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Preface

Regulatory Document RD-327, *Nuclear Criticality Safety* provides requirements for the prevention of criticality accidents in the handling, storage, processing, and transportation of fissionable materials and the long-term management of nuclear waste. This regulatory document clarifies the physical constraints and limits on fissionable materials that licensees must implement in order to ensure nuclear criticality safety during the construction, operation, decommissioning, or abandonment of the licensed facility. This document also includes requirements for alarms and shielding in areas to minimize the dose if a criticality accident does occur.

This document presents CNSC's requirements regarding nuclear criticality safety. The associated guidance document GD-327, *Guidance for Nuclear Criticality Safety*, provides information as to how these requirements may be met.

This regulatory document applies to operations with fissionable materials outside nuclear reactors, except for the assembly of these materials under controlled conditions (such as in critical experiments).

Key principles and elements used in developing this document and the associated guidance document are consistent with national and international standards.

Nothing contained in this document is to be construed as relieving any licensee from pertinent requirements. It is the licensee's responsibility to identify and comply with all applicable regulations and licence conditions.

If any discrepancies exist between this regulatory document and guidance document GD-327, *Guidance for Nuclear Criticality Safety*, then the information in this regulatory document RD-327, *Nuclear Criticality Safety* takes precedence.

Contents

RD-327, *Nuclear Criticality Safety*

1.0 Introduction

1.1 Purpose

This regulatory document provides requirements for the prevention of criticality accidents in the handling, storage, processing, and transportation of fissionable materials and the long-term management of nuclear waste.

This regulatory document clarifies the physical constraints and limits on fissionable materials that the licensee must implement in order to ensure nuclear criticality safety during the construction, operation, decommissioning, or abandonment of the licensed facility. This document also includes requirements for alarms and shielding to minimize the dose if a criticality accident does occur.

1.2 Scope

This regulatory document presents CNSC's requirements regarding nuclear criticality safety. The associated guidance document GD-327, *Guidance for Nuclear Criticality Safety* [1], provides information as to how these requirements may be met.

This regulatory document applies to operations with fissionable materials outside nuclear reactors, except for the assembly of these materials under controlled conditions (such as in critical experiments).

If any discrepancies exist between this regulatory document and guidance document GD-327, *Guidance for Nuclear Criticality Safety*, then the information in this regulatory document RD-327, *Nuclear Criticality Safety* takes precedence.

1.3 Relevant regulations

The provisions of the *Nuclear Safety and Control Act* (NSCA; this Act) and the regulations made under the NSCA relevant to this regulatory document are as follows:

- subsection 24(4) of the NSCA states that "No licence may be issued, renewed, amended or replaced unless, in the opinion of the Commission, the applicant (*a*) is qualified to carry on the activity that the licence will authorize the licensee to carry on; and (*b*) will, in carrying on that activity, make adequate provision for the protection of the environment, the health and safety of persons and the maintenance of national security and measures required to implement international obligations to which Canada has agreed"
- subsection 24(5) of the NSCA states that "A licence may contain any term or condition that the Commission considers necessary for the purposes of this Act"
- paragraphs 3(1)(*i*) and (*j*) of the *General Nuclear Safety and Control Regulations* state that "An application for a licence shall contain the following information:
  (*i*) a description and the results of any test, analysis or calculation performed to substantiate the information included in the application;
  (*j*) the name, quantity, form, origin and volume of any radioactive waste or hazardous

waste that may result from the activity to be licensed, including waste that may be stored, managed, processed or disposed of at the site of the activity to be licensed, and the proposed method for managing and disposing of that waste”

- paragraph 12(1)(*f*) of the *General Nuclear Safety and Control Regulations* states that “Every licensee shall…(*f*) take all reasonable precautions to control the release of radioactive nuclear substances or hazardous substances within the site of the licensed activity and into the environment as a result of the licensed activity”
- subsection 13(1) of the *Radiation Protection Regulations* states that “Every licensee shall ensure that the effective dose received by and committed to a person described in column 1 of an item of the table to this subsection, during the period set out in column 2 of that item, does not exceed the effective dose set out in column 3 of that item”
- paragraph 5(*i*) of the *Class I Nuclear Facilities Regulations* states that “An application for a licence to construct a Class I nuclear facility shall contain the following information…: (*i*) the effects on the environment and the health and safety of persons that may result from the construction, operation and decommissioning of the nuclear facility…”
- paragraph 6(*h*) of the *Class I Nuclear Facilities Regulations* states that “An application for a licence to operate a Class I nuclear facility shall contain the following information…: (*h*) the effects on the environment and the health and safety of persons that may result from the operation and decommissioning of the nuclear facility…”
- paragraph 7(*f*) of the *Class I Nuclear Facilities Regulations* states that “An application for a licence to decommission a Class I nuclear facility shall contain the following information…: (*f*) the effects on the environment and the health and safety of persons that may result from the decommissioning”
- paragraphs 14(3)(*c*) and (*d*) of the *Class I Nuclear Facilities Regulations* state that “Every licensee who decommissions a Class I nuclear facility shall keep a record of (*c*) the manner in which and the location at which any nuclear or hazardous waste is managed, stored, disposed of or transferred;
  (*d*) the name and quantity of any radioactive nuclear substances, hazardous substances and radiation that remain at the nuclear facility after completion of the decommissioning”
- subsection 2(1) of the *Packaging and Transport of Nuclear Substances Regulations* states that these regulations “apply in respect of the packaging and transport of nuclear substances, including the design, production, use, inspection, maintenance and repair of packaging and packages and the preparation, consigning, handling, loading, carriage, storage during transport, receipt at final destination and unloading of packages”

The *Nuclear Fuel Waste Act* and the *Nuclear Liability Act* may also apply to operations with fissionable materials.

1.4 National and international standards

Key principles and elements used in developing this regulatory document are consistent with national and international standards.

In particular, some sections of this regulatory document are extracted from the following standards from the American National Standards Institute (ANSI), with permission of the publisher, the American Nuclear Society (ANS). Where necessary, the text has been adapted to make it applicable to Canada's international obligations to the International Atomic Energy Agency (IAEA) and consistent with CNSC's regulatory requirements.

1. ANSI/ANS-8.1-1998 (Reaffirmed in 2007), *Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors*
2. ANSI/ANS-8.3-1997 (Reaffirmed in 2003), *Criticality Accident Alarm System*
3. ANSI/ANS-8.19-1996, *Administrative Practices for Nuclear Criticality Safety*

In addition, this regulatory document is consistent with:

1. IAEA Safety Standard, *Safety of Conversion Facilities and Uranium Enrichment Facilities*, IAEA SSG-5, 2010
2. IAEA Safety Standards, *Safety of Nuclear Fuel Cycle Facilities Safety Requirements*, IAEA NS-R-5, January 2009 [2]
3. IAEA Safety Standards, *Safety of Uranium Fuel Fabrication Facilities*, IAEA SSG-6, 2010 [3]
4. IAEA Safety Standards Series No. GS-R-2, *Preparedness and Response for a Nuclear or Radiological Emergency, Safety Requirements*, 2002 [4]
5. Health Canada, *Canadian Guidelines for Intervention during a Nuclear Emergency*, H46-2/03-326E, 2003 [5]
6. Canadian Standards Association (CSA) Standard N292.2-07, *Interim Dry Storage of Irradiated Fuel* [6]
7. CSA Standard N292.3-2008, *Management of Low- and Intermediate-level Radioactive Waste* [7]
8. ISO Standard 1709, *Nuclear energy—Fissile materials—Principles of criticality safety in storing, handling, and processing*, 1995 [8]
9. ISO Standard 7753, *Nuclear energy—Performance and testing requirements for criticality detection and alarm systems*, 1987 [9]
10. ISO Standard 14943, *Nuclear fuel technology—Administrative criteria related to nuclear criticality safety*, 2004 [10]
11. IEC Standard 860, *Warning Equipment for Criticality Accidents*, 1987 [11]

2.0 Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors

2.1 Introduction

Operations with some fissionable materials introduce risks of a criticality accident resulting in a release of radiation that can be lethal to nearby personnel. However, experience has shown that extensive operations can be performed safely and economically when proper precautions are exercised.

