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Nuclear energy — Performance and testing requirements for criticality detection and alarm systems

Énergie nucléaire — Prescriptions relatives aux caractéristiques techniques et aux méthodes d'essai des systèmes de détection et d'alarme de criticité

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Foreword

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Nuclear energy — Performance and testing requirements for criticality detection and alarm systems

0 Introduction

In some operations with fissionable materials the risk of nuclear criticality, while very small, cannot be eliminated. It is important in such an event to provide both a means of alerting personnel to the threat of high radiation intensity and a procedure for their evacuation.

This International Standard, which deals with the design and maintenance of criticality detection and alarm systems, is supplemented by three annexes. Annex A outlines the specification of a minimum accident of concern, annex B provides examples of application of this International Standard to process areas and annex C provides guidance for development of emergency plans.

1 Scope and field of application

This International Standard specifies performance and testing requirements for criticality detection and alarm systems; it is applicable to all operations with plutonium, uranium 233, uranium enriched in the 235 isotope, and other fissionable materials in which inadvertent criticality may occur and cause the exposure of personnel to unacceptable amounts of radiation. This International Standard does not require separate additional instrumentation when the operating instrumentation of facilities, such as nuclear reactors or critical experiments, meets the requirements of this International Standard.

This International Standard does not include details of administrative steps, which are considered to be managerial prerogatives, or specific design and description of instrumentation. Details of nuclear accident dosimetry, personnel exposure evaluations and detectors for post-accident diagnosis are not within the scope of this International Standard.

A standard which provides guidance on detailed characteristics of instrumentation to be used in criticality alarm systems is currently being drawn up by the IEC.

This International Standard is principally concerned with gamma-radiation rate-sensing systems. Specific detection criteria can be met with integrating systems or with systems detecting neutron or gamma radiation, and analogous considerations apply.

2 Definitions

For the purposes of this International Standard, the following definitions apply.

2.1 criticality accident: The release of energy as a result of accidentally producing a self-sustaining or divergent neutron chain reaction.

2.2 minimum accident of concern: The smallest accident a criticality alarm system is required to detect.

3 General principles

3.1 General

Alarm systems shall be provided wherever it is deemed that they will result in a reduction in total risk. Consideration shall be given to hazards that may result from false alarms.

3.2 Limitations and general requirements

3.2.1 The need for criticality alarm systems shall be evaluated for all activities in which the inventory of fissionable materials in individual unrelated areas exceeds 700 g of ^{235}U, 520 g of ^{233}U, 450 g of the fissile isotopes of plutonium or 450 g of any combination of these isotopes (see [1]). Attention shall be given to all processes in which neutron moderators or reflectors more effective than water are present.

In the above context, individual areas may be considered unrelated where the boundaries are such that there can be no interchange of material between areas, the minimum separation distance between material in adjacent areas is 10 cm and the surface density of fissile material, averaged over each individual area, is less than 50 g/m^2.

3.2.2 A criticality alarm system is not required under the terms of this International Standard in areas where the maximum foreseeable accidental dose in free air will not exceed 0,12 Gy. For the purpose of this evaluation, a maximum yield may be assumed not to exceed 2×10^{19} fissions for events outside reactor cores.

3.3 Detection

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

3.4 Alarm

3.4.1 The alarm signal shall be unique, sufficiently loud and shall cover a wide enough range to be heard in all areas that are to be evacuated. The alarm signal shall last long enough to allow people to reach their assembly points.

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

3.4.3 The signal to evacuate shall be sounded as soon as an accident is detected.

3.4.4 Once triggered, the signal shall continue to sound until reset even though the radiation falls below the alarm point. Manual resets, with restricted access, shall be provided outside the areas to be evacuated.

3.4.5 Areas with very high background noise levels may require that the alarm be supplemented with visual signals.

3.5 Dependability

3.5.1 Adequate consideration shall be given to avoiding false alarms. This may be accomplished by providing reliable single detector channels or preferably by requiring concurrent response of two or more detector channels to trigger the alarm. In systems employing redundant channels, failure of any single channel shall not prevent compliance with the detection criterion specified in 4.2. Warning of a malfunction without activation of the alarm should be provided.

3.5.2 A means that will not cause an evacuation should be provided to test the response and performance of the alarm system.

3.5.3 Process areas in which activities will continue during an interruption in the power supply shall have uninterruptable power supplies for criticality detection and alarm systems or else activities during such interruptions shall be monitored, using portable instruments.

