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Nuclear criticality safety — Use of criticality accident alarm systems for operations

Sûreté-criticité — Systèmes de détection et d'alarme de criticité dans le cadre de l'exploitation

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 85 *Nuclear energy, nuclear technologies, and radiological protection*, Subcommittee SC 5 *Nuclear installations, processes and technologies*.

This second edition cancels and replaces the first edition (ISO 7753:1987), which has been technically revised.

The main changes are as follows:

- clarification of the scope and title: this standard is intended for CAAS users;
- improved differentiation with IEC 60860, intended for CAAS designers, manufacturers, providers...;
- removal of CAAS need considerations from the normative part;
- more open definition of the MAC to reflect the variety of practices and possibilities;
- more developed clauses regarding management of unavailability, reliability, positioning of CAAS components;
- addition of a “continuum of detection” concept;
- better integration with other existing ISO standards related to criticality-safety (ISO 1709, ISO 11320, ISO 27467, ISO 14943, ISO 16117 and ISO 21391);
- rewriting and expansion of informative Annexes A and B:
  - Elements for the definition of the minimum accident of concern;
  - Principles for CAAS detectors positioning;
- creation of an informative Annex C: Examples of CAAS need considerations.

Any feedback or questions on this document should be directed to the user’s national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Nuclear criticality safety programs at facilities that might use or store significant quantities and concentrations of fissile material are primarily directed at avoiding nuclear criticality accidents. However, the possibility of such accidents exists and the consequences can be life-threatening. Nuclear criticality accidents are complex events that can take various forms and without warning signs. For facilities that are judged to have potential for a nuclear criticality accident, the defense-in-depth principle requires limiting their radiological consequences.

Criticality accident alarm systems (CAAS) provide a means to detect nuclear criticality accidents and to trigger an alarm to prompt the evacuation to a radiologically safe location.

This detection is very specific because of the various possible neutron kinetics and radiation fields produced by a nuclear criticality accident comprising neutrons and photons (i.e. gamma radiation) with a broad spectrum of energies. The primary purpose of CAAS is to prompt personnel to evacuate as soon as possible during a nuclear criticality accident, thus limiting individual and collective radiological doses. A CAAS cannot, and is not intended to, protect personnel from radiation from a nuclear criticality accident prior to prompt evacuation or other protective actions.

Considerations about emergency preparedness and response, including the evacuation procedure related to nuclear criticality accidents, are addressed in ISO 11320.

This document is supplemented by three informative annexes:

— Annex A outlines elements for the definition of the minimum accident of concern (MAC);

— Annex B provides examples of application of this document for the positioning of CAAS detectors;

— Annex C looks at the factors which are considered when assessing whether a CAAS is needed or not, through examples.

Nuclear criticality safety — Use of criticality accident alarm systems for operations

1 Scope

This document provides requirements and guidance regarding the use of CAAS for operations of a nuclear facility. Requirements and guidance on CAAS design are provided in the IEC 60860.

This document is applicable to operations with fissile materials outside nuclear reactors but within the boundaries of nuclear establishments.

This document applies when a need for CAAS has been established. Information about the need for CAAS is given in Annex C.

This document does not include details of administrative steps, which are considered to be activities of a robust management system (ISO 14943 provides details of administrative steps).

Details of nuclear accident dosimetry and personnel exposure evaluations are not within the scope of this document.

This document is concerned with gamma and neutron radiation rate-sensing systems. Specific detection criteria can also be met with integrating systems; systems detecting either neutron or gamma radiation can also be used. Equivalent considerations then apply.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 1709, *Nuclear energy — Fissile materials — Principles of criticality safety in storing, handling and processing*

ISO 11320, *Nuclear criticality safety — Emergency preparedness and response*

IEC 60860:2014, *Radiation protection instrumentation — Warning equipment for criticality accidents*

3 Terms and definitions

For the purposes of this document, the terms and definitions of ISO 1709 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
criticality accident alarm system
CAAS
system dedicated to the detection of nuclear criticality accidents and to the warning of the personnel to prompt their immediate evacuation

Note 1 to entry: A criticality accident alarm system is constituted of all components allowing it to ensure its main function and its optional additional functions (see 4.1) if present; these components include, where applicable: detectors, cabinet(s) (e.g. electronic processing/logic cabinet), alarm devices, device for the supervision of the system status, monitoring device in case of alarm triggering, and interconnections, as well as the system power supply(ies).

3.2
minimum accident of concern
MAC
"smallest" nuclear criticality accident that a *criticality accident alarm system* (3.1) is required to be able to detect

Note 1 to entry: The minimum accident of concern is used to determine and verify the adequate positioning of the CAAS detectors.

Note 2 to entry: The minimum accident of concern is usually expressed in terms of

— doses within a given time, or dose-rates at a given distance, or,

— fission yield within a given time, or fission yield rate, or,

— reactivity insertion, or,

— fission yield resulting in a given dose.

Note 3 to entry: Further information about the MAC is given in 4.3 and Annex A.

3.3
detection zone
area inside of which a nuclear criticality accident meeting the definition of the MAC would trigger the CAAS alarm

3.4
false alarm
unintentional activation of the alarm signal in the absence of a nuclear criticality accident

Note 1 to entry: The cause of a false alarm could be a malfunction of a part or the whole of the system, as well as the triggering due to an external cause (heat, high ambient dose, etc.) or a maintenance error.

4 General design, detection principle

4.1 CAAS functions

4.1.1 Main function

The main function of a CAAS is to provide prompt warning to personnel, in order to limit the radiological consequences due to a nuclear criticality accident. The goal of the alarm is to prompt nearby personnel to evacuate as soon as possible and to deter access to the zones that are to remain evacuated. Estimation of consequences of a potential nuclear criticality accident shall be prepared before implementing the CAAS. Guidance for such estimation is provided in ISO 27467.

This main CAAS function should be maintained as long as a presence of a CAAS provides a net benefit. Unavailability of the main CAAS function shall be identified and managed (see Clause 5).

The alarm shall be designed to provide a prompt evacuation order to all personnel inside the boundaries of the zones to be evacuated and to warn against access to those zones; these boundaries shall meet the requirements of ISO 11320. The emergency arrangements for preparedness and response should be fulfilled in accordance with ISO 11320 as appropriate.

4.1.2 Additional functions (optional)

A CAAS may provide additional functions, given its main function is not affected. These services might be, for example,

— to provide remote monitoring of an ongoing or apparently stopped nuclear criticality accident in order to plan the emergency response, or

— to record detectors' signal for analysis during or after a nuclear criticality accident.

This remote monitoring and signal recording capability should be implemented outside of zones to be evacuated.

Personnel required to operate this remote monitoring and signal recording capability shall be trained in these tasks.

4.2 Resilience

The ability to perform the CAAS main function shall be able to withstand the high radiation emission due to a nuclear criticality accident. The requirements of IEC 60860:2014, 6.6 shall apply for detectors radiation resilience.

NOTE 1 Whenever possible, electronic cabinets and power supplies (Note 1 to entry 3.1) are placed outside of areas where they might receive high radiation doses.

NOTE 2 IEC 60860 contains requirements and specifications regarding resilience of CAAS to environmental, mechanical, and electromagnetic conditions.

If additional functions (4.1.2) are implemented, it should be ensured that repeated excursions would not impair these features.

The CAAS shall be powered by an uninterruptible power supply, allowing continuous operation of the system in the case of failure of external power.