2.2 Scope

Generalized basic criteria are presented and limits are specified for ^{233}U, ^{235}U, or ^{239}Pu.

This section does not include the details of administrative controls, the design of processes or equipment, the description of instrumentation for process control, nor detailed criteria to be met in transporting fissionable materials.

2.3 Nuclear criticality safety practices

Operations with fissionable materials shall meet the requirements of this regulatory document.

2.3.1 Categorization of operations with fissionable materials

2.3.1.1 Exempted quantity of fissionable materials

An exempted quantity of fissionable materials in the licensed site is defined as an inventory of fissionable materials, 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 licensed site, 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

Licensed sites operating with exempted quantities of fissionable materials are exempt from the requirements of this regulatory document.

2.3.1.2 Small quantity of fissionable materials

A small quantity of fissionable materials in the licensed site is defined as an inventory of fissionable materials, which:

1. exceeds the exempt limits listed in section 2.3.1.1, but

2. does not exceed the following limits:
   - 500 g of ^{233}U, or 700 g of ^{235}U, or 450 g of ^{239}Pu, or 450 g of any combination of these three isotopes. These limits apply to operations with plutonium, ^{233}U, or uranium enriched in ^{233}U or ^{235}U. These limits do not apply if significant quantities of graphite, heavy water, beryllium, or other moderators more effective than light water are present, or
   - 80% of the appropriate smallest critical mass

This regulatory document is partially applicable, as further specified in section 2.3.1.4, to licensed sites operating with small quantities of fissionable materials.

2.3.1.3 Large quantity of fissionable materials

A large quantity of fissionable materials in the licensed site is defined as an inventory of fissionable materials that exceeds the limits listed in section 2.3.1.2.

This regulatory document is applicable to licensed sites operating with large quantities of fissionable materials.

Note that a licensed site containing a large quantity of fissionable materials may be subject to the *Nuclear Liability Act*.

2.3.1.4 Nuclear criticality safety program relative to categorization

A nuclear criticality safety program shall be developed and maintained in the licensed site to meet the CNSC nuclear criticality safety requirements and to support its safe operation. The extent of the program depends on the category of operations with fissionable materials:

1. licensed sites involved in operations with small quantities of fissionable materials, as defined in section 2.3.1.2, shall develop and maintain a reduced-scope program based on the applicable sections of this regulatory document, taking into account that the requirements of sections 2.3.2.2, 2.3.2.9, 3, 11, 12.5, and 12.7 are not applicable. The program shall ensure that the entire process remains subcritical such that inadvertent criticality cannot occur
2. licensed sites involved in activities with large quantities of fissionable materials, as defined in section 2.3.1.3, shall develop and maintain a full-scope program based on the applicable sections of this regulatory document and the CNSC requirements. Characteristics of a full-scope program are described in section 12.8 of this regulatory document

2.3.2 Program management practices

2.3.2.1 Responsibilities

Management shall clearly establish responsibility for nuclear criticality safety. Supervisors should be made as responsible for nuclear criticality safety as they are for production, development, research, or other functions. Each individual, regardless of position, shall be made aware that nuclear criticality safety in their work area is ultimately their responsibility. This may be accomplished through training and periodic retraining of all operating and support personnel.

Management shall provide personnel skilled in the interpretation of data pertinent to nuclear criticality safety, and familiar with operations, to serve as advisors to supervisors. These specialists should be, to the extent practicable, administratively independent of process supervisors.

Management shall establish the criteria to be satisfied by nuclear criticality safety controls. Distinction may be made between shielded and unshielded facilities, and the criteria may be less stringent when adequate shielding and confinement assure the protection of personnel.

2.3.2.2 Process analysis

Before a new operation with fissionable material is begun, or before an existing operation is changed, it shall be determined that the entire process will be subcritical under both normal and credible abnormal conditions that have frequency of occurrence equal to or greater than 10^{-6} per year [6, 7]. Examples of such conditions are given in Appendix A.

1. An adequate upper subcritical limit (USL) shall be established and justified such that:
   - if calculational methods are applied to predict neutron multiplication factors for safety assessment:
     i. the USL is calculated using the formulas presented in Appendix B; and
     ii. a minimum administrative margin of subcriticality, as presented in the formulas for calculating the USL, is 5% in neutron multiplication factor [6, 7]
   - if calculational methods are not applied to predict neutron multiplication factors for safety assessment:
     i. the USL is 500 g of ^{233}U, or 700 g of ^{235}U, or 450 g of ^{239}Pu, or 450 g of any combination of these three isotopes. These limits shall be applied only when the surrounding materials, including other nearby fissionable materials, can be shown to increase the effective multiplication factor (k_{eff}) no more than it would be increased if the unit were enclosed by a contiguous layer of water of unlimited thickness, or
     ii. otherwise, the minimum administrative margin of subcriticality shall be 20% of the critical mass [6, 7]
2. The established adequate USL shall be maintained under all normal and credible abnormal conditions, and:
   - all credible abnormal conditions having frequency of occurrence equal to or more than 10^{-6}/year are identified and assessed, and
   - the frequency of occurrence for the identified credible abnormal conditions is clearly demonstrated using quantitative or semi-quantitative methods (see GD-327, *Guidance for Nuclear Criticality Safety* [1], Appendix G

3. It shall be demonstrated that adequate mitigation measures are in place such that off-site consequences of a criticality accident, as calculated from the start of the accident, do not violate criteria established as a trigger for a temporary public evacuation by the following international standard and national guidance [6, 7]:
    - IAEA Safety Standards Series No. GS-R-2, *Preparedness and Response for a Nuclear or Radiological Emergency, Safety Requirements*, Annex III, Subsection III-2 [4]
    - Health Canada, *Canadian Guidelines for Intervention during a Nuclear Emergency*, H46-2/03-326E [5].

2.3.2.3 Written procedures

Operations to which nuclear criticality safety is pertinent shall be governed by written procedures.

All persons participating in these operations shall understand and be familiar with the procedures.

The procedures shall specify all parameters that they are intended to control. They should be such that no single, inadvertent departure from a procedure can cause a criticality accident.

2.3.2.4 Materials control

The movement of fissionable material shall be controlled. Appropriate material labelling, signs, and area posting shall be maintained specifying material identification and all limits on parameters subject to procedural control.

2.3.2.5 Equipment control

Prior to starting a new or modified process or processing line, it shall be ascertained that all equipment is consistent in dimension and material with the assumptions made to ensure subcriticality [8].

2.3.2.6 Quality management program

A quality management (QM) program that meets the applicable requirements of ANSI/ASME NQA-1-2008, *Quality Assurance Requirements for Nuclear Facility Applications* [12], CSA N286-05, *Management system requirements for nuclear power plants* [13], or equivalent, shall be established to implement the activities specified in this regulatory document.

Records shall be maintained according to the QM program to demonstrate that the facility and its equipment were constructed according to the design specifications. The licensee shall define a formal design change procedure as part of their QM program, so that all modifications made to the facility or to the facility’s processes or procedures during all stages of the life cycle are accurately recorded and their impact assessed with respect to nuclear criticality safety [2]. These QM measures are expected to be an integral part of the site’s overall QM program.

2.3.2.7 Operational control

Deviations from procedures and unforeseen alterations in process conditions that affect nuclear criticality safety shall be reported to management and shall be investigated promptly. When available, the information about incidents and events in other installations of the same type shall also be investigated and lessons learnt shall be considered. Possible improvements in criticality safety practices or equipment shall be considered and action shall be taken to prevent recurrence [2, 8].