3.5.4 Detectors shall not fail to trigger an alarm when subjected to intense radiation exceeding 10^3 Gy/h. Compliance with this provision may be demonstrated by a test of sample detectors or by a manufacturer's test of production samples.

4 Criteria for system design

4.1 Reliability

The design of the system should be as simple as is consistent with the twin objectives of ensuring reliable activation of the alarm and avoiding false alarms.

4.2 Detection criterion

Criticality alarm systems shall be designed to detect promptly the minimum accident of concern. For this purpose, in typical unshielded process areas, the minimum accident of concern may be assumed to deliver an absorbed neutron and gamma dose in free air of 0,2 Gy at a distance of 2 m from the reacting material within 60 s[1)]. Very slowly increasing excursions, while unlikely to occur, may not attain this value. Furthermore, excursions in unmoderated systems will probably occur much more rapidly.

4.3 Instrument response

In the design of radiation detectors, it may be assumed that the minimum duration of the radiation transient is 1 ms. Systems shall be designed to respond to radiation transients of this duration.

4.4 Trip point

In order to minimize false alarms, the trip point may be set as high as is considered desirable as long as the detection criterion specified in 4.2 is met. Indications should be provided to show which detection channels have been tripped.

4.5 Positioning the detectors

The location and spacing of detectors should be chosen to avoid the effect of shielding by massive equipment or materials. The spacing of detectors shall be consistent with the selected alarm trip point and with the detection criterion. Detector coverage is discussed in annex B.

4.6 Testing

4.6.1 Instrument response to radiation shall be checked periodically to confirm continuing instrument performance. In a system having redundant channels, the performance of each channel shall be monitored. The test interval may be determined on the basis of experience; however, tests should be carried out at least once a month. Records of the tests shall be maintained.

4.6.2 The entire alarm system shall be tested periodically. Each audible signal generator should be tested at least once every three months. Field observations shall establish that the signal is audible above background noise throughout all areas to be evacuated. All personnel in affected areas shall be notified in advance of an audible test.

4.6.3 Where tests reveal inadequate performance, corrective action shall be taken without delay.

4.6.4 Procedures shall be formulated to minimize false alarms, which may be caused by testing, and to return the system to normal operation immediately following the test.

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

1) Consideration of past accidents, supplemented by annex A, shows that if a criticality accident should occur, the radiation intensity may be expected to exceed this value.

Annex A

Characterization of minimum accident of concern

(This annex does not form an integral part of the standard.)

A basic consideration in the design of a criticality accident alarm system is the definition of the size of the event to be detected. A "minimum accident of concern" has been specified on the basis of accident history, supplemented by consideration of accident mechanisms, as one which will result in a dose of 0,2 Gy in the first minute at a distance of 2 m from the reacting material, assuming only nominal shielding.

Nine nuclear criticality accidents that have occurred during processing or handling of fissile material are described in [2]. Consideration of these events resulted in the specification of the minimum accident of concern given above. One may postulate mechanisms that will provide a very small energy release in an event, but a self-terminating accident must liberate enough energy to provide a shutdown mechanism. Furthermore, while a system may liberate this energy over a long time, this would require control of such delicacy that it is not to be expected in process accidents.

A typical process accident would result from the addition of reactivity to a subcritical system so that it becomes supercritical. The increase in reactivity could result from the addition of fissile material, from an increase in moderator or reflector present, or from a change in the system shape to one having a lower neutron leakage.

The supercritical system will rapidly release energy, the rate varying with the degree of supercriticality which has been attained. Some of the energy released will cause thermal expansion, boiling or other effects that will reduce the reactivity. Thus the supercriticality will quickly be compensated for, and the reaction rate will be greatly reduced. The energy released during this power transient (a characteristic of most criticality accidents) is the "spike yield".

The spike yields of the nine process accidents mentioned above are shown in figure 1. Accidents that have occurred in reactors and remotely-operated critical facilities are not included, because the mechanisms available for reactivity addition are so unlike those associated with process facilities.

Conversion of the fission yields in figure 1 to dose or dose rate near the assembly is not direct. Estimates of the dose received in four of these nine events, along with estimates of the distance of the exposed person from the excursion, are presented in [3]. These data indicate that, within a factor of about 2, the four accidents would each have resulted in about 10 Gy at a distance of 2 m. Doses were all delivered in short times, usually a few seconds.