The period during which the CAAS power supply is sustained should be such that, in the event of failure of external power, the system stays in an alarm state long enough for all evacuations to be initiated and for an access control to affected areas to be implemented. This period should also be sufficient to ensure that a CAAS function is maintained during the instigation of alternate arrangements regarding CAAS unavailability.

The sustaining of power supply is not required in situations of managed unavailability of the CAAS (see Clause 5).

4.3 Detection criterion

A CAAS shall trigger its alarm for any nuclear criticality accident whose characteristic meets or exceeds those of the MAC.

The MAC shall be justified and documented. Annex A provides elements for the definition of the MAC and guidance that can be applied to determine it. Several MACs may be defined in a facility.

NOTE The minimum accident of concern assumed in the 1987 version of this International Standard delivers *"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"*.

Predicting the location of a nuclear criticality accident and its neutron kinetics is a difficult topic. Considering Annex A, this difficulty can result in a residual risk of nuclear criticality accident with characteristics not meeting the MAC. If the response to such an accident would provide a net benefit to personnel, its detection should be considered in order to constitute a continuum of detection below the MAC. This detection may be performed with means complementary to the CAAS, such as non-dedicated radiation sensing equipment, which are then not CAAS. In this case, adequate accident response procedures shall be provisioned, in accordance with ISO 11320.

5 Management of unavailability

Provision shall be made to manage conditions where an unavailability of the CAAS is identified, unless it can be justified that there is no need for the CAAS given the particular condition.

NOTE 1 Situations where a CAAS might be unavailable include malfunction or failure (unintentional events) as well as maintenance and testing (intentional events).

Unavailability may be managed by

— ordering an evacuation of personnel from the zones which are no longer covered, or

— applying anticipated actions that would negate the need for a CAAS for the duration of this unavailability (shutdown of operations, cessation of transfers, emptying of the process equipment or facility from any fissile material, etc.), or

— maintaining the main CAAS function by other means.

The main CAAS function may temporarily be obtained by the use of portable devices or ambient radiation monitoring equipment not dedicated to nuclear criticality accidents. Any temporary substitution shall be evaluated to be able to perform as an adequate alternative to the existing permanent CAAS. In this case, any performance shortfalls of the temporary system against the existing permanent CAAS should be justified with regards of the unavailability duration.

NOTE 2 IEC 60860:2014 4.5 requires the failure of important CAAS components, including detectors, to be revealed by visual and/or audible indication.

6 System design

6.1 General

This clause presents system design requirements as derived from the scope of this document, aimed at CAAS users.

A CAAS is usually constituted of several components forming a whole. These components shall be protected from failure by design, to ensure the system responds as intended.

Any unavailability or failure should be managed according to Clause 5.

IEC 60860 details additional requirements and specifications aimed at CAAS manufacturers, including electronics, detectors and alarm.

A redundancy of components may be implemented in order to ensure continued operation of the CAAS.

The CAAS design should be reviewed as changes to the facility or operating conditions warrant.

6.2 Alarm

The CAAS shall trigger a prompt evacuation alarm inside the zones to be evacuated; this alarm shall also warn against re-entry to these zones.

The CAAS alarm shall primarily be an audible warning. Visual signals or other alarm means shall be considered to supplement the sound signal to ensure a prompt response of personnel in circumstances where a sound signal would be ineffective (high background noise level, hearing protections, outside building, etc.).

The CAAS' alarm signal shall be specific, so as to be distinct from other signals or alarms, which requires a response different from that necessary in the event of a nuclear criticality accident.

The alarm shall be automatically and promptly actuated upon detection of a nuclear criticality accident with characteristics meeting the MAC (IEC 60860:2014, 6.3). After actuation, the alarm shall be maintained even if radiation level falls below the triggering threshold. The minimum alarm duration shall be assessed to ensure that personnel, in the whole area to be evacuated, perceives the alarm and initiates evacuation. This duration should be documented in the emergency procedures. Manual resets should be provided outside the zones to be evacuated. Manual resets shall have limited access.

6.3 Connections

If several components of a CAAS are connected through a link, it should be ensured that this link is protected from disruption, failure, or interference, for the system to maintain its function in situations where the CAAS function is needed.

CAAS detectors and their connections should be implemented and maintained ensuring the minimization of common-mode failure causes.

6.4 Failure of detectors, false alarms, detection logic

Occurrence of false alarms shall be minimized, as hazards associated with prompt evacuation can be significant (injuries during evacuation, non-securing of processes, loss of containment, physical security breaches, etc.) and the frequency of false criticality alarms can eventually lead personnel to become complacent to prompt evacuation, and thus to an ineffective or incomplete evacuation.

Reduction of false alarms may be achieved by requiring several detectors to coincidentally detect the nuclear criticality accident in order to trigger the alarm (e.g. a $2/n$ logic, where n is the number of detectors assigned to the surveillance of a given zone), or by adjusting the trigger threshold or position of the detectors according to the radiological level in the facility without prejudice to the detection of the MAC.

6.5 Obsolescence, replacement parts

The availability for replacement of any CAAS components should be considered to define the life cycle of installed systems. Components different from the original ones may be used, but the modified system shall meet the requirements of this document.

6.6 Supervising

The system status shall be supervised to ensure its ability to detect a nuclear criticality accident.

Personnel who are required to interrogate the status of the system shall be trained for this task.

The provision of a remote system status supervisory station, outside of the zones needing to be evacuated, should be considered.

NOTE 1 This system status supervision capability is distinct from the optional monitoring capability cited in 4.1.

NOTE 2 During an emergency response, information gathered by remote supervision can also help to safely assess the situation, such as confirming the occurrence or termination of a nuclear criticality accident.

7 Criteria for positioning

7.1 General

The positioning of the different components of a CAAS is an important step of the implementation of a CAAS. There exist different requirements for each component, detailed thereafter.

7.2 Positioning of detectors and detection zone

Annex B provides principles for the positioning of CAAS detectors. The detection zone is mainly determined by the positioning of CAAS detectors. Attenuation brought by building elements and shielding shall be taken into account. Attenuation brought by equipment should be considered.

It shall be justified and documented that all locations where CAAS surveillance is needed are included in a detection zone.

The potential failure of detectors should be considered when determining the detection zone.

In placing the minimum required detectors to cover the zone where CAAS surveillance is needed, their placement may be optimized to extend the detection zone.

NOTE 1 Such an extension of the detection zone is supported by the feedback from past accidents which shows that a nuclear criticality accident can occur in an unexpected location.

NOTE 2 Such an extension of the detection zone also allows covering zones where future activities of the facility might stand.

NOTE 3 Adequate positioning of detectors relative to each other helps ensure that during in situ radioactive source tests, only one detector is triggered at a time.

7.3 Alarm signal

The CAAS alarm devices shall be positioned so that they can be clearly perceived at all points of the evacuation zone, and in order to deter access to these zones once an evacuation has been initiated.

NOTE IEC 60860 and EN 50849 give additional information regarding sound levels required for sound systems for emergency purposes.

7.4 Positioning of other CAAS components

CAAS components should be positioned to be able to maintain the main CAAS function in the event of a nuclear criticality accident, taking into account limitations due to their design characteristics. The radiation levels can be determined using the principles in Annex B.

If the design of any CAAS component cannot guarantee the main CAAS function would be ensured in case of a nuclear criticality accident, this component shall be protected against high radiation emissions.

8 Testing

The main CAAS function (whole system) shall be tested at commissioning and periodically; adequate frequencies of these periodic tests shall be justified and documented, in accordance with the stipulations of the manufacturer.

Instrument response to radiation shall be checked at commissioning and 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; adequate frequencies of these tests shall be justified and documented; for facilities having a large number of detectors, a rolling programme of testing of detectors may be implemented. Records of the tests shall be maintained.

