Alternative fire extinguishers such as dry chemicals, CO_2, Freon, high expansion foam and inert gases should be used without displacing or rearranging the fissile materials. Detailed firefighting procedures should be prepared.

2.3.4 Unauthorized movement of fissile material or radioactive material should be restricted in the CCA.

2.3.5 Any movement of shielding materials, such as lead bricks, lead blankets and concrete blocks, moderating material such as light water, heavy water, graphite, beryllium, polyethylene, paraffin, oil, wood, etc. should be restricted in a CCA unless specifically approved after safety evaluation. Such safety evaluations are necessary to determine fissile material limits compatible with radiation shielding, scattering and/or moderation.

2.3.6 Movement of fissile material within a facility should be carried out only in an authorized and safe storage equipment in CCA.

---

[1] All cases conceivable from a technical standpoint should refer to all conceivable single failures, or changes in peripheral conditions including reflection, absorption, moderation, and mutual interaction of neutron caused by external factors such as earthquakes, floods or fires.

2.3.7 Written procedures should be available and strictly followed for (a) fissile material handling in batch or once through operation, (b) any change in process, (c) movement of fissile material from one place to another, and (d) storage of fissile material.

2.3.8 Continuous monitoring of neutron and gamma field and also air monitoring should be ensured in the CCA. The monitoring system has to be supplemented with alternative & diverse detection system to facilitate checks for correctness of the detection system.

2.4 As Low As Reasonably Practicable

2.4.1 The facility should be designed, constructed, operated and decommissioned in such a way that the risk to both plant workers and public is shown to be as low as reasonably practicable (ALARP). The ALARP principle [1] has a central role in the demonstration of a robust operational safety of fissile material handling facilities. The acceptability of risk can be conveniently summarized in three levels as follows:

a) For any operation, there is a level of risk that is so high that the operation cannot be allowed;

b) Even when the risk is tolerable, it must be reduced to a level which is ALARP;

c) A point is eventually reached at which the risk is minimized and no further precaution is necessary.

2.4.2 Other issues of importance in the consideration of ALARP are control measures which are given below in order of preference:

a) Passive engineered safety features, i.e. measures that are continuously available and require no action by a safety system or an operator to achieve and maintain a safe state.

b) Active engineered safety features, i.e. measures requiring action by a safety system to achieve and maintain a safe state.

c) Administrative safety measures, i.e. measures requiring action by an operator to achieve and maintain a safe state.

2.5 Double Contingency Principle

2.5.1 As per the Double Contingency Principle (DCP), designs should incorporate sufficient factors of safety such that it would require at least two unlikely, independent, and concurrent changes in process conditions before a criticality accident is possible. A system to control two different physical properties and minimization of reliance on administrative practices as a control mechanism for prevention of criticality are integral part of DCP.

2.6 Defence in Depth Principle

2.6.1 The primary means of preventing accidents in a facility and mitigating the consequences of accidents, if they do occur, is the application of the concept of Defence in Depth (DID). This concept is applied to all safety related activities, whether organizational, behavioral or design related. This is to ensure that all safety related activities are subjected to independent levels in a hierarchical manner, so that if a failure were to occur in a level, it would be detected and compensated for or corrected by appropriate measures by the subsequent level. Application of DID in the design provides several levels of defence (inherent features, equipment and procedures) aimed at preventing harmful effects of radiation on people and the environment, and ensuring adequate protection and mitigation of the consequences. The independent effectiveness of each of the different levels of defence is an essential element of DID at the plant and this is achieved by incorporating measures to avoid the failure of one level of defence causing the failure of other levels [2].

2.6.2 The facility should be designed and operated or activity should be conducted such that DID against anticipated operational occurrences or accidents is achieved by the provision of different multiple levels of protection with the objective of preventing failures, or, if prevention fails, ensuring detection of failures and mitigation of the consequences. The primary objective should be to adopt safety measures that prevent a criticality accident. However, in line with the principle of DID, measures should also be put in place to mitigate the consequences of such an accident.

2.6.3 The concept of DID is normally applied in five levels (see in Appendix-I). The design features, controls and arrangements necessary to implement the DID concept should be identified mainly by means of a deterministic analysis (which may be complemented by probabilistic studies) of the design and operational regime. The analysis should be justified by the application of sound engineering practices based on research and operational experience. This analysis should be carried out during the design stage to ensure that the safety requirements are met [3].

2.6.4 The amount and type of radioactive material present, the potential for dispersion, the potential for nuclear, chemical or thermal reactions, and the kinetics of such events should all be considered in determining the levels of defence [3].

3. CRITICALITY SAFETY

3.1. Criticality safety (CS) is the main concern for a facility using fissile material. CS is generally achieved through the control of one or more parameters such as mass, concentration, moderation, geometry, isotopic composition, density, neutron absorption, reflection and neutron interaction in multi-units system.

3.2. A system will be critical if the rate of neutron production from fissions is exactly balanced by the rate at which neutrons are either absorbed or/and lost from the system due to leakage. Safe subcritical systems can be designed by ensuring that the combined rate of absorption and leakage always exceed the rate of neutron production.

3.3. The objective of criticality safety is to operate the facility within established safe criticality limits. In general, fuel fabrication plants are usually mass controlled in individual equipment; and administratively controlled so as not to exceed the safe mass limit in each process equipment to ensure criticality safety. Where multiple units/equipment are located and continuous processing is involved, such as in fuel processing or reprocessing plants each equipment is individually considered for establishing safe limit on critical parameters, taking into account neutron reflection and neutron interaction amongst the various fissile material containing equipment.

3.4. An awareness of the anomalies known to date will contribute to ensuring criticality safety. Detailed description of many of the important anomalies that have been observed in criticality safety are reported in literature [4, 5]. The design/ DBA analysis should consider anomalies and safety actions/systems should be designed to avoid such anomalies and arrest such anomalies, should they occur.

4. CRITICALITY SAFETY CRITERIA AND SAFETY MARGIN

The basic principle of criticality safety is to prevent criticality in all credible situations. Application of this principle can be made by adhering to the criticality safety criteria with adequate criticality safety margin in the design of a facility or performance of an activity (e.g. fissile material transport and storage).

4.1. Criticality Safety Criteria

4.1.1 Criticality safety limits (CSL) should be derived on the basis of one of the following criteria:

a) Criteria based on k_{eff}: Safety criteria based on the value of effective neutron multiplication factor (k_{eff}) for the system under assessment;

b) Criteria based on control parameters: Safety criteria based on the critical value of one or more control parameters, such as mass, volume, concentration, geometry (taking into account isotopic composition, density, neutron moderation, absorption, reflection and interaction).

4.2. Criticality Safety Margin

4.2.1 Adequate safety margin should be incorporated in arriving at safe operational limit on mass, concentration, geometrical dimensions etc. in all fissile material processes. The specified safe limits may be derived directly from experimentally verified values and the limits should be established with high degree of confidence in order to minimize the risk of accidental criticality.

4.2.2 Alternatively safety factors can be applied on the calculated critical parameters for the fissile material system under evaluation in order to arrive at the safe limits. The safety factors, so employed, should ensure adequate safety margin. The calculation method/codes should be validated against benchmark experiment prior to their acceptance for application to facilities handling fissile materials.

4.2.3 The k_{eff} recommended as criticality safety limits for the worst foreseeable condition of a fissile material system should not exceed 0.9. In general, this criterion is extensively applied to most of the fissile material processing facilities, where mal- operations due to human error or equipment malfunction is likely and such a safety margin in k_{eff} should be an inherent/engineered safety feature in the design and operation.

4.2.4 In case of spent fuel assembly storage the k_{eff} should preferably not exceed 0.9 for all normal operational modes.

4.2.5 However, in line with the international practice, the maximum value of k_{eff} may be relaxed up to 0.95 in the event of accidental situation in storage pool. The k_{eff} of the storage pool should be evaluated for highest enrichment of the fuel assembly without any burn-up credit (i.e. fresh fuel assumption) and worst foreseeable accident condition such as fuel assembly drop over a stored array in most reactive configuration. The relaxed limit on k_{eff} applies under the above condition.

4.2.6 Permissible CSL for various control parameters should be derived by applying appropriate safety factor. Safety factors to be used for various control parameters are given in Annexure-II.

4.2.7 Detailed Criticality Safety Assessment (CSA) and benchmark selection criteria are discussed in Chapter 6. The information to be furnished in the criticality safety analysis report is given in Appendix-II. Methodology for criticality safety margin assessment is given in Appendix-III.