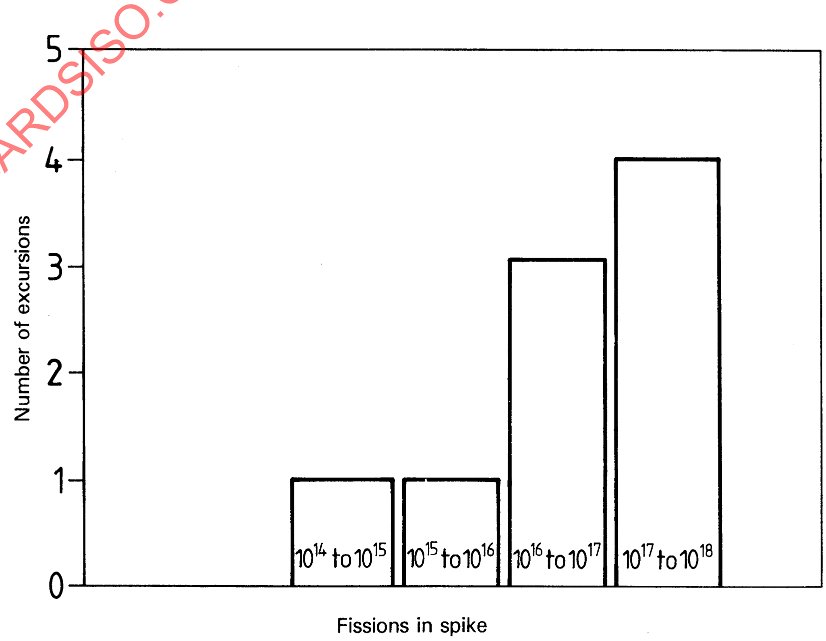

Figure 1 — Spike yields

The smallest spike yields in figure 1 resulted from hand-stacking reflector material around a 6,2 kg plutonium sphere. In one case, the reflector was tungsten carbide, in the other, beryllium. The spike yield in the first case has been estimated to have been about 2×10^{15} fissions; in the second, a factor of 10 less. Both spikes were followed by brief power plateaus so that the total yields were 10^{16} and 3×10^{15} fissions, respectively. Each assembly remained critical for about 1 s.

The persons nearest these assemblies received lethal exposures, but some uncertainty exists as to doses received. For the tungsten carbide reflected assembly, data are quite sparse and are complicated by the presence of heavy shielding. Several studies have been made to determine the doses from the beryllium-reflected sphere. A total first collision dose of 11 Gy at a distance of about 40 cm was derived in [4], based on blood sodium activation data taken at the time of the accident, with recent corrections for neutron spectral effects. One person, who was approximately 2 m from the excursion, received about 0,56 Gy.

These plutonium metal sphere accidents represent a reasonable lower limit for accidents that are terminated by an inherent shutdown mechanism. It should be noted that each of these accidents was terminated by deliberate action of the individual involved after he became aware of the occurrence. Had the critical configuration not been disassembled within a few seconds, the energy release in the first minute would have been about an order of magnitude higher.

Study of the behaviour of experimental critical assemblies adds to our understanding of the characteristics of nuclear excursions. Two of these assemblies at the Los Alamos Critical Experiment Facility are of particular interest.

"Godiva" is an unclad assembly of enriched uranium designed to be operated above prompt critical in a fast pulse mode. The temperature coefficient of reactivity for this assembly is about $-3,6 \times 10^{-3}$ dollars/°C[1)], so a temperature rise of about 300 °C is necessary to reduce the assembly from prompt critical to delayed critical, perhaps a reasonable minimum shutdown effect. This energy would be supplied from about 5×10^{16} fissions which, in turn, would result in a dose of approximately 7,5 Gy at 2 m from the assembly.

"Parka" is a uranium-loaded graphite cylindrical core having a diameter of 0,91 m and a length of 1,37 m, with a beryllium reflector 100 mm thick. For such an assembly, criticality could inadvertently occur as a result of the introduction of a small quantity of water into the assembly. If this occurred slowly, the system could exceed delayed critical by only a slight margin before the temperature rose to the boiling point of water and equilibrium was established at a power level which would maintain a constant water content. If the steady-state condition is disregarded, the initial temperature rise (approximately 70 °C) would correspond to about 2×10^{18} fissions and would result in a dose in excess of 15 Gy at 2 m from the assembly.