Periodic testing of the system should include periodic calibration of the CAAS detectors.

NOTE 1 The default frequency suggested for the periodic tests of instrument response to radiation is at least once a month.

The entire alarm system shall be tested periodically. In the case of redundant channels, care should be taken to ensure that a working channel does not mask a faulty channel. Hence, each path through the system should be regularly tested; adequate frequencies of these tests shall be justified and documented.

NOTE 2 The default frequency suggested for the periodic tests of the entire alarm system is at least once every three months.

Field observations shall establish that the alarm is either audible above background noise, or visible, throughout the zones to be evacuated as well as at all access ways to these zones. All individuals in affected areas shall be notified in advance of a test.

Function of other CAAS components shall be tested at commissioning and periodically.

Where tests reveal inadequate performance, corrective actions shall be taken without undue delay. Operations shall be adapted to this degraded performance until correction. Such an adaptation may be graded to the nature and level of the inadequate performance.

Personnel performing the tests and the corrective actions shall be trained and have a specific authorization to perform maintenance work on the CAAS.

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

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

9 Personnel familiarization

Instructions or signage regarding response to nuclear criticality accident alarm signals shall be set up at locations within the zones to be evacuated as well as all access ways to these zones.

Personnel shall be familiar with the CAAS alarm signals (see 6.2). Familiarization of personnel to procedures linked to CAAS alarm, including through drills and training, is documented in ISO 11320.

Annex A
(informative)

Elements for the definition of the minimum accident of concern

A.1 General

A basic consideration in the positioning of criticality accident alarm system detectors in a facility is the definition of the size of the “minimum accident of concern” (MAC).

A previous version of this document suggested the following definition for the MAC: “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”. According to Reference [8], this definition corresponds to a slow kinetic nuclear criticality accident for unshielded fissile solution systems. It was decided to remove this definition from the normative part of this document because its origin, its expression and its justification were not well documented and it may not apply in all circumstances.

This annex provides information to help specify a MAC, on the basis of known nuclear criticality accident history and criticality experiments, supplemented by consideration of the mechanisms governing the time evolution of the nuclear criticality accident.

A.2 General considerations

Even slow kinetic nuclear criticality accidents ($\rho < \beta_{eff}$[1)]) could lead to significant doses for personnel (in a relatively short time) if these excursions are not detected quickly. This fact, already mentioned in previous articles (for example References [6] and [7]), leads to a paradox, according to the Reference [8], for personnel close to the nuclear criticality accident. Indeed, the MAC value has no impact[2)] on the avoiding of dose for the first part of nuclear criticality accidents above prompt criticality ($\rho > \beta_{eff}$). Taking into account the fast kinetic of the accident, the CAAS cannot prevent doses resulting from the first spike even if the detection is very early and quick: it is an “unavoidable” dose. On the contrary, the MAC value has a great impact on the “avoidable” dose in case of slow kinetic accidents: the sooner this kind of accident is detected, the lower will be the doses received due to the evacuation speed of workers compared to the kinetic of this kind of accident[6]. So, a lower value of the MAC:

— will have no impact on the dose that can be avoided for fast kinetic accidents ($\rho > \beta_{eff}$),

— will save doses for personnel close to slow kinetic nuclear criticality accidents ($\rho < \beta_{eff}$),

— will increase the number of detectors for a given detection zone, and thus the cost of the CAAS, or could increase the risk of false alarm if the alarm threshold of the detectors is decreased to keep constant the number of detectors for a given detection zone.

So, a fundamental step in the MAC definition is to define if a slow kinetic nuclear criticality accident ($\rho < \beta_{eff}$) is a concern in the facility where the CAAS is installed or is going to be installed. In order to do that, the specification of the MAC will take into account the process conditions that could lead to the nuclear criticality accident and the environment (shielded cells for example)[3)]. In particular,

1) ρ is the inserted reactivity in excess of criticality and β_{eff} is the effective delayed neutron fraction of the system

2) The detection of the accident has nevertheless an interest for the avoiding of dose during the “second part” of the nuclear criticality accident. But, taking into account the diversity of the phenomenology of nuclear criticality accidents, the relative contribution of each of these two parts of the accident on the total number of fissions (so the total doses) are very variable and very difficult to predict.

3) It implies that several MAC may be defined for one facility in order to take into account the specifics of each part of the facility.

the features of the first spike are sensitive to the addition rate of inserted reactivity, to the kinetic of the fission chain reaction including reactivity feedbacks, and to the stochastic nature of the fission chain reaction (i.e. even after the critical state is reached, an initiation waiting time may occur before the first diverging fission chain reaction occurs). So, depending on the nature of the fissile material (solution, metal, powder, etc.), the kind of process (laboratory, reprocessing, fuel fabrication, etc.) and the associated faults/accident scenarios, the isotopic composition of the fissile material (HEU, LEU, civil or weapon grade plutonium) and the presence of a high neutron source background (due, for example, to spontaneous fissions or to (α,n) reactions), the MAC value could be adapted. This not only has an impact on the kinetic of the nuclear criticality accident but also on the features of the radiation particles leaving the equipment (leakage rate, energy spectrum and neutron/gamma ratio).

It should be kept in mind that the MAC definition is used for the positioning of the CAAS detectors but it is not the only parameter needed. Because the nuclear criticality accident that could occur in a facility is, by definition, not precisely predictable, an overall analysis of the assumptions made will be performed in order to evaluate the margins present in the process of determining the best location of the CAAS detectors.

The MAC is usually expressed in terms of

— doses within a given time, or dose-rates at a given distance, or

— fission yield within a given time, or fission yield rate, or

— reactivity insertion, or

— fission yield resulting in a given dose.

The third one is more linked to the neutron kinetic of the nuclear criticality accident and to the accident scenario. The first one can be more directly helpful for CAAS detectors positioning. All these parameters are linked. Given the variety of considered configurations, care should be given to the interdependencies between these parameters which are not trivial.

A.3 Past nuclear criticality accidents

The spike yields of the 22 documented process nuclear criticality accidents from 1953 through 1999 that occurred in fuel processing facilities are shown in Table A.1. Accidents that have occurred in reactors and remotely-operated critical facilities are not included, because the mechanisms or reactivity addition are not representative of process facilities.

The lessons learned from past nuclear criticality accidents occurring in process facilities[9] are quite limited due to the low number of known events (22). All accidents except one occurred with solution or slurry systems. This exception occurred with Pu metal ingots and the accident seems to be prompt critical ($\rho > \beta_{eff}$). Reference [9] reports that, at least accidents labelled #9, #18, #19, #21 seem to be delayed critical and many of them (#5, #6, #9, #10, #13, #15, #18) have a specific number of fissions within the first spike (or a specific total number of fissions) below 10^{15} fissions per litre, the value considered in References [10] and [11] as representative of the boundary between the prompt criticality accident and the delayed criticality accident for solution systems.

Conversion of fission yields in Table A.1 to dose or dose rate near the assembly is not direct and should be considered with care, taking into account the numerous unknown parameters. Estimates of the dose received in four US accidents (#4, #5, #10 and #14), along with estimates of the distance of the exposed person from the excursion, are presented in Reference [17]. These data indicate that the four accidents would each have resulted in about 10 Gy (without discriminating neutron and gamma doses) at a distance of 2 m for a normalized 10^{17} fissions in the first spike.