4.2.8 In applying safety margins, consideration should be given to uncertainty in the k_{eff} or the critical value of control parameters, including the possibility of any code bias, and sensitivity with respect to changes in nuclear data and process parameters affecting criticality safety.

4.2.9 Adequate Criticality Safety Margins (CSM) should be assessed at all stages such as design and operation of systems/facilities under consideration. Any deviation from the approved design should be reassessed with respect to criticality safety.

4.2.10 In determining Operational Limits and Conditions (OLC) for a facility or activity, sufficient and appropriate safety measures should be put in place to detect and intercept deviations from normal operation before any CSL is exceeded. Uncertainties in measurement, instruments and sensor delay should also be considered. Alternatively, design features should be put in place to effectively prevent criticality. This should also be demonstrated in the criticality safety assessment. OLC should be identified in terms of measurable parameters, like fissile mass, concentration, moderator content, liquid flow rates, temperature, etc.

4.2.11 Safety measures, both engineered and administrative should be identified, implemented, maintained and periodically reviewed to ensure that all activities are conducted within specified OLC that ensure sub-criticality below CSL.

4.3. Exemptions

4.3.1 In some facilities or activities, the amount of fissile material handled may be below exempted quantity (Annexure-I) or its composition may be such that a criticality safety assessment would not be necessary. Exemption criteria should be developed by Responsible Organization (RO)/Plant Management (PM) and submitted to the regulatory body for review and acceptance, as appropriate.

4.3.2 The primary approach in seeking exemption should be such as to demonstrate that the inherent characteristics of the fissile material itself are sufficient to ensure sub-criticality, while the secondary approach should be such as to demonstrate that the maximum amount of fissile materials involved are far below critical values and no specific safety measures are necessary to ensure sub-criticality under all circumstances.

4.3.3 Modifications to the facilities and/or activities should be evaluated before being implemented, to determine whether the bases for the exemption are still met.

4.3.4 For transport of fissile materials, fissile exception criteria are specified in the AERB safety code on “Safe Transport of Radioactive Material”, “AERB/NRF-TS/SC- 1 (Rev. 1)” [6].

4.4. Burn-Up Credit

4.4.1 The use of burn-up credit in criticality safety assessment means that credit is given for the reduction in spent fuel nuclear reactivity as a result of burn-up undergone. It differs from the more conservative 'fresh fuel' assumption and, consequently, may be considered a more realistic approach. A decision to take credit for burn-up should be fully justified with accurate data from approved calculation methods, validated and verified computer codes in accordance with international standards. This applies to both inventory determination calculations and criticality calculations without taking into account the effect of fission product neutron poison. A license application for the storage of spent fuel with the inclusion of burn-up credit should be supported by an adequate safety assessment that demonstrates that in addition to criticality safety other associated safety aspects (e.g., radiological safety, decay heat removal, confinement of radioactivity etc.) are addressed.

4.5. Criticality Safety in Transport of Fissile Material Packages

4.5.1 Fissile materials may be transported only in packages of design approved by the Regulatory Body and in compliance with the requirements of AERB Safety Code No. "AERB/NRF-TS/SC- 1 (Rev. 1)" [6].

4.5.2 The maximum number of packages which may be permitted to be transported in a conveyance or stored in transit should be so determined that the sum of the CSI of all the packages in the conveyance does not exceed the limits specified in the AERB Safety Code No. AERB/NRF-TS/SC- 1(Rev. 1) [6]

5. CRITICALITY CONTROL PARAMETERS

5.1. General

5.1.1 Criticality safety criteria (section 4.1) should be used to derive the critical and safe value of one or more control parameters, such as mass, volume, concentration, geometrical dimensions for the fissile material system under consideration.

5.1.2 Controls on process parameters should be derived based on the criticality safety assessment (Chapter 6). These controls, passive, active or administrative, should be implemented by inherently safe or fault-tolerant plant designs. If passive or active designs are not practicable, the controls may be achieved by administrative measures such as operating procedures, job instructions and other means to eliminate/minimize the potential for any unsafe situation such as a criticality accident.

5.1.3 While designing fissile material process systems, criticality safety should be ensured by meeting the requirements of double contingency principle and adhering to provisions in section 2.5 in fixing the safe limits.

5.2. Mass Control

5.2.1. Critical mass is the smallest mass of a fissile material that can start/support a chain reaction under a specified set of conditions. Reference minimum critical mass for three major fissile isotopes under optimum water moderation and water reflection in spherical system are given in Annexure-III.

5.2.2. Criticality safety can be achieved by restricting the mass of a fissile material below its critical mass corresponding to the given process condition. If this approach is adopted, prevention of fault sequences which would lead to the introduction of excess fissile material should be ensured. Safety factor on mass as given in Annexure–II should be applied to prevent batch doubling and ensure adequate safety margin.

5.2.3. Simple, reliable and all practically achievable safety measures should be put in place to prevent the accumulation of unsafe mass, since mass control is an administrative action.

5.2.4. Mass control is generally employed for a batch or semi-continuous process such as fuel fabrication.

5.2.5. In case of fissile material causing significant radiation exposure, radiological safety and criticality safety aspects should be considered together. This is due to the fact that in some cases the estimated mass limit from criticality safety assessment may be higher than the limit estimated from radiological safety assessment. In such cases, radiological safety should be the overriding criterion.

5.3. Criticality Aspects of Isotopic Composition

The most common fissile isotopes in nuclear applications are U^{233}, U^{235}, Pu^{239} and Pu^{241}. Uranium normally comprises of U^{235} and U^{238} whereas plutonium normally comprises of Pu^{239}, Pu^{240}, Pu^{241}, and Pu^{242} with increasing proportions with higher fuel burn up.

5.3.1. Limitation on the isotopic composition of the fissile material, is essential for ensuring criticality safety in fuel processing. Fissile material with different isotopic compositions should be processed in separate campaigns with appropriate criticality safety limit.

5.3.2. Safety limits and conditions with regard to isotopic composition should be derived across the expected moderation range.

5.3.3. If the isotopic composition varies during the design life time, then the design should be made assuming most reactive composition of the fissile isotopes.

5.4. Volume Control

5.4.1. Another method of achieving criticality safety is restricting the volume of fissile material solution system to below the critical volume corresponding to the process condition e.g. sump of safe volume is employed to collect the leakage of solution from the process vessels. Safety factor to obtain the safe volume from the critical volume is given in Annexure-II.

5.4.2. Volume control is applicable only for fissile solution system and it cannot be adopted for un-moderated fissile material/solid system.

5.4.3. Volume control parameter calculation for achieving CS should take into account the potential fault sequences which could increase the neutron multiplication of a system, e.g., the introduction of additional liquid (fissile or non-fissile), dilution, concentration (through evaporation or precipitation/colloid formation) etc. Reliable and practical safety measures should be put in place to prevent accumulation of an unsafe volume beyond the volume control limit determined for achieving CS.

5.5. Concentration Control

5.5.1. In operations involving aqueous solutions, particularly those containing low concentration of fissile material, safety can be ensured by restricting the concentration of fissile material in an equipment.

5.5.2. The minimum critical concentration or limiting concentration is the value corresponding to k_∞ =1.0 i.e. only an infinite system can go critical at this concentration. Thus even large tanks will remain safe, if the concentration under the worst foreseeable condition does not exceed this limiting critical value. Annexure-III gives the minimum critical concentrations for the three fissile isotopes.

5.5.3. For handling process concentration higher than the minimum critical/limiting concentration (see para 5.5.2 above), vessels of specified dimensions with concentration control should be adopted. For such equipment:

a) Safe concentration limit corresponding to k_{eff} = 0.9 should be evaluated; or,

b) Critical concentration should be computed and safe concentration limit should be arrived at by applying safety factor given in Annexure-II (i.e. 0.85).

5.5.4. Safety interlock systems are required for plants handling high concentrations of fissile material to prevent inadvertent transfer of solution to unsafe tanks/vessels and unintended accumulation of fissile material in any process equipment.

5.6. Geometry Control

5.6.1. Geometrically favorable and safe equipment, such as cylindrical, slab and annular tank, can be designed so that homogeneous solution of fissile material of any concentration or up to a certain maximum concentration will remain subcritical with adequate safety margin. The main advantage of geometry control is that in addition to allowing increased throughputs, it does not involve risk of human error.

5.6.2. Wherever practicable, criticality control should be based on geometric limits of equipment in which dimensions are fixed and limited. The controlling dimensions should be derived based on the system configuration for the maximum fissile material concentration attainable in the process equipment.