2.3.2.8 Operational reviews

Operations shall be reviewed frequently (at least annually) to verify that procedures are being followed and that process conditions have not been altered in any way that would affect the applicable nuclear criticality safety evaluation (NSCE). These reviews shall be conducted in consultation with operating personnel, by individuals who are knowledgeable in nuclear criticality safety and who, to the extent practicable, are not immediately responsible for the operation.

2.3.2.9 Emergency procedures

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

2.3.3 Technical practices

2.3.3.1 Controlled parameters

All controlled parameters and their limits shall be specified. The influence of variations in these parameters on the k_{eff} of the system shall be understood.

2.3.3.2 Availability and reliability

The licensee shall ensure that the necessary levels of availability and reliability are maintained for nuclear criticality safety controls, as established by the process analysis for normal and credible abnormal conditions.

The following principles shall be incorporated as appropriate to attain the required availability and reliability of engineered nuclear criticality safety controls [2].

Double contingency principle

Process designs should incorporate sufficient factors of safety to require at least two unlikely, independent, and concurrent changes in process conditions before a criticality accident is possible.

Testability

All engineered nuclear criticality safety controls shall be designed and arranged so that:

1. their safety function can be adequately inspected and tested

2. the engineered nuclear criticality safety controls can be maintained, as appropriate before commissioning and at suitable and regular intervals thereafter in accordance with their importance to safety

If it is not practicable to provide adequate testability of a component, the safety analysis should take into account the possibility of undetected failures of such equipment [2].

2.3.3.3 Geometry control

Where practicable, reliance should be placed on equipment design in which dimensions are limited rather than on administrative controls. Full advantage may be taken of any nuclear characteristics of the process materials and equipment. All dimensions and nuclear properties on which reliance is placed shall be verified prior to the beginning of operations, and control shall be exercised to maintain them.

2.3.3.4 Subcritical limit

Where applicable data are available, subcritical limits shall be established on bases derived from experiments, with adequate allowance for uncertainties in the data. In the absence of directly applicable experimental measurements, the limits may be derived from calculations made by a method shown by comparison with experimental data to be valid in accordance with section 2.3.4.

2.3.3.5 Neutron reflection

Where applicable, neutron reflection shall be considered as a parameter for criticality control. The most effective neutron reflector commonly encountered in handling and in processing fissionable material is water of thickness sufficient to yield maximum nuclear reactivity. However, careful consideration shall be given to systems where significant thicknesses of other common structural materials (e.g., wood, concrete, steel), which may be more effective neutron reflectors than water, may be present. For some situations, the reflection provided by personnel may be important [8] (the material content of the human body can provide significant moderating capability [refer to GD-327, *Guidance for Nuclear Criticality Safety* [1], Appendix F]).

2.3.3.6 Neutron interaction

Consideration shall be given to neutron interaction between units when at least two units containing fissionable material are present. It is possible to reduce neutron interaction to acceptable proportions either by spacing units, by insertion of suitable neutron-moderating and absorbing materials between units, or by some combination of these methods [8].

2.3.4 Validation of a calculational method

Suitable calculational methods for determining the subcritical state of a system shall be selected and justified in accordance with an applicable quality assurance standard. The methods vary widely in basis and form, and each has its place in the broad spectrum of situations encountered in the nuclear criticality safety field. However, the general procedure to be followed in establishing validity is common to all. For an example of validation of a calculational method, refer to GD-327, *Guidance for Nuclear Criticality Safety* [1], Appendix C.

2.3.4.1 Establishment of bias

Bias shall be established by correlating the results of critical and exponential experiments with results obtained for these same systems by the calculational method being validated.

When no experimental data are available, establishment of the bias for a calculational method is not possible and the requirements of this section cannot be satisfied. Validation of a calculational method by comparing the results with those of another calculational method, for example, is unacceptable.

2.3.4.2 Bias uncertainties

The uncertainty in the bias shall contain allowances for uncertainties in the experimental conditions, for lack of accuracy and precision in the calculational method, and for extension of the area (or areas) of applicability. After allowances are made for the accuracy and precision of the method and for the bias and uncertainty, a margin in the k_{eff} or other correlating parameter shall be applied that is sufficiently large to ensure that conditions (calculated by the method to be subcritical by this margin) will actually be subcritical. Like the bias and its uncertainty, this margin may vary with composition and other variables.

2.3.4.3 Computer dependence

If the calculational method involves a computer program, checks shall be performed to confirm that the mathematical operations are performed as intended. Any changes in the computer program shall be followed by reconfirmation that the mathematical operations are performed as intended.

2.3.4.4 Validation report

A written report of the validation shall be prepared. This report shall:

1. describe the method with sufficient detail, clarity, and lack of ambiguity to allow independent duplication of results
2. identify the experimental data and list the parameters derived from the data for use in the validation of the method
3. state the area (or areas) of applicability
4. state the bias and uncertainties over the area (or areas) of applicability
5. state the margin of subcriticality over the area (or areas) of applicability, including the justification for the adequacy of the margin of subcriticality
6. state the upper subcritical limit (see Appendix B for details)

2.4 Single- and multi-parameter limits for fissile nuclides

If single- and multi-parameter limits for ^{233}U, ^{235}U, and plutonium given in sections 2.4 and 2.5 of GD-327, *Guidance for Nuclear Criticality Safety* [1] are used, an adequate administrative margin of subcriticality shall be applied to ensure compliance with section 2.3.2.2.

3.0 Criticality Accident Alarm System

3.1 Introduction

In most operations with fissionable materials the risk of inadvertent criticality is very low; however, this risk cannot be eliminated. Where a criticality accident may lead to an excessive radiation dose, it is important to provide a means of alerting personnel and a procedure for their prompt evacuation, or other protective actions to limit their exposure to radiation.

3.2 Scope

Section 3 (this section) applies to all operations involving fissionable materials in which inadvertent criticality can occur and cause personnel to receive an excessive radiation dose.

3.3 General principles

3.3.1 General

The purpose of an alarm system is to reduce risk to personnel. Evaluation of the overall risk should recognize that hazards may result from false alarms and subsequent sudden interruption of operations and relocation of personnel.

Subject to the evaluation of the overall risk described above, a criticality alarm system meeting the requirements of this regulatory document shall be installed in areas where:

1. inadvertent criticality can occur, and
2. excessive radiation dose to personnel is credible should the inadvertent criticality occur

Where alarm systems are installed, emergency procedures shall be maintained. Information on the preparation of emergency plans is provided in section 16.

3.3.2 Coverage

3.3.2.1 Evaluation of criticality alarm systems

In view of the requirement of item 1 in section 3.3.1, the need for criticality alarm systems shall be evaluated:

1. for all activities involving ^{233}U, ^{235}U, and ^{239}Pu, in which the inventory of fissionable materials (containing any of these three isotopes) exceeds 500 g of ^{233}U, 700 g of ^{235}U, 450 g of ^{239}Pu, or 450 g of any combination of these three isotopes, or

2. for all activities involving fissionable materials in which neutron moderators or reflectors more effective than light water are present, or unique material configurations exist such that critical mass requirements may be less than the subcritical mass limits listed above, or
3. for all activities in which inventory of fissionable materials exceeds 80% of the appropriate critical mass if subcritical mass limits listed above are not applicable, or not appropriate

This evaluation shall be performed for all activities in which the inventory of fissionable materials in individual unrelated areas exceeds the subcritical mass limits noted above.

For this evaluation, individual areas may be considered unrelated when the boundaries between the areas are such that there can be no transfer of materials between areas [9], the minimum separation between material in adjacent areas is 10 cm, and the areal density of fissile material averaged over each individual area is less than 50 g/m^2. This stipulation applies only to ^{233}U, ^{235}U, and ^{239}Pu.