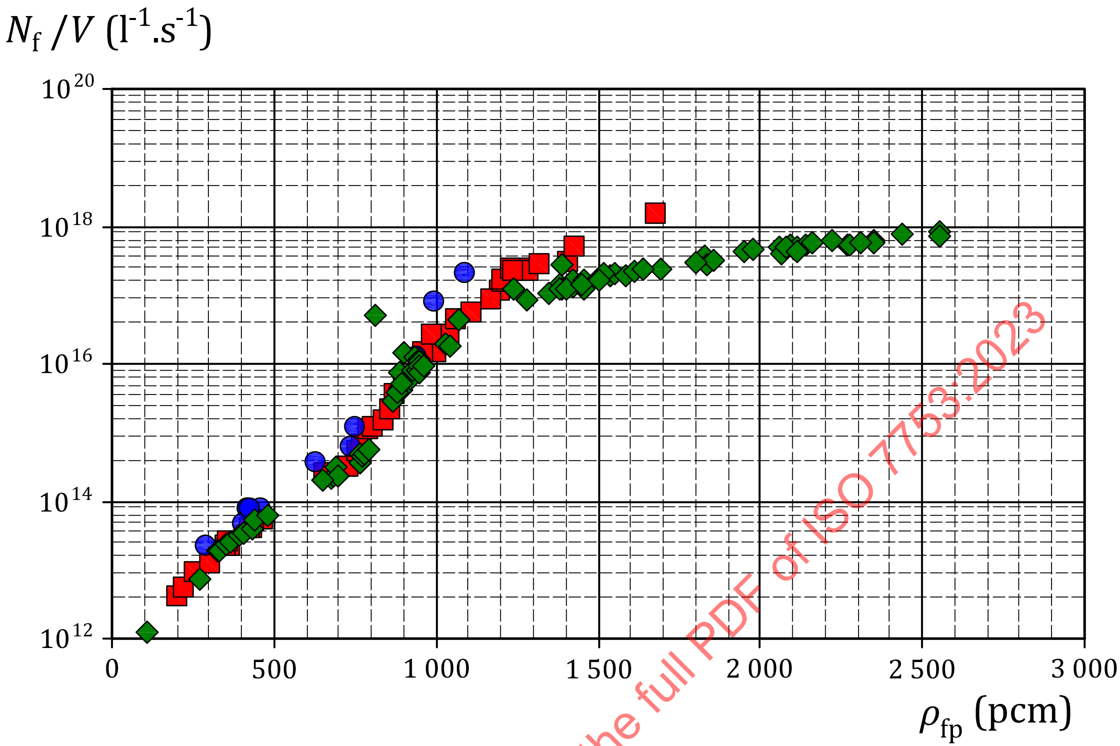
In addition, using available information from Reference [9], for nuclear criticality accidents with only “nominal” shielding (#2, #3, #15, #20 and #22), it is confirmed that for 10^{17} fissions, 10 Gy is exceeded for distances closer than 1 m.

Table A.1 — Main characteristics of nuclear criticality accidents in nuclear fuel processing plants (from ISO 16117)

No.	Site	Date (year/ month/ day)	Fuel type	Fissile media	Fuel volume l	Fissions in initial burst	Total fissions	Duration	Specific fissions in initial burst l^{-1}	Specific total fissions l^{-1}	Ratio initial burst/total %
1	Mayak	1953/03/15	Solution	Pu	31	unknown	$2,0 \times 10^{17}$	< 1 min	unknown	$6,5 \times 10^{15}$	unknown
2	Mayak	1957/04/21	Slurry	U(90)	30	unknown	$1,0 \times 10^{17}$	10 min	unknown	$3,3 \times 10^{15}$	unknown
3	Mayak	1958/01/02	Solution	U(90)	58,4	$2,0 \times 10^{17}$	$2,0 \times 10^{17}$	< 1 min	$3,4 \times 10^{15}$	$3,4 \times 10^{15}$	100
4	Y-12	1958/06/16	Solution	U(93)	56	$6,0 \times 10^{16}$	$1,3 \times 10^{18}$	20 min	$1,1 \times 10^{15}$	$2,3 \times 10^{16}$	4,6
5	LASL	1958/12/30	Solution (Org.)	Pu	160	$1,5 \times 10^{17}$	$1,5 \times 10^{17}$	< 1 min	$9,4 \times 10^{14}$	$9,4 \times 10^{14}$	100
6	ICPP	1959/10/16	Solution	U(91)	800	$1,0 \times 10^{17}$	$4,0 \times 10^{19}$	20 min	$1,3 \times 10^{14}$	$5,0 \times 10^{16}$	0,25
7	Mayak	1960/12/05	Solution	Pu	19	unknown	$2,5 \times 10^{17}$	1 h 50 min	unknown	$1,3 \times 10^{16}$	unknown
8	ICPP	1961/01/25	Solution	U(90)	40	$6,0 \times 10^{16}$	$6,0 \times 10^{17}$	< 3 min	$1,5 \times 10^{15}$	$1,5 \times 10^{16}$	10
9	Tomsk	1961/07/14	Solution (Org.)	U(22,6)	42,9	none	$1,2 \times 10^{15}$	< 1 min	-	$2,8 \times 10^{13}$	-
10	Hanford	1962/04/07	Solution	Pu	45	$1,0 \times 10^{16}$	$8,0 \times 10^{17}$	37 h 30 min	$2,2 \times 10^{14}$	$1,8 \times 10^{16}$	1,3
11	Mayak	1962/09/07	Solution	Pu	80	none	$2,0 \times 10^{17}$	1 h 40 min	-	$2,5 \times 10^{15}$	-
12	Tomsk	1963/01/30	Solution	U(90)	35,5	unknown	$7,9 \times 10^{17}$	10 h 20 min	unknown	$2,2 \times 10^{16}$	unknown
13	Tomsk	1963/12/02	Solution (Org.)	U(90)	64,8	none	$1,6 \times 10^{16}$	16 h	-	$2,5 \times 10^{14}$	-
14	Wood River	1964/07/24	Solution	U(93)	51	$1,0 \times 10^{17}$	$1,3 \times 10^{17}$	1 h 30 min	$2,0 \times 10^{15}$	$2,5 \times 10^{15}$	77
15	Electrostal	1965/11/03	Slurry	U(6,5)	100	none	$1,0 \times 10^{16}$	< 1 min	-	$1,0 \times 10^{14}$	-
16	Mayak	1965/12/16	Solution	U(90)	28,6	none	$5,5 \times 10^{17}$	7 h	-	$1,9 \times 10^{16}$	-
17	Mayak	1968/12/10	Solution (Org.)	Pu	28,8	$3,0 \times 10^{16}$	$1,3 \times 10^{17}$	> 15 min	$1,0 \times 10^{15}$	$4,5 \times 10^{15}$	23
18	Windscale	1970/08/24	Solution (Org.)	Pu	40	None	$1,0 \times 10^{15}$	10 s	-	$2,5 \times 10^{13}$	-
19	ICPP	1978/10/17	Solution	U(82)	315,5	unknown	$2,7 \times 10^{18}$	~2 h	unknown	$8,6 \times 10^{15}$	unknown
20	Tomsk	1978/12/13	Metal	Pu	0,54	$3,0 \times 10^{15}$	$3,0 \times 10^{15}$	< 1 min	$5,6 \times 10^{15}$	$5,6 \times 10^{15}$	100
21	Novosibirsk	1997/05/15	Slurry	U(70)	Unknown	None	$5,5 \times 10^{15}$	27 h 5 min	unknown	unknown	-
22	Tokai-mura	1999/09/30	Solution	U(18,8)	45	$5,0 \times 10^{16}$	$2,5 \times 10^{18}$	19 h 40 min	$1,1 \times 10^{15}$	$5,6 \times 10^{16}$	2,0

A.4 Criticality experiments

References [8], [12], [13] and [14] provide information about CRAC and SILENE experiments (highly enriched uranium solution systems) and also about SHEBA and TRACY reactors (low enriched uranium solution systems). For example, the relationship between the inserted excess reactivity during the first spike and the number of fissions per litre per second in the first spike is presented in the two following figures. The value of β for the Figure A.1 is between 700 pcm[4)] and 850 pcm.