5.6.3. The controlling dimensions of the equipment such as cylinder diameter, slab thickness or annular width should be determined such that the k_{eff} has adequate CSM for all conceivable states.

5.6.4. Provisions should be made in order to prevent the following situations or to overcome their consequences:

a) Accidental deformation of equipment: This needs consideration, at the design stage, of the risk of a rise in pressure or temperature, and of external causes of deformation (e.g., earthquake, movements of heavy loads nearby, fire, etc.);

b) Leaks or overflows of fissile material solutions from equipment: This requires manufacture of the equipment with appropriate quality control, setting-up, underneath them, of drip-trays capable of containing the largest volume of fissile material solution liable to be spilled, and fitted with fluid detectors and means of recovery. The drip-trays should meet the criticality safety criteria in the event of getting filled up to the full extent;

c) Transfer of fissile material solutions into unsafe geometry containers, located in auxiliary circuits (e.g., vents, vacuum tank, reagent tank, heating/cooling jacket, etc.);

d) Placing of movable containers near the equipment: This requires movable containers to be surrounded by a rigid structural framework that ensures sufficient spacing/separation from the fixed equipment;

e) The process vessels should be designed as far as possible to be in a safe geometry under worst flooding conditions.

5.7. Nuclear Poison Control-Fixed and Soluble poisons

5.7.1. Neutron poisoning is employed when the process requires use of equipment of large volume which otherwise cannot be made safe from criticality point of view, or when it is necessary to provide isolation from neutron interaction between equipment.

5.7.2. Homogeneous neutron poisoning is ensured by the presence of a neutron poison dissolved in fissile material solution. Whereas, heterogeneous poisoning is ensured by the introduction of neutron absorbing material in process equipment in fixed and non-soluble form such as boron-stainless steel plates in the form of a cartridge. With soluble poison a process step is required to remove the poison effectively from the final product.

5.7.3. Materials such as boron, cadmium, and gadolinium are very effective as absorbers for low-energy neutrons. Any possibility of neutron spectrum hardening, i.e. an increase in the distribution of neutron energy, caused by operating conditions or accident conditions, should be considered, as this may result in a decrease in the effectiveness of the neutron absorption. Also monitoring of the credible long term degeneration and/or degradation of neutron absorbers should be in place to ensure that the safety function of neutron absorber is effective as per design intent from CS point of view.

5.7.4. Neutron poisons in soluble form, such as boric acid, sodium borate, and gadolinium nitrate are used in large size dissolvers in reprocessing plant. Soluble neutron poison should not be used as primary protection to preclude criticality unless the system is behind a massive shield such as hot cell.

5.7.5. It is recommended in literature that, addition of soluble neutron poison should be equal to twice the concentration calculated for k-infinity equal to 1.0 [7]. However, safety criterion as specified in paragraph 4.2.3 of this guide may also be applied to such poisoned systems.

5.7.6. The use of soluble poison should be based on a fail-safe system of poison addition. Reliable neutronic device should be installed for checking the presence of poison in the make-up solution in addition to multiple sampling.

5.7.7. In the case of homogeneous poisoning, provision should be made to avoid dilution or precipitation and plate-out of the poison.

5.7.8. Use of enriched neutron poison should be avoided and if used, strict control and monitoring of the enrichment should be followed specially when used in liquid form.

5.7.9. In the case of heterogeneous poisoning, the integrity of the neutron-absorbing component should be guaranteed against all possible hazards including corrosion and fire.

5.7.10. Neutron absorber's presence should be ensured before commencement of the operation if the equipment is disassembled for maintenance, or repair, or accessed for in-service inspection.

5.8. Spacing and Isolation of Equipment

5.8.1. Multiple fissile units, each of which is subcritical in isolation, may become critical when combined as a system due to neutron interaction between the units. In cases where interaction effects are important, safety measures should be put in place to ensure criticality safety. Such measures may take the form of spacers to constrain/ensure the separation of the units, or neutron absorbing material placed between the units. Adequate spacing between sub critical units and the maintenance of the spacing under all conditions should be considered in the design of plant facilities and in storage and transportation of the fissile material.

5.8.2. Material located between or around fissile material units may act not only as a reflector but also as a moderator and/or a neutron absorber and can therefore increase or decrease the neutron multiplication factor of the system. The inclusion or omission of any such materials from the criticality safety assessment should be justified by evaluating their effect on the neutron multiplication factor.

5.8.3. Interaction between units of fissile material should be considered, as this interaction can increase neutron multiplication factor of the system. Criticality safety should be ensured by specifying minimum separation distances or by introducing screens of neutron absorbers. Wherever practicable, separation should be ensured by engineered means, for example fixed racks for storage of fissile material or by birdcages.

5.8.4. The design of spacer should be such that there will be 20 cm minimum thickness of water between the units in case of flooding, in order to isolate the units from neutron interaction.

5.9. Neutron Moderation

5.9.1. All materials containing hydrogen, and/or carbon are good moderators. Such materials include water, polyethylene, paraffin, oil, and graphite. Fissile material normally occurs as solution in aqueous or organic phase with hydrogen as a predominating moderating element.

5.9.2. Criticality safety aspects restrict fire-fighting methods in view of the inherent moderation. Fire-fighting restrictions should be included in fire-fighting procedures and the restrictions are required to be displayed in the plant to warn firefighting staff.

5.9.3. The risks of accidental moderation from external origins (floods, firefighting, etc.) and from internal origins (leaking pipes, oil spatter, etc.) should be taken into account in CSA.

5.10. Neutron Reflection

5.10.1. In criticality safety assessment, all reflecting materials that are present around the fissile material system should be considered. In addition, the reflecting effects of nearby process vessels, pipes carrying solution and concrete structural members should also be addressed.

5.10.2. Criticality safety assessments usually consider water reflector of a thickness sufficient to achieve the maximum neutron multiplication factor. However, the possible presence of other reflector materials (e.g., polyethylene, concrete, steel, lead and aluminum, etc.), or several reflector materials used in combination, should be considered, if this could result in a greater increase of the neutron multiplication factor than by water reflection.

5.10.3. Radiation shielding materials also serve as neutron reflectors, when located very close to fissile materials. Examples of such materials include lead, steel, concrete, water, and polyethylene. For this reason, shielding materials are restricted in a CCA unless specifically evaluated. Such evaluations should be carried out to determine criticality safety limits on control parameters, taking into account radiation shielding geometry and material.

6. CRITICALITY SAFETY ASSESSMENT

6.1 General

6.1.1 Criticality Safety Assessment (CSA) should be performed prior to the commencement of any new or modified activity involving fissile material. CSA should be carried out during the design, prior to and during construction, commissioning and operation of a facility or activity, and also prior to and during post-operational clean-out and decommissioning of the facility, transport and storage of fissile material.

6.1.2 The objective of the CSA is to determine whether an adequate level of safety has been achieved and to document the appropriate limits and conditions and safety measures required to prevent a criticality accident and mitigate its consequence, should it occur.

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

6.1.4 Safety margin adopted in setting criticality control parameters should be justified and documented to allow an independent review.

6.1.5 The CSA should be carried out by suitably qualified and experienced staff who are knowledgeable in all relevant aspects of criticality safety and are familiar with the facility or activity concerned, and should also include inputs from operating experience feedback.

6.1.6 Criticality safety of a single unit of specified shape and dimensions in normal and all mal-operating states should be verified by scrutinizing the quantities and physical and chemical forms of the fissile material and other materials contained in the unit.

6.1.7 To verify the criticality safety of multiple units, the neutron interaction effects in both normal and mal-operating states should be evaluated taking into account the distance between units and the thickness of shielding material, if any.

6.1.8 While verifying sub-criticality by calculation, the evaluation must provide sufficient safety margins by considering the reliability of the data and the calculation method and may also be verified by comparison with experimental data from a system physically similar to the working unit, if available.

6.1.9 A systematic approach to the CSA should be adopted as outlined below, including, but not limited to, the following steps [8]:

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

b) Determination of the process/activity involving the fissile material;

c) Selection of methodology for CSA;

d) Verification and validation of the calculation methods and nuclear data;

e) Performance of criticality safety analyses.

These aspects are elaborated in the following sections 6.2 to 6.6.

6.2 Determination of the Fissile Material

The characteristics of the fissile material (e.g., mass, concentration/density, isotopic composition, enrichment) should be determined and documented. Estimates of the normal range of these characteristics, including conservative or bounding estimates of any anticipated variations in the characteristics, should be determined and documented.