3.3.2.2 Installation of criticality alarm systems

A criticality alarm system meeting the requirements of this section shall be installed in areas where personnel would be subject to an excessive radiation dose. For this purpose, the maximum fission yield integrated over the duration of the accident may be assumed not to exceed 2.0×10^{19} fissions. The basis for a different maximum fission yield shall be documented.

If criticality accidents of lesser magnitude than the minimum accident of concern given in section 3.4.3 are of concern, then other detection methods (e.g., audible personnel dosimetry) should be considered. These other detection methods are not considered to be criticality alarm systems and are not covered by section 3 of this regulatory document.

3.3.2.3 Detection of criticality accidents

In areas in which criticality alarm coverage is required, a means shall be provided to detect a criticality accident and to signal that prompt protective action is required.

3.3.3 Criticality alarm

Criticality alarm signals shall be for prompt evacuation or other protective actions. The criticality alarm signals should be uniform throughout the system. The signals shall be distinctive from other signals or alarms that require a response different from the response necessary in the event of a criticality accident.

The signal generators shall be automatically and promptly actuated upon detection of a criticality accident.

After actuation, the signal generators shall continue to function as required by emergency procedures, even if the radiation falls below the alarm point, and at least long enough to allow people to reach their evacuation assembly points and perform the procedures to account for all personnel. Manual resets, with limited access, should be provided outside areas that require evacuation [9].

A means for manual actuation of the criticality alarm signal may be provided.

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

3.3.4 Dependability

Consideration shall be given to the avoidance of false alarms. This may be accomplished by providing reliable single detector channels or by requiring concurrent response of two or more detectors to initiate the alarm.

In redundant systems, failure of any single channel shall not prevent compliance with the detection criterion specified in section 3.4.3.

Where portable instruments are used to meet the intent of section 3 of this regulatory document, the usage shall be evaluated to determine appropriate criteria are met. Criteria for such use of portable instruments shall be specified in procedures.

Process areas in which activities will continue during power outages shall have emergency power supplies for alarm systems, or such activities shall be monitored continuously with portable instruments.

Adequate sensitivity of the alarm system to respond to the minimum accident of concern is addressed in section 3.4.4.

Detectors shall not fail to trigger an alarm when subjected to intense radiation exceeding 1000 Gy/h. Compliance with this provision may be demonstrated by a test of sample detectors or by a manufacturer's test of production samples [9].

3.4 Criteria for system design

3.4.1 Reliability

The system shall be designed for high reliability and should use components that do not require frequent servicing (such as lubrication or cleaning).

3.4.2 Response time

The system shall be designed to produce the criticality alarm signal within one half-second (0.5 s) of detector recognition of a criticality accident.

3.4.3 Detection criterion

Criticality alarm systems shall be designed to respond immediately to the minimum accident of concern. In situations where there is only nominal shielding, the definition of minimum accident of concern provided in the glossary should be used. The basis for a different definition of minimum accident of concern shall be documented.

3.4.4 Sensitivity

Criticality alarm systems shall be designed so that alarm actuation shall occur as a result of the minimum duration transient. It may be assumed that the minimum duration of the radiation transient is one millisecond (1 ms).

The alarm trip point shall be set low enough to detect the minimum accident of concern. The alarm trip point should be set high enough to minimize the probability of an alarm from sources other than criticality.

3.4.5 Placement of detectors

The spacing of detectors shall be consistent with the selected alarm trip point and with the detection criterion.

3.5 Testing

3.5.1 Initial tests

Initial tests, inspections, and checks of the system shall verify that the fabrication and installation were made in accordance with design plans and specifications.

3.5.2 Special tests

Following modifications or repairs, or events that call the system performance into question, there shall be tests and inspections adequate to demonstrate system operability.

3.5.3 Response to radiation

System response to radiation shall be measured periodically to confirm continuing instrument performance. The test interval should be determined on the basis of experience. In the absence of experience, tests should be performed at least monthly.

Records of tests shall be maintained. System designs may incorporate self-checking features to automate portions of this testing.

3.5.4 Periodic tests

The entire alarm system shall be tested periodically. Each signal generator should be tested at least annually. Field observations shall establish that criticality alarm signals are functional throughout all areas where personnel could be subject to an excessive radiation dose. All personnel in affected areas shall be notified before testing of the criticality alarm signals.

3.5.5 Corrective action

When tests reveal inadequate performance, corrective action shall be taken without unnecessary delay. If portable instrument use is required, the criteria of section 3.3.4 shall be met.

3.5.6 Test procedures

Procedures for system testing shall minimize both false alarms and inadvertent initiation of emergency response. The procedures shall require that the systems be returned to normal operation immediately following tests.

The IEC 860 Standard, *Warning Equipment for Criticality Accidents* [11], holds useful information regarding electrical characteristics and testing procedures for alarm equipment. This document may be used as a guide in these areas.

3.5.7 Records

Records of tests and corrective actions for each system shall be maintained.

3.5.8 Out of service

The licensee shall develop and implement out-of-service criteria for the nuclear criticality alarm system.

If the system is removed from service due to an unforeseen problem, the licensee shall immediately inform CNSC as to the cause of the removal and its expected duration.

3.6 Employee familiarization

3.6.1 Posted instructions

Instructions regarding response to criticality alarm signals shall be posted at strategic locations within areas requiring alarm coverage.

4.0 Use of Borosilicate-Glass Raschig Rings as a Neutron Absorber in Solutions of Fissile Material

The purpose of Raschig rings in criticality safety applications is to assure subcriticality for normal and credible abnormal conditions over the operating life of a vessel. General requirements for use of Raschig rings for criticality control are:

1. the nuclear criticality safety criteria of section 2 shall be applied
2. the physical and chemical properties of Raschig rings specified in GD-327, *Guidance for Nuclear Criticality Safety* [1] shall be verified before their initial use as a criticality control
3. subsequent to initial use, periodic verification shall assure that the required physical and chemical properties of the Raschig rings are maintained
4. the extent and frequency of the verification of the physical and chemical properties may be determined from a documented history of trends in these properties of the Raschig rings in the particular environment in which they are used. Otherwise, the initial interval for inspection of rings shall not exceed 13 months for rings not subjected to agitation, or 7 months for rings subjected to agitation
5. methods for measuring the Raschig ring properties shall be documented and reviewed by qualified personnel for applicability and technical validity
6. Raschig rings shall be compatible with the chemical environment and physical conditions of the solutions in which they are immersed
7. use of Raschig rings in criticality safety applications other than those addressed by this document should be evaluated on a case-by-case basis

For additional safety information and guidance on the use of borosilicate-glass Raschig rings as a neutron absorber for criticality control in ring-packed vessels containing solutions of ^{235}U, ^{239}Pu, or ^{233}U, refer to section 4 of GD-327, *Guidance for Nuclear Criticality Safety* [1].

5.0 Safety in Conducting Subcritical Neutron Multiplication Measurements In Situ

Personnel protection during *in situ* experiments depends on the avoidance of a criticality accident. Safety criteria and practices for conducting such experiments shall be followed.

For additional safety information and guidance on conducting subcritical neutron-multiplication measurements where physical protection of personnel against the consequences of a criticality accident is not provided, refer to section 5 of GD-327, *Guidance for Nuclear Criticality Safety* [1].

6.0 Nuclear Criticality Safety in the Storage of Fissile Materials

All operations with fissile material, including storage, shall be conducted in accordance with section 2. If the limits given in section 6 of GD-327, *Guidance for Nuclear Criticality Safety* [1] are used, an adequate administrative margin of subcriticality shall be applied to ensure compliance with section 2.3.2.2.