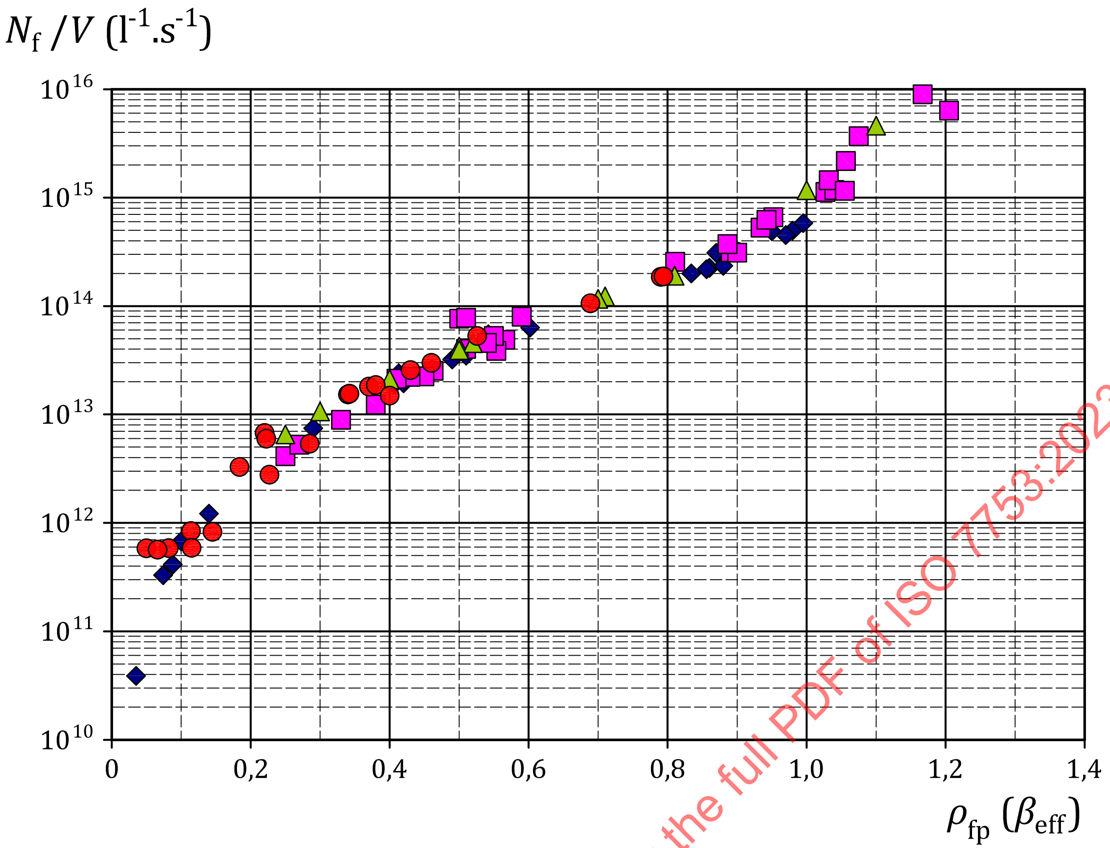


Key

ρ_{fp}	inserted reactivity in excess of criticality at the top of the first peak (pcm)
N_f / V	fission rate density: number of fissions per litre and per second at the top of the first peak ($l^{-1} \cdot s^{-1}$).
■ (red square)	CRAC 300
● (blue circle)	CRAC 800
◆ (green diamond)	SILENE

Figure A.1 — Maximum fission rate density for the first peak as a function of the inserted reactivity in excess of criticality at the top of the first peak (from Reference [14])

4) pcm stands for “per cent mille”, and is worth 10^{-5}.

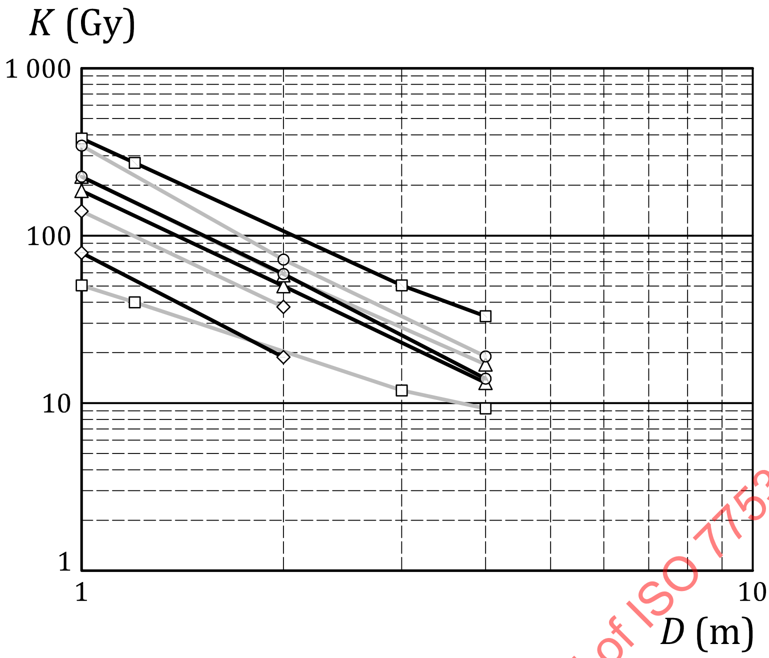


Key

ρ_{fp}	inserted reactivity in excess of criticality at the top of the first peak (β_{eff})
$N_f\ /V$	fission rate density: number of fissions per litre and per second at the top of the first peak ($l^{-1} \cdot s^{-1}$).
◆	SILENE
■	CRAC
▲	TRACY
●	SHEBA

Figure A.2 — Maximum fission rate density for the first peak as a function of the inserted reactivity in excess of criticality at the top of the first peak (from Reference [6])

Reference [13] also presents the relationship between the number of fissions and the doses at given distances for various solution and metal systems, as illustrated in the following figure. References [15] and [16] also present information for other systems.



Key

D	distance (m)
K	dose for 10^{18} fissions (Gy)
—□— (black)	CALIBAN 19,5 cm neutron dose
—□— (grey)	CALIBAN 19,5 cm gamma dose
—△— (black)	SILENE 36 cm (71 g/l) neutron dose
—△— (grey)	SILENE 36 cm (71 g/l) gamma dose
—◇— (black)	CRAC 80 cm (28 g/l) neutron dose
—◇— (grey)	CRAC 80 cm (28 g/l) gamma dose
—○— (black)	CRAC 30 cm (80 g/l) neutron dose
—○— (grey)	CRAC 30 cm (80 g/l) gamma dose

Figure A.3 — CRAC, SILENE and CALIBAN: Variation of the neutron and gamma experimental kerma tissue dose as a function of the distance to the axis of the core for different critical assemblies and for a released energy of 10^{18} fissions (from Reference [13])

The information given related to the doses might not be directly usable. Indeed, care should be given to the detection efficiency of the CAAS detectors as a function of the energy of neutron and gamma when using the previous information.