6.3 Determination of the Process/Activity Involving Fissile Material

6.3.1. A description of the operations being assessed should be provided, which should include all relevant systems, processes and interfaces. To provide clarity and understanding, the description of the operations should be substantiated by relevant drawings, illustrations and/or graphics as well as operating procedures.

6.3.2. The OLC of the activity involving the fissile material should be determined. Any assumptions made about the operations and any associated systems, processes and interfaces that could impact the criticality safety assessment should be documented.

6.3.3. If the CSA is limited to part of a facility or activity, the potential for interactions with other parts, systems, processes or activities should be described and their effects on criticality should be estimated.

6.4 Selection of Methodology for criticality safety assessment

6.4.1. The criticality safety assessment should identify all credible initiating events, i.e. all incidents that could lead to mal-operation condition. These should then be analyzed and documented with account taken of possible aggravating events. The following should be considered when performing the analysis:

a) A structured and auditable approach should be used to identify all credible initiating events. This approach should also include a review of lessons learned from previous incidents occurred in national and international facilities, including accidents. Techniques available to identify credible initiating events/scenarios include, but not limited to, the following:

   i. Cause–consequence methods;

   ii. Qualitative event trees or fault trees;

   iii. Hazard and operability study (HAZOP);

   iv. Bayesian networks;

   v. Failure modes and effects analysis.

b) Input into the CSA should also be obtained from operating personnel and process specialists who are familiar with the operations and initiating events that could credibly occur.

6.4.2. The CSA should be performed by using a verified and validated methodology. The CSA should provide a documented technical basis that demonstrates that sub-criticality will be maintained in operational states and mal-operations in accordance with the DCP or the single failure approach. The CSA should identify the safety measures required to ensure sub-criticality, and should specify their safety functions, including requirements for reliability, redundancy, diversity and independence, and also any requirements for equipment qualification.

6.4.3. The CSA should describe the methodology used to establish the OLCs for the activity being evaluated. Methods [8] that may be used for the establishment of these limits include, but are not limited to, the following:

a) Reference to national and international standards;

b) Reference to accepted handbooks;

c) Reference to experiments, with appropriate adjustments of limits to ensure sub-criticality;

d) Use of validated calculation models and techniques.

6.4.4. The applicability of reference data to the system of fissile material being evaluated should be justified. Where applicable, any nuclear cross-section data used should be specified together with any cross-section processing codes that were used.

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

6.5 Verification and Validation of the Calculation Methods and Nuclear Data

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

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

6.5.3. The results of the calculations should be cross-checked by using independent nuclear data or different computer codes (deterministic or probabilistic).

6.5.4. After verification of the calculation method is complete and prior to its use in performing a criticality safety analysis, it should be validated. The validation should be against selected benchmarks that are representative of the system being evaluated.

6.5.5. Following benchmarks selection criteria (BSC) [8] should be used in validation and verification of computer code:

a) Benchmarks should be used that have relatively small uncertainties.

b) Benchmarks should be reviewed to ensure that their neutronic, geometric, physical and chemical characteristics encompass the characteristics of the system of fissile material to be evaluated. The characteristics should include homogeneity or heterogeneity and uniformity or non-uniformity, including gradients of fissile and non-fissile materials.

c) The sensitivity of the system to any simplification of geometry and neutron energy spectrum should be considered.

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

e) Calculation methods should also be re-verified following changes to the computer code periodically.

6.5.6. Once the calculation method has been verified and validated, it should be managed within a documented quality assurance programme as part of the overall management system.

6.6 Criticality Safety Analyses

6.6.1. Criticality safety analysis forms a part of overall Criticality Safety Assessment (CSA). If no benchmark experiments exist that encompass the system being evaluated, it may be possible to interpolate or extrapolate from other existing benchmark data to that system, by making use of trends in the bias. Where the extension from the benchmark data to the system at hand is devious/indirect, the method should be supplemented by other calculation methods to provide a better estimate of the bias, and especially of its uncertainty in the extended area. An additional margin maybe necessary to account for validation uncertainties in this case. Sensitivity and uncertainty analysis may be used to assess the applicability of benchmark problems to the system being analyzed and to ensure an acceptable CSM.

6.6.2. Accuracy and reliability of the input data and the calculation results are an important part of criticality safety analysis. This includes, for example, verification that Monte Carlo calculations have properly converged.

6.6.3. When the CSA of a fissile material system is done using a Monte Carlo method based probabilistic code then the average effective multiplication factor (k_{eff}) calculated should include 3 times the standard deviation (i.e. 3σ) added to the calculated mean value. The multiplication factor thus estimated must be less than or equal to the CSL [9].

6.6.4. Uncertainty and sensitivity studies should be carried out to determine existence of any cliff edge effect.

6.6.5. Procedure to calculate CSM is given in Appendix-III.

7. EMERGENCY PREPAREDNESS AND RESPONSE

7.1 General

7.1.1 Priority should be given to the prevention of criticality accidents by means of DID principle. Despite all the precautions that are taken in the handling and use of fissile material, there remains a possibility that any failure (e.g. of instrumentation and controls, or an electrical, mechanical or operational error) or an event (caused by multiple failures) may give rise to a criticality accident. In some cases, this may give rise to exposure of persons to ionizing radiation beyond prescribed limit or a release of radioactive material within the facility and/or to the environment beyond discharge limits, which may necessitate emergency response actions. Adequate measures are required to be established and maintained in response to a nuclear or radiological emergency.

7.1.2 Probable causes that may lead to criticality accident are:

a) Erroneous transfer of solutions containing fissile materials from safe to unsafe equipment;
b) Inadvertent accumulation of fissile material;
c) Improper identification of fissile materials;
d) Exceeding safe concentration or mass limit due to non -representative sampling of solutions having concentration gradient or precipitation or sledging;
e) Third phase formation in extraction contactors;
f) Failure of solvent extraction equipment leading to high fissile material concentrations;
g) Non-adherence to the administrative procedure for criticality control such as incorrect chemical addition or failure to add chemicals;
h) Flooding – accidental moderation as a result of water leaks from broken lines or firefighting systems;
i) Loss of neutron absorber through precipitation, dissolution, leaching or breakages, failure to add neutron absorber;
j) Reflection due to accidental movement of reflecting materials such as shielding blocks, other equipment etc.;
k) Neutron interaction due to exceeding storage limits of containers;
l) Multiple /over-batching of fissile material;
m) Inadvertent transfer of organic solvent into vessel containing aqueous solution;
n) Wrong addition of neutron poison/inadvertent poison removal/wrong tank coding;
o) Falling of fuel pin magazine or fuel assembly on already stored arrays of those units due to failure of transfer mechanism;
p) Moisture ingression;
q) Instrumentation and control failure;
r) Fire hazards;
s) Human errors.

7.2 Radiation Hazards

In a criticality accident, radiation hazards arise from prompt neutrons, prompt gammas, and gamma radiation from neutron capture (i.e., secondary gamma) and from fission products and activation products generated during the excursion. Radiation hazard is also dependent on the type of system, solution or un-moderated solid system in which the excursion arises.

7.3 Impact Assessment

7.3.1 Locations at which a criticality accident is foreseeable should be identified and documented, together with an appropriate description and layout of the facility. Evaluation of a criticality accident should include an estimate of the fission yield (i.e. the total number of fissions in a nuclear criticality excursion) and radiation doses at all locations of concern to assist emergency planning.

7.3.2 Impact assessment may be conducted by normalizing to a value of total fissions for the excursion taking into account of its temporal profile. The normal range for the yield from a criticality accident is between 10^{15} and 10^{20} fissions, with 10^{17} fissions as a nominal mean value. For a criticality accident consequence analysis, 10^{18}fissions is generally used as reference yield [4].

7.3.3 The methodology for determining the dose from a criticality accident should include the following steps:

a) Identification of the location of the criticality accident;

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

c) Calculation of the effect of any shielding between the location of the criticality incident and operating personnel likely to be affected;

d) Calculation of the dose received by those likely to be affected.

7.3.4 The determination of the dose should be conservative but not overly conservative as to cause unnecessary evacuation of personnel.

7.3.5 As part of periodic safety review, consideration should be given to identify further measures to prevent a criticality accident and to mitigate the consequences.

7.4 Emergency Action Plans

7.4.1 Facilities handling significant amount of fissile materials have a potential for criticality accidents and emergency response action plan should be prepared. Each facility in which fissile material is handled and for which the need for a Criticality Detection and Alarm System (CDAS) has been identified should have in place an emergency response plan, procedure, programme and capabilities to respond to criticality accidents. Wherever a CDAS is not required to be installed in view of handling less than safe mass of fissile material, analyses should be conducted to determine whether an emergency response plan is necessary for the facility.