For additional safety information and guidance on general storage criteria based on validated calculations, refer to section 6 of GD-327, *Guidance for Nuclear Criticality Safety* [1]. GD-327 includes additional engineering and administrative practices appropriate to the storage of fissile material.

7.0 Criteria for Nuclear Criticality Safety Controls in Operations with Shielding and Confinement

If adequate shielding against radiation and confinement of radioactive materials are provided, the hazards normally attendant with criticality in a facility lacking shielding and confinement are minimized.

This section applies to operations, with ^{235}U, ^{233}U, ^{239}Pu and other fissile and fissionable materials outside of nuclear reactors, in which shielding and confinement are provided for protection of personnel and the public, except the assembly of these materials under controlled conditions, such as in critical experiments. Criteria for criticality control under these conditions shall be provided for:

1. the prevention of nuclear criticality accidents in facilities with shielding and confinement
2. the adequacy of the required shielding and confinement

This section does not apply to those operations requiring entry of personnel inside the shielded process areas wherein fissile and fissionable materials are contained. This section does not include engineering specifications for shield design nor for establishing its adequacy. Nothing in this section shall be interpreted as discouraging additional safety features that can be conveniently incorporated.

This section does not include the details of administrative procedures for control (which are considered to be management prerogatives) or details regarding the design of processes and equipment or descriptions of instrumentation for process control.

For additional safety information and guidance, refer to section 7 of GD-327, *Guidance for Nuclear Criticality Safety* [1].

8.0 Nuclear Criticality Control and Safety of Plutonium-Uranium Fuel Mixtures Outside Reactors

This section applies to operations with plutonium-uranium oxide fuel mixtures outside nuclear reactors, except the assembly of these materials under controlled conditions, such as in critical experiments.

Operations within the scope of this section shall be conducted in accordance with section 2. If the limits for plutonium-uranium mixtures given in section 8 of GD-327, *Guidance for Nuclear Criticality Safety* [1] are used, an adequate administrative margin of subcriticality shall be applied to ensure compliance with section 2.3.2.2. Attention shall be given to credible abnormal conditions such as those listed in Appendix A.

The administrative and technical practices for criticality safety and control as described in section 12 are applicable herein.

For additional guidance, refer to section 8 of GD-327, *Guidance for Nuclear Criticality Safety* [1].

9.0 Use of Soluble Neutron Absorbers in Nuclear Facilities Outside Reactors

The use of soluble neutron absorbers for criticality accident prevention shall be conducted in accordance with section 2.

For guidance on the use of soluble neutron absorbers for criticality control, neutron absorber selection, system design and modifications, safety evaluations, and quality assurance programs, refer to section 9 of GD-327, *Guidance for Nuclear Criticality Safety* [1].

10.0 Nuclear Criticality Control of Special Actinide Elements

This section applies to operations with the following: ${}^{237}_{93}\mathrm{Np}$, ${}^{238}_{94}\mathrm{Pu}$, ${}^{240}_{94}\mathrm{Pu}$, ${}^{241}_{94}\mathrm{Pu}$, ${}^{242}_{94}\mathrm{Pu}$, ${}^{241}_{95}\mathrm{Am}$, ${}^{242m}_{95}\mathrm{Am}$, ${}^{243}_{95}\mathrm{Am}$, ${}^{243}_{96}\mathrm{Cm}$, ${}^{244}_{96}\mathrm{Cm}$, ${}^{245}_{96}\mathrm{Cm}$, ${}^{247}_{96}\mathrm{Cm}$, ${}^{249}_{98}\mathrm{Cf}$, and ${}^{251}_{98}\mathrm{Cf}$.

Operations within the scope of this section shall be conducted in accordance with section 2. If the limits given in section 10 of GD-327, *Guidance for Nuclear Criticality Safety* [1] are used, an adequate administrative margin of subcriticality shall be applied to ensure compliance with section 2.3.2.2. Attention shall be given to credible abnormal conditions such as those listed in Appendix A.

The administrative and technical practices for criticality safety and control as described in section 12 are applicable herein.

For additional guidance, refer to section 10 of GD-327, *Guidance for Nuclear Criticality Safety* [1].

11.0 Criticality Safety Criteria for the Handling, Transportation, Storage, and Long-term Waste Management of Reactor Fuel Outside Reactors

The handling, transportation, storage, and long-term waste management of fuel for nuclear reactors represents a health and safety risk to personnel involved in these activities, as well as to the general public. Within the boundaries of the licensed site, appropriate design of equipment and facilities, handling procedures, and personnel training can minimize this risk.

Operations within the scope of this section shall be conducted in accordance with section 2.

For information related to the transportation of fissile material outside the licensed site, refer to the *Packaging and Transport of Nuclear Substances Regulations*, the IAEA safety guide *Regulations for the Safe Transport of Radioactive Material* (TS-R-1)[14], the associated guidance document *Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material* (TS-G-1.1)[15], and RD-364 *Joint Canada—United States Guide for Approval of Type B(U) and Fissile Material Transportation Packages* [16].

For additional guidance applicable to handling, transportation, storage, and long-term waste management of reactor fuel units in any phase of the fuel cycle outside the reactor core and within the boundaries of the licensed site, refer to section 11 of GD-327, *Guidance for Nuclear Criticality Safety* [1].

12.0 Administrative Practices for Nuclear Criticality Safety

12.1 Introduction

Although the extent and complexity of safety-related activities may vary greatly with the size and type of operation with fissionable material, certain safety elements are common. This section represents a codification of such elements related to criticality safety.

12.2 Scope

This section provides criteria for the administration of a nuclear criticality safety program for operations outside reactors for which there exists a potential for criticality accidents.

Responsibilities of management, supervision, and the nuclear criticality safety staff are addressed. Objectives and characteristics of operating and emergency procedures are included.

General requirements for nuclear criticality safety can be found in section 2.

12.3 Responsibilities

12.3.1 Management responsibilities

Management shall:

1. accept overall responsibility for safety of operations and provide regular and systematic oversight
2. formulate nuclear criticality safety policy and make it known to all employees involved in operations with fissionable material. Distinction may be made between shielded and unshielded facilities, with appropriate criticality controls in all cases
3. assign responsibility and delegate commensurate authority to implement established policy. Responsibility for nuclear criticality safety should be assigned in a manner compatible with that for other safety disciplines. Each individual, regardless of position, shall be made aware that nuclear criticality safety in their work area is their responsibility
4. provide personnel familiar with the physics of nuclear criticality and with associated safety practices to furnish technical guidance appropriate to the scope of operations. This function should, to the extent practicable, be administratively independent of operations
5. establish a method of monitoring the nuclear criticality safety program
6. periodically participate in auditing the overall effectiveness of the nuclear criticality safety program
7. establish a defined process and procedures for equipment change control [10]
8. establish operating procedures and a process for modifying those procedures [10]

Management may use consultants and nuclear criticality safety committees to achieve the objectives of the nuclear criticality safety program.

12.3.2 Supervisory responsibilities

Each supervisor shall:

1. accept responsibility for the safety of operations under their control
2. be knowledgeable in those aspects of nuclear criticality safety relevant to operations under their control. Training and assistance should be obtained from the nuclear criticality safety staff
3. provide training and require that personnel under their supervision have an understanding of procedures and safety considerations such that they may be expected to perform their functions without undue risk. Criticality safety training programs are addressed in section 13. Records of training activities and verification of personnel understanding shall be maintained
4. develop or participate in the development of written procedures applicable to the operations under their control. Maintenance of these procedures to reflect changes in operations shall be a continuing supervisory responsibility

5. require conformance with good safety practices including unambiguous identification of fissionable materials and good housekeeping

12.3.3 Nuclear criticality safety staff responsibilities

The nuclear criticality safety staff (NCS staff) shall:

1. provide, and accept responsibility for, technical guidance in the design of equipment and processes and for the development of operating procedures [10]
2. maintain familiarity with current developments in nuclear criticality safety standards, guides, and codes. Knowledge of current nuclear criticality information should be maintained. The NCS staff should consult with knowledgeable individuals to obtain technical assistance as needed
3. maintain familiarity with all operations within the organization requiring nuclear criticality safety controls
4. assist supervisors, on request, in training personnel
5. conduct or participate in audits of criticality safety practices and compliance with procedures as directed by management
6. examine reports of procedural violations and other deficiencies for possible improvement of safety practices and procedural requirements, and shall report their findings to management
7. upon request, participate in the verification of compliance with nuclear criticality-safety specifications for intended new or modified processes or equipment [10]

12.4 Operating procedures

The purpose of written operating procedures is to facilitate and document the safe and efficient conduct of the operation. Procedures should be organized for convenient use by operators and be easily available. They should be free of extraneous material. Copies of applicable written procedures should be posted up or available in operating areas [8].