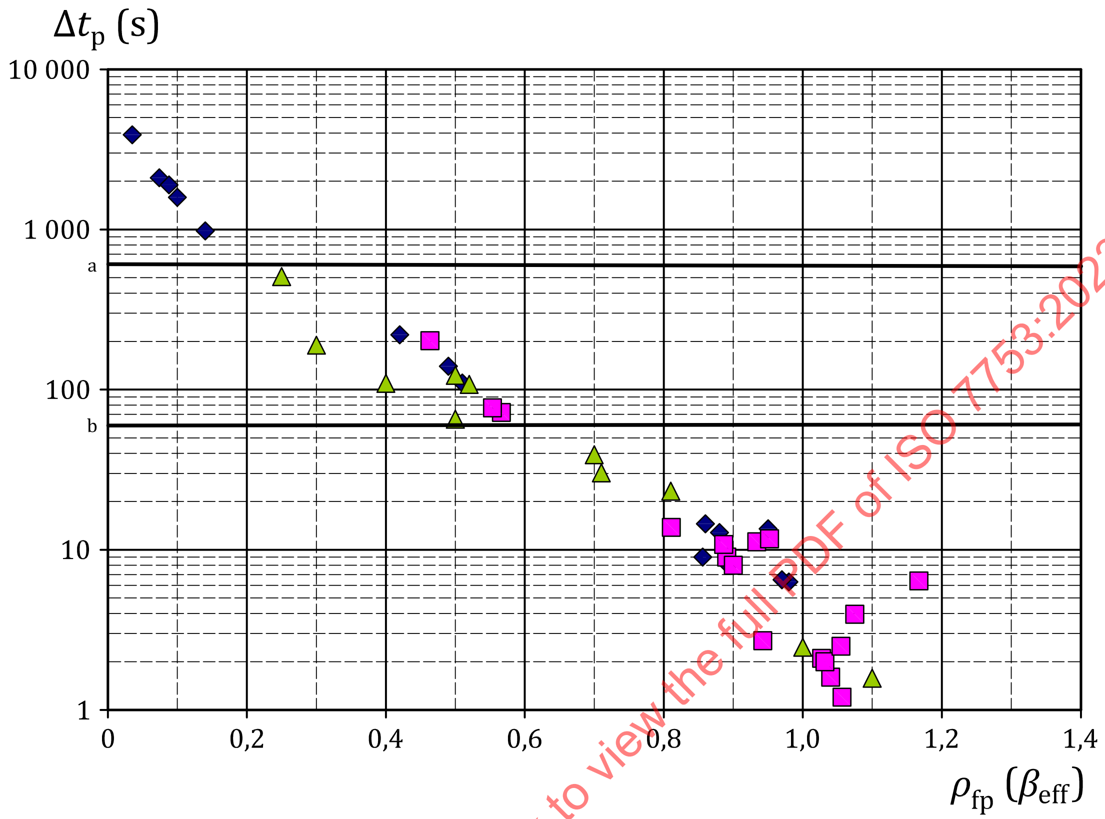
A.5 Other considerations to determine the MAC

For a slow kinetic accident, a MAC value could also be seen as a “boundary” between two methods of nuclear criticality accident detection

— CAAS that detects nuclear criticality accidents with characteristics meeting the MAC,

— other means of detection (radiological protection instrumentations, electronic personal dosimeters, etc.) that detect nuclear criticality accidents with characteristics not meeting the MAC.

The features of each method of detection should be compatible with the MAC value and should allow to limit at best the radiological consequences of the nuclear criticality accident. Additional information can be found in Reference [8]. In this case, a physical parameter important to account for is the time interval between the beginning of the divergent fission chain reaction and the moment when the maximal fission rate is reached. Indeed, the detection and the evacuation should occur as soon as possible and in any case before the maximal fission rate occurs, when the dose benefit for operators will be the most significant. It is presented for solution systems experiments in the following figure.



Key

ρ_{fp} inserted reactivity in excess of criticality at the top of the first peak (β_{eff})

Δt_p time interval between the beginning of the divergent fission chain reaction and the moment when the maximal fission rate is reached (s)

◆ SILENE

■ CRAC

▲ TRACY

a 10 min.

b 1 min.

Figure A.4 — Time interval Δt_p between the beginning of the divergent fission chain reaction and the moment when the maximal fission rate is reached as a function of the inserted reactivity in excess of criticality at the top of the first peak (from Reference [6]).

A.6 Considerations for systems other than solutions

The information presented above is mainly dedicated to solutions systems. Nevertheless, other kinds of systems can become critical. These systems are briefly discussed hereafter.

Nuclear criticality accidents with dry powder or powder with a low moderation have never occurred nor have been experimentally studied, so that the phenomenology could only be presumed.

Nuclear criticality accidents with rods in water have only occurred in reactors and critical experiment facilities. At first glance, these types of accidents can be considered in the same way as solution nuclear criticality accidents. For detection and radiological consequences, the water level above the rods may cause a large radiation attenuation, and is thus a key parameter to define a detectable MAC.

More information is available for metal systems. In addition to the metal ingots nuclear criticality accident (#20) presented in Reference [8], 15 nuclear criticality accidents occurred in reactor and critical experiment facilities with bare or reflected metal systems. All accidents, except one, resulted in a “short time” nuclear criticality accident (<1 min) also referred as a “single excursion”; for those, the total number of fissions varied from 3×10^{15} to $6{,}1 \times 10^{17}$ fissions. The 1997 Sarov nuclear criticality accident lasted more than six days and produced about 10^{19} fissions; its first spike was about 2×10^{17} fissions.

Annex B
(informative)

Principles for CAAS detectors positioning

B.1 Purpose

This annex provides an example of compliance verification of the detection criterion (see 4.3). Conformity with this criterion requires that detectors are positioned within the detection zone (see 7.2), which can be achieved through positioning the detectors as such by design, or by verifying the compliance of an existing detector positioning.

For information, documents in References [18] and [19] provide guidance for such a study.

B.2 Process description

This example takes place in a facility with two rooms:

— Room 1 is where the fissile material is present. A 90 mm thick steel shield is also present in this room;

— Room 2 is separated from Room 1 by a chicane corridor, with two 508 mm thick concrete walls.

The installed CAAS has 4 detectors, and monitors Room 1. The system is set so that the alert associated to one detector is triggered whenever this detector measures an air kerma rate higher than 60 mGy/h; it uses detectors sensitive to both gamma and neutron radiations.

NOTE Reference photon radiation fields are supposed to be calibrated in air kerma or air kerma rate (see Reference [20], 4.1). Therefore, a simple and reliable calibration of radiation instruments such as gamma-neutron CAAS detectors is achieved when instruments are also calibrated in air kerma rate. In this example, the alert threshold is expressed in total (photons + neutrons) air kerma rate. Definition of dose and kerma is provided in Reference [21].

In this example, the scenario of nuclear criticality accident that has been identified takes place at the center of Room 1. The question addressed in this annex consists in defining where the detectors should be located, taking into account several criteria:

a) each of the 4 detectors shall be able to detect the MAC occurring in Room 1 (see 4.3);

b) detectors positions are to be defined in order to extend the CAAS detection zone if possible (see 7.2);

c) a spread of the detectors is considered, in this example, in order to limit the risk of common failure.