The "Parka" assembly in size, weight and heat capacity is probably much more like the process accidents with which one should be concerned than is "Godiva", and accidents involving systems as compact as the 6,2 kg plutonium sphere are considered very unlikely today.

Calculated values of energy density as a function of time for reactivity additions of 1 dollar and 1,20 dollars with neutron lifetimes varying from 10^{-8} to 10^{-4} s are also provided in [2]. For the smaller reactivity additions, energy densities are several hundred joules per cubic centimetre in the first 60 s of the excursion. From these values, one may predict more than 10^{17} fissions in the first minute of an excursion in a minimum critical volume of plutonium solution (6 l), as a consequence of the system becoming prompt critical.

The series of CRAC experiments performed by the Section Expérimentale d'Études de Criticité de Valduc [5], [10] provides insight into the behaviour of supercritical quantities of enriched uranium solution in vessels typical of those found in many process areas. Highly enriched uranium in solution at various concentrations was transferred into a vessel to provide the supercritical configurations. The smallest fission yields were obtained for slow excursions where reactivity additions were between 30 and 60 cents above delayed critical. The peak power for these excursions varied from $7,8 \times 10^{14}$ to $7,4 \times 10^{15}$ fissions/s. The average power over the duration of the excursions varied from approximately 10^{14} fissions/s to approximately 10^{15} fissions/s. Larger values are generally associated with larger vessels, so that the power density shows significantly smaller variances.

Criticality accident studies with solution systems have been continued at Valduc with the SILENE reactor [6], [11]. Following reactivity additions to a few cents above delayed critical, very slow excursions have been produced with periods of several minutes and peak fission rates from 10^{12} to 10^{13} fissions/s.

Similar experiments at the SHEBA [7] with reactivities from about 7 to 11 cents above delayed critical resulted in peak fission rates of a few times 10^{13} fissions/s.

Experience from the two fatal process accidents described in [2] (Los Alamos 1958 and Wood River 1964) indicates doses of approximately 100 Gy at a distance of 0,5 m from a solution of approximately 10^{17} fissions, corresponding to approximately 0,06 Gy at 2 m from 10^{15} fissions.

1) One dollar is equivalent to the reactivity change between delayed and prompt criticality and is equal to 100 cents.

Using the value of 8 × 10^{15} fissions/min provided by the smallest of the CRAC slow excursions, this would represent about 0,5 Gy/min at 2 m. Since the peak power of the pulse was about five times the average power, and the excess reactivity was about 33 cents, the detection criterion of 0,2 Gy in 60 s at 2 m will provide an alarm for small solution accidents involving an excess reactivity of only a few tens of cents. This is adopted in this International Standard as the specification for the minimum accident of concern.

This detection criterion may be inadequate to detect very slowly developing delayed critical excursions.

The SILENE experiments show that such very slow excursions might go undetected, however, these excursions require control of great delicacy and are not to be expected in process equipment. Thus, this situation is considered a special case outside the definition of the minimum accident of concern.

Annex B

Calculations of detector radius of coverage versus alarm trip point

(This annex does not form an integral part of the standard.)

B.1 Assumptions

Several assumptions make possible a simple calculation of the radius of coverage that a detector will have at any given trip point. These basic assumptions are as follows:

a) The system shall respond to an accident that will cause a neutron plus gamma dose of 0,2 Gy at an unshielded distance of 2 m within 60 s (see 4.2).

b) The detector is a gamma rate meter.

c) The accident may be a fast transient in an unmoderated, unreflected metallic fissile material or it may be either a rapid transient or a sustained fission reaction in moderated fissile material.

d) The detector response to fast transients is at least 1/2 500 of the actual dose rate. (This assumption is based on measurements presented in [8].) Fast transients are assumed to have a pulse width of 1 ms or more.

e) The gamma radiation intensity varies inversely as the square of the distance from the source. An air attenuation factor of 3 was assumed at large distances. (This factor should overestimate the attenuation at all distances of interest.)

f) A neutron-to-gamma dose ratio of 12 was assumed for the fast transient in an unmoderated, unreflected metallic assembly. (Two very similar criticalities occurred in a metallic, partially reflected ^{239}Pu assembly [2].) A transient of 3 × 10^{15} fissions produced, at 1,8 m, 0,51 Gy, due to neutrons, and 0,051 Gy, due to gamma rays [4]. A neutron-to-gamma dose ratio of 12 for an entirely bare metallic ^{239}Pu assembly is assumed. Therefore, the 0,2 Gy combined neutron and gamma ray dose at 2 m would consist of 0,185 Gy from neutrons and 0,015 Gy from gamma rays. (This dose would result from 1,86 × 10^{15} fissions.)