Procedures shall include those controls and limits significant to nuclear criticality safety. Procedures should be such that no single inadvertent departure from a procedure can cause a criticality accident.

Supplementing and revising procedures, as improvements become desirable, shall be facilitated.

Operating procedures shall be reviewed periodically by supervisory personnel.

New or revised procedures that affect nuclear criticality safety shall be reviewed by the NCS staff and by the supervisory personnel, and shall be approved by management [10].

Deviations from operating procedures and unforeseen alterations in process conditions that affect nuclear criticality safety shall be reported to management, investigated promptly, corrected as appropriate, and documented. Action shall be taken to prevent a recurrence.

Operations shall be reviewed frequently (at least annually) to ascertain that procedures are being followed and that process conditions have not been altered so as to affect the nuclear criticality safety evaluation (NCSE). These reviews shall be conducted, in consultation with operating personnel, by individuals who are knowledgeable in criticality safety and who, to the extent practicable, are not immediately responsible for the operation.

12.5 Process evaluation for nuclear criticality safety (nuclear criticality safety evaluation)

Before the start of a new operation with fissionable material, or before an existing operation is changed, it shall be determined and documented that the entire process is subcritical under both normal and credible abnormal conditions.

The NCSE shall determine and explicitly identify the controlled parameters and their associated limits upon which nuclear criticality safety depends. The effect of changes in these parameters, or in the conditions to which they apply, shall be understood.

The NCSE shall be documented with sufficient detail, clarity, and lack of ambiguity to allow independent judgment of results.

Before the start of operation, there shall be an independent assessment that confirms the adequacy of the NCSE.

12.6 Materials control

The movement of fissionable materials shall be controlled as specified in documented procedures. The transport of fissionable materials within the public domain shall comply with appropriate national and international regulations [10,14,15,16].

Appropriate material labelling and area posting shall be maintained, specifying material identification and all limits on parameters that are subject to procedural criticality control.

If reliance for criticality control is placed on neutron-absorbing materials that are incorporated into process materials or equipment, procedural control shall be exercised to maintain their continued presence with the intended distributions and concentrations.

Access to areas where fissionable material is handled, processed, or stored shall be controlled.

Control of spacing, mass, density, and geometry of fissionable material shall be maintained to assure subcriticality under all normal and credible abnormal conditions (note: this requirement is not applicable to operations with a small quantity of fissionable materials).

12.7 Planned response to nuclear criticality accidents

Nuclear criticality accident alarm systems are addressed in section 3. Emergency planning and response are addressed in section 16.

Emergency procedures shall be prepared, and shall be approved by management. Organizations on- and off-site, that are expected to provide assistance during emergencies, shall be informed of conditions that might be encountered. They should be assisted in the preparation of suitable emergency response procedures.

Emergency procedures shall clearly designate evacuation routes. Evacuation should follow the quickest and most direct routes practicable. These routes shall be clearly identified and should avoid recognized areas of higher risk.

Personnel assembly stations, outside the areas to be evacuated, shall be designated. Means to account for personnel shall be established.

Personnel in the area to be evacuated shall be trained in evacuation methods and informed of evacuation routes and assembly stations. Provision shall be made for the evacuation of transient personnel. Drills shall be performed at least annually to maintain familiarity with the emergency procedures. Drills shall be announced in advance.

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

Planning shall include a program for the immediate identification of exposed individuals and should include personnel dosimetry. Guidance for dosimetry can be found in the ANSI publication N13.3-1969, *Dosimetry for Criticality Accidents* [17].

Instrumentation and procedures shall be provided for the determination of the radiation intensity at the assembly area and in the evacuated area following a criticality accident. Information should be correlated at a central control point.

Emergency procedures shall address re-entry procedures and the membership of response teams.

Emergency procedures shall provide for shutting off ventilation to prevent release of fission gases outside of affected area. Consideration should be given that shutting off ventilation does not generate other safety hazards.

12.8 Content of a nuclear criticality safety program

The nuclear criticality safety program:

1. identifies applicable nuclear criticality safety standards, guidelines, and the CNSC requirements (including the applicable sections of this regulatory document)
2. lists the requirements that must be met to comply with the applicable standards, guidelines, and the CNSC requirements
3. defines a model for the implementation of these requirements
4. identifies responsibilities arising from requirements
5. describes how the program meets the applicable nuclear criticality safety requirements in every functional category (such as administration, NCSE, criticality alarm system, engineering design, procedures, materials control, training, emergency response, ongoing oversight)
6. identifies the administrative margin of subcriticality (depending on whether it is based on k_{eff} or on mass limits, or both, or other parameters), identifies the method

used to determine the margin of subcriticality for safety and the upper subcritical limit (USL)

7. identifies the risk assessment methodology to be used to demonstrate that the USL will not be exceeded in all (out-of-reactor) nuclear processes under normal and credible abnormal conditions; that is, accidents or accident sequences that have a frequency of occurrence equal to or more than 10^{-6} per year

For an example of a nuclear criticality safety program, refer to Appendix G of GD-327, *Guidance for Nuclear Criticality Safety* [1].

13.0 Nuclear Criticality Safety Training

Training of employees associated with fissionable material operations outside reactors where potential exists for criticality accidents shall be performed.

For additional guidance on nuclear criticality safety training, refer to section 13 of GD-327, *Guidance for Nuclear Criticality Safety* [1].

14.0 Use of Fixed Neutron Absorbers in Nuclear Facilities Outside Reactors

The purpose of fixed neutron absorbers in criticality control applications is to assure sub-criticality for normal and credible abnormal conditions over the operating life of the facility or equipment. For the purposes of this document, fixed neutron absorbers are materials that:

1. are an integral part of a facility, equipment, or fuel components
2. have neutron absorption properties
3. are incorporated into designs to assure margins for subcriticality as needed for normal and abnormal conditions

The use of fixed neutron absorbers for criticality control application shall be conducted in accordance with section 2. Verification of the absorbers and their effectiveness to capture neutrons shall be required before the materials are used. After the installation, there shall be verification to ensure that the neutron absorber system is in place as intended.

For additional guidance on the use of fixed neutron absorbers in the design, construction, and operation of nuclear facilities outside reactors, refer to section 14 of GD-327, *Guidance for Nuclear Criticality Safety* [1].

15.0 Nuclear Criticality Safety Based on Limiting and Controlling Moderators

For many operations, criticality safety is achieved through the limitation of parameters such as geometry, mass, enrichment, and spacing of fissionable materials. The amount of fissionable material that can be safely handled, stored, or processed at one time can also depend on the credible range of neutron moderation. Optimum moderation, by definition, results in the lowest critical mass of fissionable materials, other conditions being unchanged.

Operations within the scope of this section shall be conducted in accordance with section 2. Safety criteria and practices for achieving criticality safety by the limitation and control of moderators in the range from no moderation to optimum moderation for fissionable materials shall be documented and followed.