These last two criteria lead to define the following preliminary layout for CAAS detectors:

— one detector in Room 1, on a wall near the postulated nuclear criticality accident location;

— one detector in Room 1 behind the steel shield, allowing a physical separation and distance from the first detector, which limits the risk of common failure;

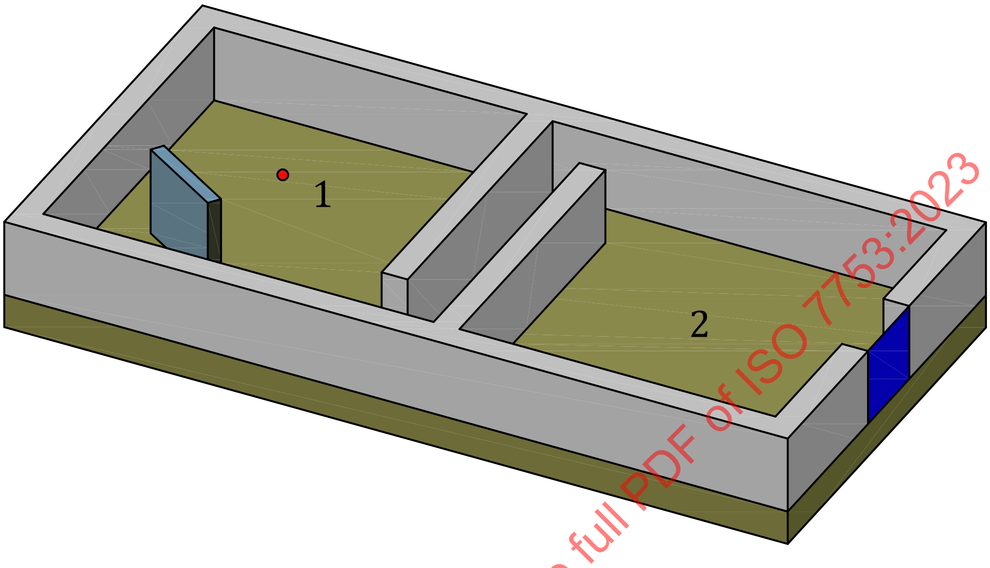
— two detectors in Room 2, allowing to limit the risk of common failure as well as extending the CAAS detection zone.

The study developed below aims to verify that it is possible to define such a layout for CAAS detectors while meeting the mandatory criterion a) on MAC detection capabilities.

The facility studied in this example is pictured below:

— Figure B.1 shows a 3D view of the facility;

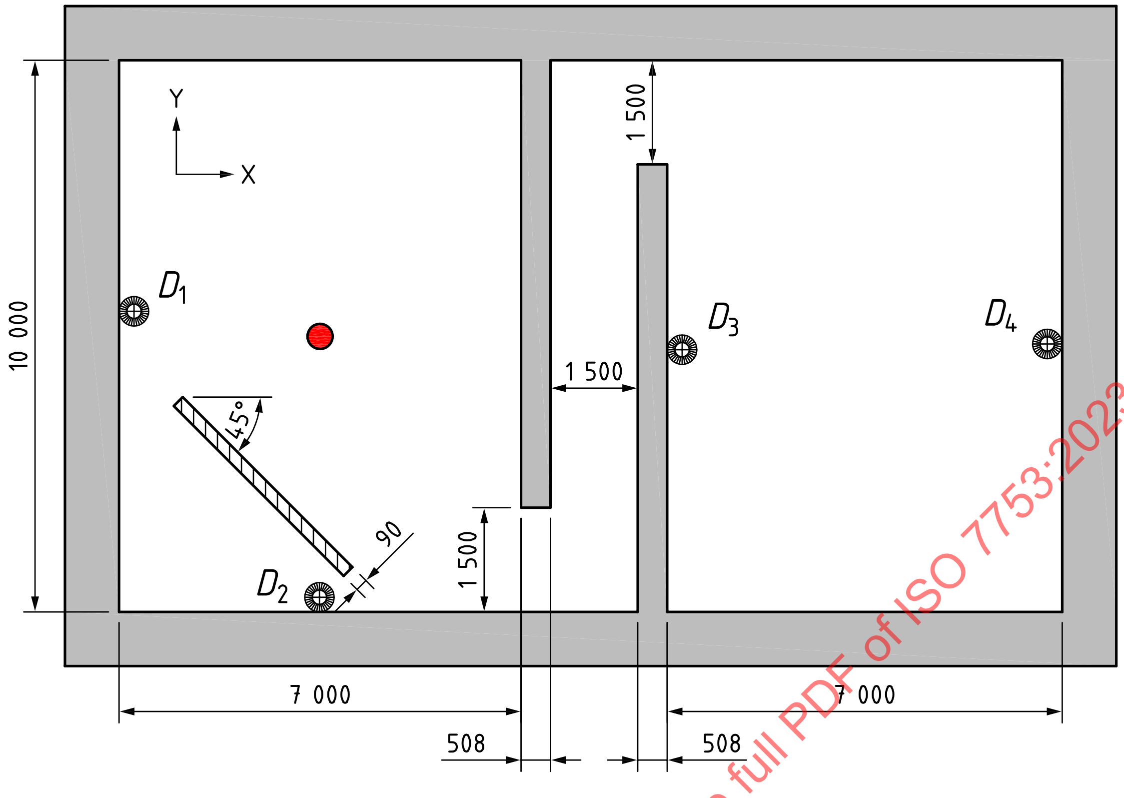
— Figure B.2 shows a drawing of the facility in a horizontal XY view. Rooms are assumed to be 3 m high (internal dimension). The postulated MAC location, at the centre of Room 1, is thus at 1,5 m above the ground.



Key

1	room 1
2	room 2
●	MAC

Figure B.1 — 3D view of the facility



Key

D_1	detector 1
D_2	detector 2
D_3	detector 3
D_4	detector 4
(grey box)	concrete
(hatched box)	steel
(white box)	air
(red dot)	MAC

Figure B.2 — Drawing of the facility with an example of a preliminary layout of CAAS detectors – horizontal XY view (dimensions in mm)

B.3 Use of the minimum accident of concern for CAAS detectors positioning

As described above, all 4 detectors shall be able to detect the MAC. The first step in a study that aims at verifying that this criterion is met is to define the MAC. Three properties of the MAC may be distinguished:

— Two extrinsic properties, that can easily be derived from an analysis of the process taking place in the facility:

  — MAC location: in this example, the MAC is assumed to take place at the center of Room 1;

  — MAC shielding: the fissile material assumed to be the cause of the nuclear criticality accident may be found inside a vessel or inside a specific container, either of which providing potential shielding that should be accounted for. In this example, for the sake of simplicity, no specific shielding is considered;

— One intrinsic property: the MAC features, which allow a quantification of the accident intensity, and its physical characteristics (spectra, self-absorption…). This clause focuses on this topic.

Regarding the size of the accident, it is postulated that an assessment according to Annex A has been conducted; the resulting MAC is a usual definition with a radiation exposure expressed as kerma. Thus, the MAC is assumed to be an accident which delivers a total neutron and gamma air kerma of 0,2 Gy at a distance of 2 m from the reacting material within 60 s.

— For detectors located in Room 1, these characteristics can be used as is. The methodology developed below only uses this data.

— For detectors located in Room 2: the methodology developed below requires data that is not given by the MAC characteristics expressed above. Gamma and neutron emission rates, as well as the associated spectra, must be evaluated. So as to enable such evaluation, it is assumed in this example that the MAC occurs in a uranium sphere defined as follows, chosen as a textbook case for illustration purposes only:

  — the radius of the fissile material sphere is 8,68 cm,

  — fissile material is made of metal uranium with 93 % ^{235}U mass enrichment,

  — its density is at the theoretical maximal: 18,94 g/cm^3.