7.4.2 The main risk in a criticality accident is to operating personnel in the immediate vicinity of the event. Generally, radiation doses to operating personnel more than a few tens of meters away are not life threatening. The radiation dose may still be significant, even for people located at some distance from the accident. Identifying appropriate evacuation and assembly points should be in place.

7.4.3 The plant design should provide diverse communication systems to ensure reliability of communication under operational states and accident conditions.

7.4.4 Provision for additional means of shielding should also be considered in minimizing the radiation exposure from a criticality accident.

7.4.5 The emergency procedures should describe the means for alerting emergency response personnel and relevant authorities at the site.

7.5 Evacuation

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

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

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

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

7.5.5 Reliable means should be established for ascertaining that all personnel have been evacuated from the area where the criticality incident has occurred.

7.6 Re-entry

7.6.1 Any re-entry into the affected area for survey and rescue operations should only be made after detailed assessment of the situation and should be permitted after proper authorization. Re-entry should be made by two persons; one of them for carrying out radiation survey and the other to monitor the safety status.

7.6.2 Consent for re-entry to the affected area should be given after initial evaluation of the criticality accident based on

a) Radiation monitors' data, eyewitness accounts, facility records etc.;

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

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

d) Feedback and quenching mechanisms present for limiting or terminating the event.

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

7.6.4 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 at the assembly points.

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

7.6.6 Re-entry should be made only if radiological surveys indicate that the radiation levels are acceptable. Radiation monitoring should be carried out during re-entry using monitors that have an annunciation (visual and audio alarm) capability.

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

7.7 Criticality Dosimetry

7.7.1 Dosimetry procedures should be prepared and it should be ensured that the dosimetry equipment and trained personnel are available to quickly evaluate the results of the dosimetry.

7.7.2 All personnel, who work in a CCA should wear a TLD badge and a criticality locket device, encasing foils, pellets and discs of various material to provide information on the neutron spectrum and the dose received as well. These are:

a) Sulphur disc for the measurement of fast neutron flux by $S^{32}(n,p)P^{32}$ threshold reaction (threshold energy 2.5 MeV).

b) Indium for the identification of irradiated personnel by $In^{115}(n,\gamma)In^{116}$ reaction, and for the measurement of the fast neutron flux by the $In^{115}(n,n')In^{115m}$ threshold reaction.

c) Gold ($Au^{197}(n,\gamma)Au^{198}$) plus cadmium foils for the measurement of intermediate and thermal neutron fluxes.

d) Copper ($Cu^{63}(n,\gamma)Cu^{64}$) foils-bare and Cd-covered for estimating thermal and epithermal neutron fluxes.

The response of the foil to neutron dose will depend markedly on the orientation of the human body and on the nature of neutron spectrum.

7.7.3 Useful information on neutron exposure can also be obtained from measurement of the induced Na^{24} activity in the body or in sample of blood or blood serum. Additional information can be obtained from measurement of the activation of sulphur in human hair, or articles such as coins which the person may have been carrying.

7.7.4 Accidental dosimetry systems should also be positioned in and around the facility at select locations (risk areas) that will provide a representative estimate of the gamma and neutron fields.

7.8 Medical Care

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

7.8.2 Emergency planning should ensure that personnel are provided with dosimeters for prompt identification of exposed individuals. Provision for assessment for external as well as internal contamination of affected personnel should be available.

7.8.3 Planning and arrangements should provide for a central emergency/criticality accident control station for collecting and assessing information useful for emergency response and medical care.

7.9 Emergency Equipment

7.9.1 The criticality alarms act as an aid in rapidly activating the emergency response and initiation of an immediate evacuation of the facility.

7.9.2 The emergency plan should include procedures for the rapid screening of personnel to identify potential victims, and the screening equipment should be calibrated. Since these events are very rare, the plan should include regular verification of the operability and availability of this screening equipment.

7.9.3 Provision should be made for appropriate protective clothing and equipment for emergency response personnel. These equipment should include respiratory protection equipment and personal monitoring devices.

7.9.4 Emergency equipment and its inventory should be kept in a state of readiness at specified locations.

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

7.10 Mitigation of Criticality Consequences

7.10.1 Consideration should be given during facility design, operation and periodic review to the actions that may be necessary to make the facility safe following a criticality accident.

7.10.2 A fast-acting mechanism may be necessary to terminate an accident by "poisoning" the system by adding a solution or powder containing neutron-absorbing substances, transferring the involved fissile medium into a geometry that ensures a sub-critical state and eliminating neutron reflection (by draining the water in the cooling jacket etc.).

7.10.3 The radiological exposure from a criticality accident should be evaluated and reduced as per ALARP principle. This should include identification of those individuals at risk from radiation injury and identification of the range of measures that have the potential to reduce exposure. Such measures should be commensurate with the level of risk and may include fixed warning systems, portable gamma monitors and the provision of suitable shielding.

8. CRITICALITY DETECTION AND ALARM SYSTEM

8.1 General

8.1.1 The prompt detection and annunciation of criticality are the prerequisites for safety of the plant and the personnel. The need for a Criticality Detection and Alarm System (CDAS) should be evaluated for all activities involving, or potentially involving, the risk of exceeding a Criticality Safety Limit (CSL).

8.1.2 In determining the need for a CDAS, individual areas of a facility may be considered isolated if the boundaries are such that there could be no inadvertent interchange of material between the areas and neutron interaction is negligible.

8.1.3 The main function of radiation detector is to raise an alarm on criticality to alert the personnel and provide signal to initiate control and mitigation actions and initiate evacuation as per emergency preparedness plan [10]. A CDAS will help to minimize the radiation exposure to plant personnel.

8.1.4 Exceptions to the recommendation to provide a CDAS may be justified in the following cases:

a) Where a documented assessment concludes that no foreseeable set of circumstances could initiate a criticality accident;

b) Massive shielded facilities such as hot cells in which there is a potential for inadvertent criticality accident, and resulting radiation dose is lower than the acceptable level at the exterior surface of the shield;

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

8.2 Detection Basis

8.2.1 The CDASs are usually based on the detection of neutrons and/or gamma radiation. Advantage of having neutron detecting warning system rather than gamma based system, would be the elimination of the possibility of false alarms resulting from the movement of any gamma source [10].

8.2.2 Neutron based detector is preferable for solid systems such as fuel pellet, fuel pin, fuel assembly, pin magazine etc. Gamma based detector is preferable for solution system such as process tanks, storage tanks.

8.2.3 The design parameters for a CDAS are based on a detection of threshold and a minimum incident in terms of the fission spike yield and rate of rise of the neutrons from the burst. These data are translated into a dose figure and an assessment of the same at some predetermined distance [11].

8.3 Design Criteria

8.3.1 The design of the CDAS should be single failure tolerant and should be consistent with the objectives of ensuring reliable actuation of the alarm and avoiding false alarms.

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

8.3.3 Uninterruptible power supplies should be available for the CDAS.

8.3.4 The design parameters for a criticality monitoring and alarm system are based on a detection of threshold and a minimum incident in terms of the fission spike yield and duration of the burst. These data are translated into a dose figure and an assessment of the same at some predetermined distance.

8.3.5 The recommended detection threshold for integrated dose measuring systems is 10^{15} fissions for uranium processes and 10^{14} fissions for plutonium processes over any duration from 1 msec to 3 sec for low ambient gamma dose-rate area.

8.3.6 In areas with very high ambient gamma dose-rates, the detection threshold for the rate of rise instrument should be a power increment of the following [12]:

a) For uranium systems, an increment of 10^{15} fissions/sec over any duration from 200 µsec to 2 sec

b) For plutonium systems, an increment of 10^{14} fissions/sec over any duration from 200 µsec to 2 sec

In terms of gamma dose, this corresponds to a rate of rise of 200 µSv/sec at a distance of 10 m.

8.3.7 The set point for the CDAS should be kept sufficiently low to detect the minimum accident of concern [12], but sufficiently high to minimize false alarms. Indications should be provided to show which detector has exceeded the set point.

8.3.8 2 out of 3 coincidence logic should be used for alarm instrumentation in all criticality detection systems. Separate faulty detector annunciation should be available for all detectors in order to identify the faulty detector.

8.4 Criticality Detection Area

8.4.1 Criticality alarm coverage is required in all areas where excessive radiation doses or dose rates due to accident are envisaged and to initiate prompt protective action such as evacuation of personnel.