For additional guidance, refer to section 15 of GD-327, *Guidance for Nuclear Criticality Safety* [1].

16.0 Nuclear Criticality Accident Emergency Planning and Response

Nuclear criticality safety programs at facilities that use fissionable material are primarily directed at the avoidance of nuclear criticality accidents. However, the possibility of such accidents exists and the consequences can be life-threatening. This possibility mandates advance planning practice in planned emergency responses and verification of readiness.

Criticality accident emergency planning and response procedures shall be maintained in any facility where a criticality accident alarm system, as specified in section 3, is in use. The provisions of this section may be considered in emergency planning for nuclear power plant sites and research reactor facilities. This section does not apply to off-site accidents, or to off-site emergency planning and response.

For additional guidance on minimizing risks to personnel during emergency response to a nuclear criticality accident outside reactors, refer to section 16 of GD-327, *Guidance for Nuclear Criticality Safety* [1].

Appendix A
Normal and Credible Abnormal Conditions

The determination that a process will be subcritical under normal and credible abnormal conditions requires careful study. The criticality accidents that have occurred in industrial operations have resulted from failure to anticipate conditions that might arise; none has resulted from a faulty calculation of k_{eff}.

The engineered nuclear criticality safety controls should be designed to withstand the effects of extreme loadings and environmental conditions (for example, extremes of temperature, humidity, pressure, or radiation) arising from the following initiating conditions and any other conditions having a direct effect on nuclear criticality safety [2]:

1. external postulated initiating events:
    - natural phenomena
        - extreme weather conditions (precipitation: rain, hail, snow, ice; frazil ice; wind: tornadoes, hurricanes, cyclones, dust or sand storm; lightning; high or low temperatures; humidity)
        - flooding
        - earthquake and eruption of volcano
        - natural fires
        - effect of terrestrial and aquatic flora and fauna (blockage of inlets and outlets, damages on structure)
    - human induced phenomena
        - fire, explosion or release of corrosive or hazardous substance (from surrounding industrial and military installations or transport infrastructure)
        - aircraft crash
        - missiles due to structural or mechanical failure in surrounding installations
        - flooding (failure of a dam, blockage of a river)
        - power supply and potential loss of power
2. internal postulated events:
    - loss of energy and fluids (electrical power supplies, air and pressurized air, vacuum, superheated water and steam, coolant, chemical reagents, and ventilation)
    - use of electricity or chemicals
    - mechanical failure including drop loads, rupture (pressure retaining vessels), leaks (corrosion), plugging
    - instrumentation and control, human failures
    - internal fires and explosions (gas generation, process hazards)
    - flooding, vessel overflows
    - addition of organic solvent to aqueous solution (or vice versa) to cause unexpected concentration of fissile components in new solvent

The following are typical examples of variations in process conditions that should be considered:

1. a change in intended shape or dimensions resulting from bulging, corrosion, or bursting of a container, or failure to meet specifications in fabrication
2. an increase in the mass of fissionable material in a location as the result of operational error, improper labelling, equipment failure, or failure of analytical techniques
3. a change in the ratio of moderator to fissionable material resulting from:
    - inaccuracies in instruments or chemical analyses
    - flooding, spraying, or otherwise supplying units or groups of units with water, oil, snow (i.e., low-density water), cardboard, wood, or other moderating material
    - evaporating or displacing moderator
    - precipitating fissionable material from solutions
    - diluting concentrated solutions with additional moderator
    - introducing air bubbles between rows of fuel assemblies in a storage basin
4. a change in the fraction of the neutron population lost by absorption resulting from:
    - loss of solid absorber by corrosion or by leaching
    - loss of moderator
    - redistribution of absorber and fissionable material by precipitation of one but not the other from a solution
    - redistribution of solid absorber within a matrix of moderator or solution by clumping
    - failure to add the intended amount of absorber to a solution or failure to add it with the intended distribution
    - failure of analytical techniques to yield correct amounts of concentrations
5. a change in the amount of neutron reflection resulting from:
    - an increase in reflector thickness by adding additional material (e.g., water or personnel)
    - a change in reflector composition such as loss of absorber (e.g., by corrosion of an outer casing of absorber)
6. a change in the interaction between units and reflectors resulting from:
    - the introduction of additional units or reflectors (e.g., personnel)
    - improper placing of units
    - loss of moderator and absorber between units
    - collapse of a framework used to space units
7. an increase in the density of fissionable material

Appendix B
Establishing the Upper Subcritical Limit

Where calculational methods of analysis are applied to predict neutron multiplication factors for safety assessments, the calculated multiplication factor, k_p, for that application, plus its associated uncertainties, $|\Delta k_p|$, shall not exceed an established allowable value (the upper subcritical limit (USL)) for the neutron multiplication factor for all normal and credible abnormal conditions as follows:

$$k_p + |\Delta k_p| \leq \text{USL}$$

In these calculations, USL is the result of the validation process and may be expressed as:

$$\text{USL} = k_c - |\Delta k_c| - |\Delta k_m|$$

where:

k_c = the mean k_{eff}, which results from the calculation of the benchmark criticality experiments through the use of a particular calculational method.

If the calculated multiplication factors for the criticality experiments exhibit a trend with a parameter, then k_c shall be determined on the basis of a best fit to the calculated values. The experiments used as benchmarks in computing k_c should have material compositions (fissionable materials, neutron absorbers, and moderators), geometric configurations, neutron energy spectra, and nuclear characteristics (including reflectors) similar to those of the system being evaluated. The difference between the experimentally measured value of k_{eff} and k_c is defined as the bias. This bias is expected to be a function of composition and other variables and should be examined for trends.

Δk_c = a margin for k_c bias and bias uncertainty, which includes allowance for:

- uncertainties in the critical experiments
- statistical or convergence uncertainties, or both, in the computation of k_c
- uncertainties due to extrapolation of k_c outside the range of experimental data
- uncertainties due to limitations in the geometrical or material representations used in the computational method

Δk_m = a minimum administrative margin of 50 mk to ensure the subcriticality of USL.

k_p = the calculated multiplication factor, k_{eff}, of the system being evaluated for normal and credible abnormal conditions or events.

Δk_p = an allowance for:

- statistical or convergence uncertainties, or both, in the computation of k_p
- uncertainties due to limitations in the geometric or material representations used in the computational method

The various uncertainties may be combined statistically if they are independent (an example of this can be found in [18]). Correlated uncertainties should be combined additively.

Methods that do not directly yield k_{eff}, but whose validity has been established in accordance with section 2, may be used to ensure subcriticality.

Appropriate experimental data or data derived from experiments, with an allowance adequate to ensure subcriticality, may be used directly.

In situ measurements performed in accordance with section 5 may be used to confirm subcriticality.

Example

For all normal and credible abnormal conditions, the following condition is to be demonstrated:

$$k_p + 2\sigma \leq USL$$

Where k_p is the calculated multiplication factor, σ is its statistical or convergence uncertainty, and USL is the established upper subcritical limit.

Abbreviations

ANS	American Nuclear Society
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
CSA	Canadian Standards Association
CSC	criticality safety control
IAEA	International Atomic Energy Agency
NCS	nuclear criticality safety
NCSE	nuclear criticality safety evaluation
NCS staff	nuclear criticality safety staff
QM	quality management
USL	upper subcritical limit

Glossary

accidents or accident sequences
Events or event sequences, including external events, that lead to violation of subcriticality margin (i.e., to exceeding the USL). This definition is of a restricted nature for the purposes of this document.

areal density
The product of the thickness of a uniform slab and the density of fissionable material within the slab; hence, it is the mass of fissionable material per unit area of slab. For nonuniform slurries, the areal density limits are valid for a horizontal slab subject to gravitational settling, provided the restrictions for uniform slurries are met throughout.

bias
A measure of the systematic differences between calculational method results and experimental data.

calculational method
The calculational procedures—mathematical equations, approximations, assumptions, associated numerical parameters (e.g., cross sections)—that yield the calculated results.