g) A neutron-to-gamma dose ratio of 0,30 was assumed for moderated assemblies. An experimental model of the Y-12 accident was operated at a sustained rate of 9,5 × 10^{12} fissions/s for 42 min. This produced a neutron dose of 0,47 Gy at 1,9 m, and the neutron-to-gamma dose ratio was 0,30 [9]. Thus an assumed dose of 0,2 Gy at 2 m would be composed of 0,047 Gy of neutron dose and 0,153 Gy of gamma dose. (This dose would result from 2,2 × 10^{15} fissions.)

B.2 Calculated detector radius of coverage

Using these assumptions, the maximum distance that a detector can be from potential accident locations (detector radius of coverage) may be calculated for any alarm trip point. As an example, for a fast transient in a bare metallic assembly, the gamma detector response, T_r, at a given alarm trip point, at a distance r, will be

$$T_r = \dot{D} \times \left(\frac{a}{r}\right)^2 \times \frac{1}{d_{\text{air}}} \times \varepsilon$$

where

$\dot{D}$ is the absorbed dose rate, in grays per millisecond, at a distance a;

a = 2 m;

r is the detector radius of coverage;

d_{air} is the air attenuation factor (d_{air} = 3, see clause B.1);

ε is the assumed response to a fast transient ($\varepsilon = \frac{1}{2\,500}$, see clause B.1).

If an alarm trip point of 5 × 10^{-4} Gy/h is assumed, thus

$$5 \times 10^{-4} = 0{,}015 \times 3{,}6 \times 10^6 \times \left(\frac{2}{r}\right)^2 \times \frac{1}{3} \times \frac{1}{2\,500}$$

hence

r = 240 m

Values for other excursions are given in the table.

Table

Values in metres (Values in feet in parentheses)

Type of excursion	Detector radius of coverage for an alarm trip point of 5 × 10^{-4} Gy/h
Transient — unmoderated, unreflected metallic assembly	240 (790)
Transient — moderated assembly	766 (2 530)
Steady state — moderated assembly	156 (520)

From the results given in the table, it can readily be seen that the detector radius of coverage will be smallest for steady-state accidents in moderated assemblies.

For this generally limiting case, a curve showing alarm trip point versus detector radius of coverage can be plotted (see figure 2) in order to meet the detection criteria in this International Standard. The values are based on the limiting case of a steady-state reaction in a moderated assembly.

Where a coincidence between two channels is required to trigger an alarm and failure of any one channel will not render the system inoperative, three detectors (set to trip at 5 × 10^{-4} Gy/h, would be required within a radius of 150 m of each point in a process area.

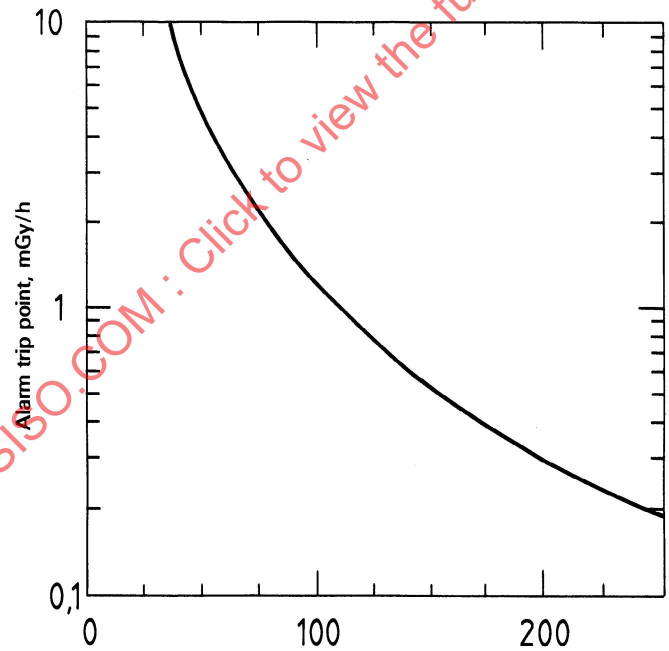

Figure 2 — Alarm trip point for a gamma-ray rate meter versus detector radius of coverage