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

8.4.3 The criticality monitors should be placed in such a way that at least two of them should detect the occurrence of an incident anywhere in the areas covered by the system. The positions of these detectors should be determined based on results of the calculations of dose rates likely to result from a minimum accident.

8.5 Alarms

8.5.1 The criticality signals should be distinctive from other signals or alarms that require a response different from that necessary in the event of a criticality accident.

8.5.2 For all occupied areas where personnel protective action is required in the event of criticality accident, the number and placement of criticality alarm signal generators should be such that the signals are adequate to notify personnel promptly throughout those areas.

8.5.3 The alarm signal should meet the following criteria:

a) It should be unique and immediately recognizable by personnel as a criticality alarm.

b) It should actuate as soon as the criticality accident is detected and continue until manually reset, even if the radiation level falls below the alarm set point.

c) It should continue to alarm for a time sufficient to allow complete evacuation.

d) Systems to manually reset the alarm signal, with secured limited access, should be provided outside areas that require evacuation.

e) The alarm signal should be audible in all areas to be evacuated.

f) It should be supplemented with visual signals in all areas for better reliability/redundancy.

8.6 Testing of Criticality Accident Alarm System

8.6.1 Initial tests, inspections and checks of the CDAS should verify that the manufacture, fabrication and installation were made according to design specifications. After modifications or repairs, or events that call for the system performance into question, there should be tests and inspections adequate to demonstrate system operability.

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

8.6.3 Testing should be done as per approved procedure to minimize false alarms and inadvertent initiation of emergency response. The procedure should ensure that the systems return to normal operation immediately after completion of the tests.

8.6.4 The entire CDAS should be tested periodically. Performance testing of the systems should include periodic calibration of the detectors.

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

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

9. ADMINISTRATIVE CONTROL

9.1 General

9.1.1 Before initial operation of a plant, or of a module that is new or modified, confirmation of the proper condition of its components is mandatory. Confirmation includes testing of instrumentation, valves, seals, transfer devices, and ventilation and fire-protection equipment. At this point, adequacy of training should be established.

9.1.2 Before a new operation with fissile material is begun or before an existing operation is changed, it should be ensured that the entire process will remain subcritical under both normal and credible abnormal conditions.

9.1.3 Operations to which nuclear criticality safety is pertinent, should be governed by written procedures. All persons participating in these operations should be familiar with the procedures.

9.1.4 Movement of fissile material should be controlled within the CCA. Appropriate materials labeling and area posting should be maintained specifying material identification and all limits on parameters that are subjected to procedural control.

9.1.5 Operations should be reviewed periodically (atleast annually) to ascertain that procedures are being followed and that process conditions have not been altered so as to affect the criticality safety evaluation.

9.1.6 Deviations from procedures and changes in process conditions that affect criticality safety should be documented, reported to management and investigated promptly. Action should be taken to prevent a recurrence. A report on such deviations and result of the investigation along with the action taken to prevent recurrence should be submitted to the regulatory body.

9.1.7 Emergency procedures should be prepared and approved by management. Organizations, local and off-site, that are expected to respond to emergencies should be made aware of conditions that might be encountered, and they should be assisted in preparing suitable procedures governing their responses.

9.1.8 Accountability for safety should reside with the personnel involved in the operations. These personnel should have complete knowledge of the process. Good safety practices must address the specific elements of each process.

9.2 Management System

9.2.1 Human error and related failures of supervisory personnel or management oversight have been a feature in nearly all criticality accidents that have occurred to date. Consequently, human factors, the human machine interface and organizational factors should be considered for criticality safety management system.

9.2.2 Design, safety assessment and the implementation of criticality safety measures should be carried out in accordance with a clearly established and well controlled management system.

9.2.3 Management should establish a comprehensive criticality safety programme to ensure that safety measures for ensuring sub-criticality are specified, implemented, monitored, audited, documented and periodically reviewed throughout the entire lifetime of the facility or activity. Management should ensure that a plan for corrective action is established as required, implemented and updated when necessary.

9.2.4 Management should clearly identify the personnel who are responsible for ensuring criticality safety.

9.2.5 Management should ensure that suitably qualified and experienced criticality safety staff are provided.

9.2.6 Management should ensure that any modification to existing facilities or activities or the introduction of new activities undergoes review, assessment and approval at the appropriate level before it is implemented.

9.2.7 If unexpected operational deviations occur, operating personnel should immediately place the system into a known safe condition. Operating personnel should promptly inform their supervisor in the event of any unexpected operational deviations.

9.2.8 Deviation from operational procedures and unforeseen changes in operations or in operating conditions should be reported and promptly investigated by management. The investigation should be carried out to analyze the causes of the deviation, to identify lessons to be learned, to determine and implement corrective actions to prevent re-occurrences. The investigation should include an analysis of the operation of the facility and of human factors, and a review of the criticality safety assessment and analyses that were previously performed, including the safety measures that were originally established.

9.2.9 Management should arrange for internal and independent inspection of the criticality safety measures, including examination of the arrangements for emergency response plans. The findings from inspection should be documented and submitted for management review and action, if necessary.

9.2.10 Management should ensure that operating personnel receive training and refresher training at suitable intervals, appropriate to their level of responsibility.

9.2.11 The management system should include means of incorporating lessons learned from operating experience and criticality accidents/events in similar national and international facilities to ensure continuous improvement in operational practices and assessment methodology.

9.3 Decommissioning

9.3.1 Special arrangements may need to be employed during decommissioning of facilities, where the level of uncertainty with regard to fissile material inventory may be higher than for normal operation of a facility. In particular, there may be uncertainty in the amount, form and location of fissile material present, and a need to derive bounding assumptions.

9.3.2 In such circumstances, it would be expected that such uncertainties are taken into account when deriving demonstrably conservative sub-critical margins, which may result in an additional safety factor being applied. Increased levels of inspection and monitoring may be required to verify assumptions derived in the case and resolve uncertainties.

APPENDICES

Appendix-I

Levels of Defence in Depth [8]

Levels	Objective	Means
Level-1	Prevention of deviations from normal operation and prevention of system failures.	Conservative design, construction, commissioning[(a)], maintenance and operation in accordance with appropriate safety margins, engineering practices and quality levels.
Level-2	Detection and interception of deviations from normal operation in order to prevent anticipated operational occurrences from escalating to accident conditions.	Control, indication and alarm systems and operating procedures to maintain the facility within operational states.
Level-3	Control of the events within the design basis (or the equivalent) to prevent a criticality accident	Safety measures, multiple and as far as practicable independent barriers and procedures for the control of events.
Level-4	Mitigation of the consequences of accidents in which the design basis (or the equivalent) of the system may be exceeded and ensuring that the radiological consequences of a criticality accident are kept as low as practicable.	Provision of criticality detection and alarm systems and procedures for safe evacuation and accident management[(b)] measures designed to terminate the criticality accident, e.g., injection of neutron absorbers, use of shielding and calculated dose contours to minimize exposure.
Level-5	Mitigation of radiological consequences of release of radioactive material	Provision of an emergency control centre and plans for on-site and off-site emergency response.

a) In the context of fuel cycle facilities, commissioning is the process by means of which systems and components, having been constructed, are made operational and verified to be in accordance with the design and to have met the required performance criteria. Commissioning may include both non-nuclear and/or non-radioactive and nuclear and/or radioactive testing.

b) In the context of fuel cycle facilities, accident management is the taking of a set of actions during the evolution of a beyond design basis accident: to prevent the escalation of the event into a more severe accident; to mitigate the consequences of such beyond design basis accidents; and to achieve a long term safe and stable state.

Appendix-II

Information to be furnished in the Criticality Safety Analysis Report

1. Description of the system with maximum possible details
2. Schematic diagram of the system with dimensions
3. Information on material composition (e.g. isotopic composition, chemical composition, density/concentration etc.)
4. Validation exercise through Benchmark analysis/experimental value
5. Calculation methodology
6. Nuclear data used
7. Sensitivity/uncertainty studies
8. Criticality assessment for normal operation
9. Criticality assessment for abnormal operating conditions/postulated accident condition including multiple failures
10. Criticality safety margin assessment
11. Provisions to prevent abnormal operating condition, prevent AOO from reaching accident condition and control & mitigate consequence of accidents etc.
12. Firefighting procedure
13. Conclusions
14. References

Criticality Safety Margin Assessment Methodology

Criticality safety margin is the difference between criticality safety limit provided in this guide (e.g., 0.9 as given in Figure AIII.1) and the estimated effective neutron multiplication factor of the given system. Conservative or best estimate methodology can be used in criticality safety assessment. Upper bounds of neutron multiplication factor due to code bias, input uncertainty and model uncertainty should be used to estimate the neutron multiplication factor. An illustration of criticality safety margin assessment for conservative and best estimate method has been shown in Figure AIII.1.