CNSC nuclear criticality safety requirements
Regulatory requirements and derived acceptance criteria listed in operating licence conditions or other legally enforceable documents. This definition is of a restricted nature for the purposes of this document.

controlled parameter
A parameter that is kept within specified limits, and, when varied, influences the margin of subcriticality.

credible abnormal conditions
Accidents or accident sequences that have frequency of occurrence equal to or more than one in a million years.

criticality accident
The release of energy as a result of accidental production of a self-sustaining or divergent neutron chain reaction.

criticality safety control (CSC)
Structures, systems, equipment, components, and activities of personnel that are relied on to prevent potential accidents at a facility or to mitigate their potential consequences. This does not limit the licensee from identifying additional structures, systems, equipment, components, or activities of personnel (i.e., beyond those in the minimum set necessary for compliance with the performance requirements) as items relied on for safety. All safety controls (active engineered control, passive engineered control, simple administrative control, and enhanced administrative control) are CSC. Also called *nuclear criticality safety control (CSC)*.

criticality safety staff
See *nuclear criticality safety staff (NCS staff).*

double contingency principle
A characteristic or attribute of a process that has incorporated sufficient safety factors so that at least two unlikely, independent, and concurrent changes in process conditions are required before a nuclear criticality accident is possible.

drill
Supervised instruction intended to test, develop, maintain, and practice the skills required in a particular emergency response activity. A drill may be a component of an exercise.

effective multiplication factor (k_{eff})
Physically, the ratio of the total number of neutrons produced during a time interval (excluding neutrons produced by sources whose strengths are not a function of fission rate) to the total number of neutrons lost by absorption and leakage during the same interval. Mathematically (computationally), the eigenvalue number that, when divided into the actual mean number of neutrons emitted per fission in an assembly of materials, would make the calculated result for the nuclear chain reaction of that assembly critical.

emergency response
Actions taken from the time of identification of a suspected, imminent, or actual criticality accident to stabilization of the event. These actions include the assumption that an accident has occurred, response to the emergency, and actions to begin subsequent recovery operations.

excessive radiation dose
Any dose to personnel corresponding to an absorbed dose from neutrons and gamma rays equal to or greater than 0.12 Gy (12 rad) in free air.

external event
An event for which the likelihood cannot be altered by changes to the regulated facility or its operation. This would include all *natural phenomena* events, plus airplane crashes, explosions, toxic releases, fires, etc., occurring near or on the nuclear site.

fissile material
A material, other than natural uranium, that is capable of sustaining a thermal neutron chain reaction.

fissile nuclide
A nuclide capable of undergoing fission by interaction with slow neutrons provided the effective thermal neutron production cross section, $\upsilon\sigma_f$, exceeds the effective thermal neutron absorption cross section σ_a. Most actinide nuclides containing an even number of neutrons are non-fissile, but there may be exceptions, such as ^{232}U and ^{236}Pu (which have even numbers of neutrons and approximately equal thermal capture and fission cross sections), which perhaps can be made critical with slow neutrons. Conversely, whereas most nuclides with an odd number of neutrons are fissile, ^{237}U (which is an odd number of neutrons nuclide with a very small thermal fission cross section) cannot be made critical with thermal neutrons.

fissionable
Capable of undergoing fission.

fixed neutron absorber
Neutron absorbers in solids with an established geometric relationship to the locations occupied by fissionable material.

fuel unit
The fundamental item to be handled, stored, or transported. It may be an assembly of fuel rods, canned spent fuel, or consolidated fuel rods.

***in situ* experiment**
Neutron multiplication or other nuclear reactivity-determining measurement on a subcritical fissile assembly where protection of personnel against the consequences of a criticality accident is not provided.

k_{eff}
See *effective multiplication factor (k_{eff})*.

long-term management of nuclear waste (long-term waste management)
Long-term management by means of storage or disposal, including handling, treatment, conditioning, or transport for the purpose of storage or disposal.

minimum accident of concern
The accident resulting in a dose to free air of 0.20 Gy (20 rad) in the first minute at a distance of 2 metres from the reacting material. This definition is of a restricted nature for the purposes of this document.

moderation
The process of decreasing the energy of neutrons through successive collisions with moderator nuclei without appreciable competing capture.

moderator
A material that reduces neutron energy by scattering without appreciable capture. Materials of prime concern are those containing light nuclei with large scattering cross sections and relatively low absorption cross sections.

natural phenomena event
Earthquakes, floods, tornadoes, tsunamis, hurricanes, and other events that occur in the natural environment and could adversely affect safety. *Natural phenomena events* may be credible or incredible, depending on their likelihood of occurrence.

natural uranium
Reference throughout this document to natural uranium shall be interpreted to mean uranium in which the concentration of the ^{235}U isotope is equal to or less than 0.71 wt%.

neutron absorber
A neutron-capture material also referred to as a neutron poison.

neutron absorber system
Any combination of fixed neutron absorbers, fixed moderators, and other materials with an assigned nuclear criticality safety function.

nuclear criticality
Of or pertaining to a system that supports a sustained fission chain reaction.

nuclear criticality safety
Protection against the consequences of a criticality accident, preferably by prevention of the accident.

nuclear criticality safety control (CSC)
See *criticality safety control (CSC).*

nuclear criticality safety staff (NCS staff)
Specialists skilled in the techniques of nuclear criticality safety assessment and familiar with plant operations while, to the extent practicable, administratively independent of process supervision; also called *criticality safety staff*.

operations with fissionable materials
Any activity involving the handling, use, processing, movement and storage of fissionable materials within nuclear facilities and long-term management of nuclear waste containing fissionable materials.

process evaluation
A document that identifies and defines all known criticality safety concerns; documents criticality safety assumptions, requirements, limits, and controls; and demonstrates subcriticality. The process evaluation is often referred to as a nuclear criticality safety evaluation (NCSE).

quality management (QM)
A planned and systematic pattern of all means and actions designed to provide adequate confidence that items or services meet specified requirements and will perform satisfactorily in service.

Raschig ring
A small, hollow, borosilicate-glass cylinder having approximately equal length and diameter.

reactivity
The quantity $(k_{eff} - 1) / k_{eff}$, where k_{eff} is the effective neutron multiplication factor. The reactivity of a subcritical assembly is a negative quantity indicating the degree of subcriticality. The reactivity of a critical assembly is zero.

site
A defined area that contains one or more facilities.

soluble neutron absorber
Any neutron poison easily dispersed in liquid, solution, or suspension, used specifically to reduce the reactivity of a system and for which reactivity credit is taken in the nuclear criticality safety evaluation (NCSE) of the system.

solution
Liquid containing dissolved material, or a suspension of that material in the liquid. This includes aqueous (water based) solutions but excludes those where the hydrogen is replaced by either deuterium or tritium.

subcritical limit
The limiting value assigned to a controlled parameter that results in a subcritical system under specified conditions. The subcritical limit allows for uncertainties in the calculations and experimental data used in its derivation but not for contingencies; e.g., double batching or inaccuracies in analytical determinations.

training
Instruction that imparts knowledge and skills necessary for safe and efficient on-the-job performance.

uncertainty in the bias
A measure of both the accuracy and the precision of the calculations and the uncertainty of the experimental data.

upper subcritical limit (USL)
The maximum allowed value of the calculated k_{eff} or of a single-parameter subcritical limit, under both normal and credible abnormal conditions, including allowance for the bias, uncertainty in the bias, and an administrative margin of subcriticality.

verification
The process of confirming that an installed computer code correctly performs the intended numerical calculations.

vessel
A container designed to hold solution. This includes any volume within which criticality control is provided by Raschig rings.

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