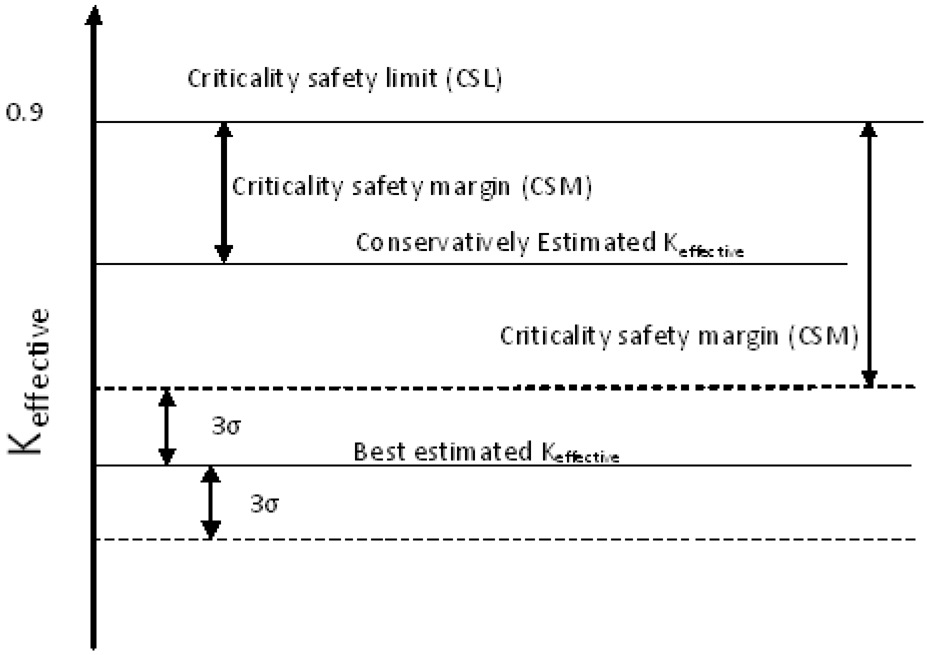

Figure AIII.1: Illustration of Criticality Safety Margin

Best estimate code should be used with uncertainty assessment. Uncertainty analysis due to the process parameter variation should be assessed based on the methodology given in the Appendix-IV. The estimated system k_{eff} should include code bias factor and 99% single sided confidence level in case of adopting a probabilistic method as given in equation (A3.1).

$$k_{eff} = k_{code} + \Delta k_{codeBias} + \Delta k_{99\%CL} \qquad (A3.1)$$

Corresponding criticality safety margin will be calculated as given in equation (A3.2).

$$CSM = CSL - k_{eff} \qquad (A3.2)$$

Uncertainty Analysis Methodology due to the Process Parameter Variation

The methodology involves following five steps:

Step 1: Define assessment end point.

Step 2: List all potentially important uncertain parameters based on sensitivity analysis.

Step 3: Define the variability in terms of range and probability distribution of uncertain parameters.

Step 4: Using either analytical or numerical procedures, propagate the uncertainty in the model parameters to produce a probability distribution of model predictions.

Step 5: Derive quantitative statements of uncertainty about the assessment endpoint.

The process involved in the uncertainty analysis is shown in Figure AIV.1.

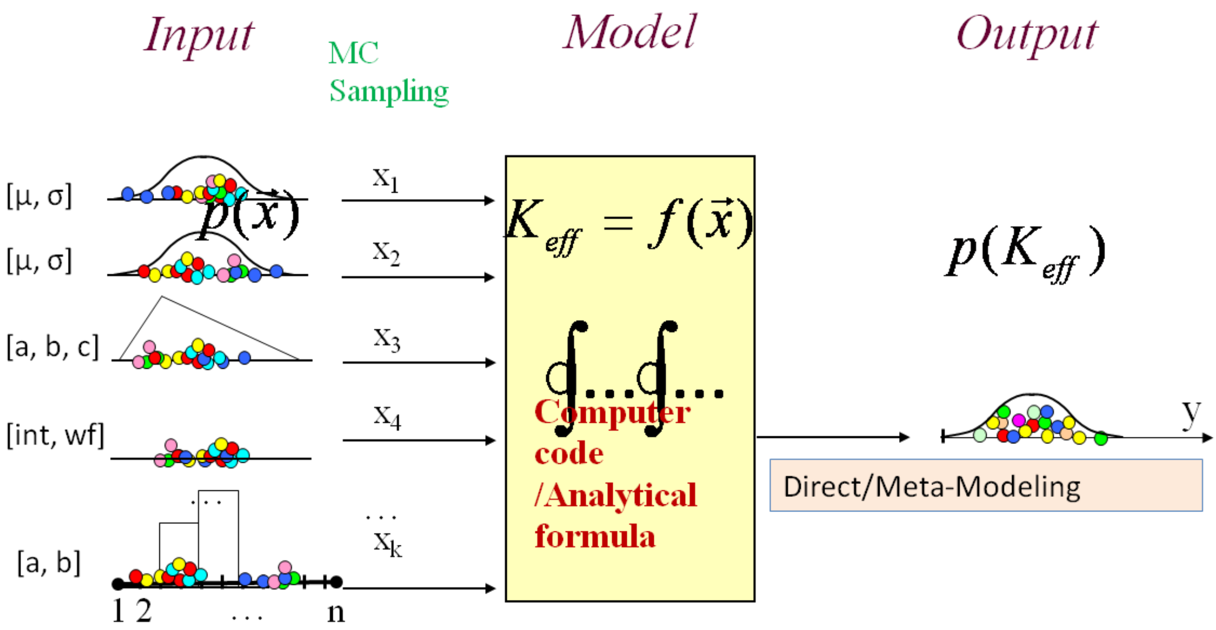

Figure AIV.1: Uncertainty Analysis Methodology

ANNEXURES

Annexure-I

Exempted Quantities

Exempted quantity of a fissionable material in the licensed site is defined as an inventory of fissionable material [13], as follows:

1. Less than 100 g of ^{233}U or ^{235}U or ^{239}Pu or of any combination of these three isotopes in fissionable material combined in any proportion, or

2. An unlimited quantity of natural or depleted uranium or natural thorium, if no other fissionable materials nor significant quantities***** of graphite, heavy water, beryllium, or other moderators more effective than light water are allowed in the Criticality Controlled Area (CCA), or,

3. Less than 200 kg in total of natural or depleted uranium or natural thorium if some other fissionable materials are present in the licensed site, but the total amount of fissile nuclides in those fissionable materials is less than 100 g.

***** Quantity of moderator material that is sufficient to render the fissile configuration to reach the criticality safety limit.

Annexure-II

Safety Factors for Criticality Control Parameters

Safe operating limits are obtained by application of a suitable safety factor on the criticality control parameter. The safety factor should be used to provide allowance for:

1. Uncertainty in the value of **<u>nuclear constant</u>** used as inaccuracies in the method of computation

2. Inhomogenities arising due to **<u>varying concentrations</u>** e.g., presence of sludge, undissolved particles in solution, non-uniform distribution brought about by the change of state

3. Difficulties in obtaining a **<u>representative and consistent sample</u>**, particularly of non-uniform medium

4. Analysis uncertainties

5. Mal-operation on the part of plant personnel or plant control mechanism, e.g., batch doubling

6. Other unforeseen circumstances

Safety factors for criticality control parameters are given in Table A2.1

Table A2.1: Safety Factor for Criticality Control Parameters

Controlling Parameter	Mass		Volume	Cylinder Diameter	Slab Thickness	Concentration
	Batch Doubling					
	Possible	Not Possible				
Heterogeneity possible	0.43	0.7	0.75	0.85	0.75	0.85
Heterogeneity Impossible	0.43	0.85	0.85	0.9	0.85	

Allowed Mass {CSL when the control parameter is Mass) = 0.43*Critical Mass (Estimated based on Criticality analysis (i.e., for $k_{eff} = 1$)}.

Annexure-III

Minimum Critical Value of Control Parameters

The minimum critical value of criticality control parameters for three fissile isotopes i.e., ^{235}U, ^{233}U and ^{239}Pu with infinite water reflection condition are given in Table A4.1 [7].

Table A4.1. Reference minimum critical value of control parameters

^{235}U	^{233}U	^{239}Pu
Mass in solution (kg)		
0.82	0.59	0.51
Metal mass (kg)		
22.8	7.5	5.6 (α-phase)
		7.6 (δ-phase)
Diameter of Infinite Cylinder for solution (cm)		
13.7	11.1	12.4
Thickness of Infinite Slab for solution (cm)		
4.3	3.0	3.3
Solution Volume (litre)		
6.3	3.3	4.5
Concentration in Solution {g (of isotope)/litre}		
12.1	11.2	7.8

REFERENCES

[1] Russell L. Bowden, Andrew Barnes, Peter R. Thorne and Jack Venner, "ALARP considerations in criticality safety assessments", JAERI-Conf 2003-019.

[2] Atomic Energy Regulatory Board, Safety Code (AERB/NPP-LWR/SC/D), "Design of light water reactor based nuclear power plants", Mumbai, India, 2015.

[3] IAEA Safety Standards "Safety of Nuclear Fuel Cycle Facilities", Specific Safety Requirements No. SSR-4, 2017.

[4] Thomas P. McLaughlin, et al., "A review of criticality accidents", Los Alamos report, La-13638, 2000.

[5] E. D. Clayton, 'Anomalies of nuclear criticality', Pacific Northwest National Laboratory, PNNL-19176, Richland, Washington, 2010.

[6] Atomic Energy Regulatory Board, Safety Code (AERB/NRF-TS/SC-1/Rev-1), "Safe transport of radioactive material", Mumbai, India, 2015.

[7] A. D. Callihan et al., 'Nuclear safety guide', TID-7016, Rev 1, 1961.

[8] IAEA Safety Standards, 'Criticality Safety in the Handling of Fissile Material', Specific Safety Guide No. SSG-27, 2014.

[9] "Nuclear criticality safety handbook", Japan Atomic Energy Research Institute, JAERI-Review 95-013, 1995.

[10] B. A. J. Lister, "Health physics aspects of Plutonium handling", ARE-L151, Atomic Energy Research Establishment, Harwell, Berkshire, 1964.

[11] S. Janardhanan, S. Krishnamony, T. N. Krishnamurthi, C. S. Gopalan, "Design parameters and testing techniques for criticality accident detection systems used in various nuclear establishments - a review", Bulletin of Radiation Protection, Vol. 4, No. 3 & 4, 1981.

[12] S. Janardhanan and S. Krishnamony, "Criticality monitoring systems: design specifications and testing procedures", Second topical meeting of Indian Association for Radiation Protection, Bombay, 1975.

[13] "Nuclear criticality safety", Regulatory Document (RD-327), Canadian Nuclear Safety Commission, 2010.

[14] IAEA Safety Standards, "Regulations for the Safe Transport of Radioactive Material", Specific Safety Requirements No. SSR-6 (Rev.1), 2018.

BIBLIOGRAPHY

[1] J. T. Thomas, 'Nuclear safety guide', TID-7016, Rev 2, NUREG/CR-0095, 1978.

[2] USNRC Regulatory Guide 3.71/Rev 2, December 2010, "Nuclear Criticality Safety Standards for Fuels and Material Facilities".

[3] DOE standard, "Guidelines for Preparing Criticality Safety Evaluations at Department of Energy Nonreactor facilities", United States of America, DOE-STD-3007-2017.

[4] Los Alamos National laboratory, 'A review of criticality accidents', LA-13638, LANL, NM, 2000.

[5] ANSI/ANS-8.3-1997, "Criticality alarm system."

[6] ANSI/ANS-8.19-1996, "Administrative practices for nuclear criticality safety".

[7] ISO Standard 1709:2018, "Nuclear energy - Fissile materials - Principles of criticality safety in storing, handling and processing".

[8] T. N. Krishnamurthi, "Physical means for prevention of accidental criticality in nuclear installations", Second topical meeting of Indian Association for Radiation Protection, Bombay, 1975.

[9] T. S. Laxminarayanan, "Administrative control measures for prevention of accidental criticality", Second topical meeting of Indian Association for Radiation Protection, Bombay, 1975.

[10] OECD, NEA Report, "Burn-up Credit Criticality Safety Studies", NEA/NSC/R (2016)1.

[11] R. D. Carter, G. R. Keil, K. R. Ridgway, "Criticality Handbook" Atlantic Richfield Hanford Company, ARH-600, Richland, Washington, 1968.

[12] GALET, C., Le BARS, I., "Nuclear criticality risks and their prevention in plant and laboratories", Analysis Guide, DSU/SEC/T/2010-334 - Index A, IRSN, 2010.

[13] IAEA Safety Reports Series No. 9, "Safe Handling and Storage of Plutonium", 1998.

[14] Norman L. Pruvost, Hugh C. Paxton, "Nuclear Criticality Safety Guide", Los Alamos report, LA-12808, 1996.

[15] NEA CSNI Report, "Operational and Regulatory Aspects of Criticality Safety: Workshop Proceedings", NEA/CSNI/R (2016)3, 2016, JT03399979.

[16] Proceedings of Ninth International Conference on Nuclear Criticality (ICNC-2011), Edinburgh, Scotland, UK, September 19-22, 2011.

[17] Proceedings of International Conference on Nuclear Criticality Safety (ICNC-2015), Charlotte, North Carolina, USA, September 13-17, 2015.

[18] Proceedings of International Conference on Nuclear Criticality Safety (ICNCS-2019), Paris, France, December 30-31, 2019.

[19] International handbook of compilation of high quality integral criticality benchmarks, https://icsbep.inl.gov/

In-House Working Group

Members of In-House Working Group for preparing R0 Draft

Shri U. K. Paul, NSAD, AERB	Convener
Dr. D. K. Mohapatra, SRI, AERB	Co-opted Member
Shri Rajnish Kumar, NPSD, AERB	Member
Shri Dhanesh B. Nagrale, NSAD, AERB	Member
Shri Susheel Kumar, NSAD, AERB	Co-opted Member
Shri Amandeep Singh, NSAD, AERB	Co-opted Member
Shri Subrata Bera, NSAD, AERB	Member-Secretary

Task Force Meetings

Dates of meeting :

May10-11, 2018
May30-31, 2018
July 18-19, 2018
August 21, 2018
August 28, 2018
November 19-20, 2018
January24, 2019
February 8, 2019
March 11-12, 2019
April 11-12, 2019
June 28, 2019

Members of Task Force

Shri T. N. Krishnamurthi, Ex-AERB	: Convenor
Shri U. K. Paul, AERB	: Co-Convenor
Shri S. Chandrashekhar, IGCAR	: Member
Shri N. Krishnan, IGCAR	: Member
Dr. K. P. Singh, BARC	: Member
Dr. D. K. Mohapatra, AERB	: Member
Dr. M. P. S. Fernando, NPCIL	: Member
Shri Rajnish Kumar, AERB	: Member
Shri G. M. Behera, AERB	: Member
Shri Subrata Bera, AERB	: Co-opted Member
Shri Soumen Koner, AERB	: Member-Secretary

ADVISORY COMMITTEE ON NUCLEAR & RADIATION SAFETY (ACNRS)

Dates of meeting	:
	January 7, 2016
	August 3, 2019
	March 22, 2022

Members of ACNRS

Shri S. S. Bajaj	: Chairman
Shri C.S. Varghese	: Member
Shri D.K. Shukla	: Member
Dr. N. Ramamoorthy	: Member
Shri S. C. Chetal	: Member
Shri K. K. Vaze	: Member
Dr. M. R. Iyer	: Member
Shri. H. S. Kushwaha	: Member
Shri A.R. Sundararajan	: Member
Shri Atul Bhandarkar	: Member
Shri Sanjay Kumar	: Member
Shri A. Jyotish Kumar	: Member
Dr. A.N. Nandakumar	: Member
Prof. C.V.R. Murty	: Member
Shri. S. K. Ghosh	: Member
Shri H. Ansari	: Member-Secretary

EXPERTS and STAKEHOLDERS

Shri J. R. Deshpande, SD, KGS-3&4

Dr. H.P. Gupta, Ex-ThPD, BARC

Shri R. K. Agnani, SD, RAPS-5&6

Dr. Aditi Ray, Head, ThPS, BARC

Dr. Ganesan, Ex-RPDD, BARC

TECHNICAL EDITING AND COPY EDITING

Dr. Obaidurrahman K, AERB

Shri H. Ansari, AERB

AERB SAFETY GUIDE NO. AERB/FCF/SG-3

Published by: Atomic Energy Regulatory Board,
Niyamak Bhavan, Anushaktinagar.
Mumbai – 400 094