Such an isolated sphere (in air, without reflector) has a k_{eff} equal to 1. Calculation codes (e.g. based on Monte-Carlo simulations) can then be used so as to calculate the fission rate inside this critical sphere leading to a kerma rate of 0,2 Gy/min measured 2 meters away from the outer boundary of the sphere. Results of such calculations are provided below:

— fission yield: $2{,}67 \cdot 10^{14}$ s^{-1}

— 2,583 neutrons per fission

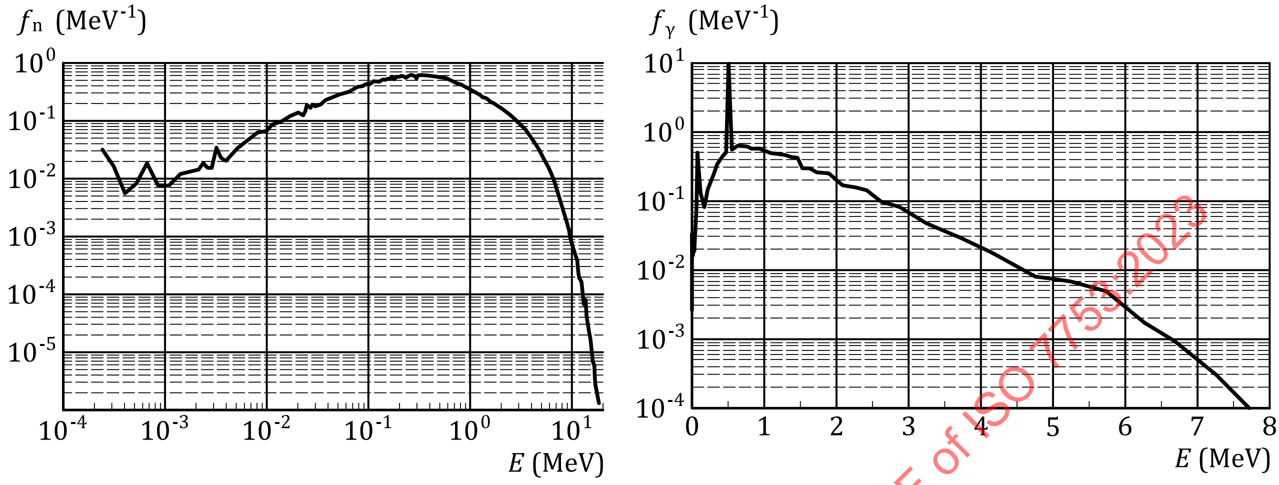
— Gamma kerma rate at 2 m = 0,054 8 Gy/min

— Neutron kerma rate at 2 m = 0,145 2 Gy/min

The associated gamma and neutron energy spectra may also be calculated (see Figure B.3).

Gamma and neutron emission rate may be derived from these data if needed; so that all the data required to define a source in transport calculation is available through these results.

a) Neutron spectrum escaping the critical sphere | **b) γ photon spectrum escaping the critical sphere**



Key

E energy (MeV)

f_n probability density for neutrons (MeV^{-1})

f_γ probability density for gammas (MeV^{-1})

Figure B.3 — Neutron and gamma energy spectra escaping the critical sphere – metal uranium with 93 % ^{235}U mass enrichment

B.4 Detection criterion compliance assessment

Detectors located in Room 1:

— For detector 1, a $1/d^2$ radiation attenuation law may be used. As a conservative approach, the highest distance D between the MAC location and the room walls is calculated:

$$D=\sqrt{5\,000^2+3\,500^2+1\,500^2}=6\,285\ \text{mm}$$

and then, the total kerma rate K_{tot} can be calculated:

$$K_{tot}=0{,}2\cdot\frac{2\,000^2}{6\,285^2}=\ 0{,}020\ \text{Gy/min} = 1{,}2\times10^3\ \text{mGy/h}$$

The alert is triggered when the total kerma rate exceeds 60 mGy/h. This simple approach shows that detectors may be placed at any unshielded location in Room 1.

NOTE 1 A simple $1/d^2$ radiation attenuation law is considered in this example. For large distances in free air (typically about 100 m or more), some effects are no longer negligible (skyshine, which omission is conservative, and attenuation in air).

NOTE 2 Reflections on walls are neglected here, which is a conservative approach.

— For detector 2, an additional attenuation by the 90 mm thick steel shield has to be considered. Note that the actual thickness crossed by neutron and gamma radiation may be higher due to the angle of incidence. In Figure B.2, detector 2 is pictured for about the maximum thickness that can be met in this example, equal to $90/[\cos(\pi/4)] = 127$ mm (5 in). Reference data can then be used, such as that provided in Figure 1 a) of Reference [22], to estimate prompt radiation dose reduction factors:

— gamma kerma rate is to be multiplied by 0,15 behind a 127 mm-thick steel shield,

— neutron kerma rate is to be multiplied by 0,25 behind a 127 mm-thick steel shield;

As a conservative approach, the total kerma rate calculated previously is multiplied by the lowest of these two coefficients. Therefore, the minimum total kerma rate K_{tot}^{min} behind the steel shield is assessed considering maximum shielding (127 mm thick steel) and maximum distance (6 285 mm):

$$K_{tot}^{min} = 0,15 \cdot 1,2 \cdot 10^3 = 1,8 \cdot 10^2 \text{ mGy / h}$$

Considering the significant margin with the detection criteria (60 mGy/h), the detector may be placed anywhere behind the steel shield.

NOTE 3 The reference data that is used must be chosen with special care. Reduction factors strongly depend on gamma or neutron spectra, as well as distance, which depend themselves on the fissile material where the accident is assumed to take place.

Detectors located in Room 2:

Thereafter, the simplified methodology developed in Room 1 is applied first, showing its limitations in this configuration. A more complete approach, based on numerical simulations, is then presented.

— *Simplified approach:*

The kerma rate attenuation with distance may be calculated using again the $1/d^2$ attenuation law. The maximum distance D between the accident location and Room 2 walls is calculated:

$$D = \sqrt{5\,000^2 + 13\,016^2 + 1\,500^2} = 14\,024 \text{ mm}$$

Attenuation brought by a 508 mm-thick concrete (20 in) shield is provided in Figure 1 a) of Reference [22]:

— gamma kerma rate is to be multiplied by 0,05,

— neutron kerma rate is to be multiplied by 0,008.

There are two concrete walls, each of them being 508 mm-thick. As a first approximation, one can assume that the total neutron kerma rate reduction is given by multiplying the kerma rate by $0,008^2$ = $6,4 \cdot 10^{-5}$.

This leads to calculate a conservative minimum kerma rate K_{tot}^{min} value in Room 2, just behind the wall, where detector 3 is located, as follows:

$$K_{tot}^{min} = 0,2 \cdot \frac{2\,000^2}{14\,024^2} \cdot 0,008^2 = 2,6 \cdot 10^{-7} \text{ Gy / min} = 0,016 \text{ mGy / h}$$

This kerma rate is far too low to trigger the detectors, the assumed alert level being at 60 mGy/h in this example. A more favourable distance could be used in this calculation, which would also lead to a very low kerma rate: 0,085 mGy/h for 6 016 mm.

This approach leads to over-conservative results in this case, as it neglects the contribution of the particles scattering through the chicane. In the above example for Room 2 it may be useful to perform a calculation for K_{tot}^{min} based on a more favourable location in the room. This may reveal position(s) where a detector might be located to detect the minimum accident of concern (MAC). Also, a significant contribution may be brought by secondary gamma photons produced by (n,γ) reactions in the concrete wall.

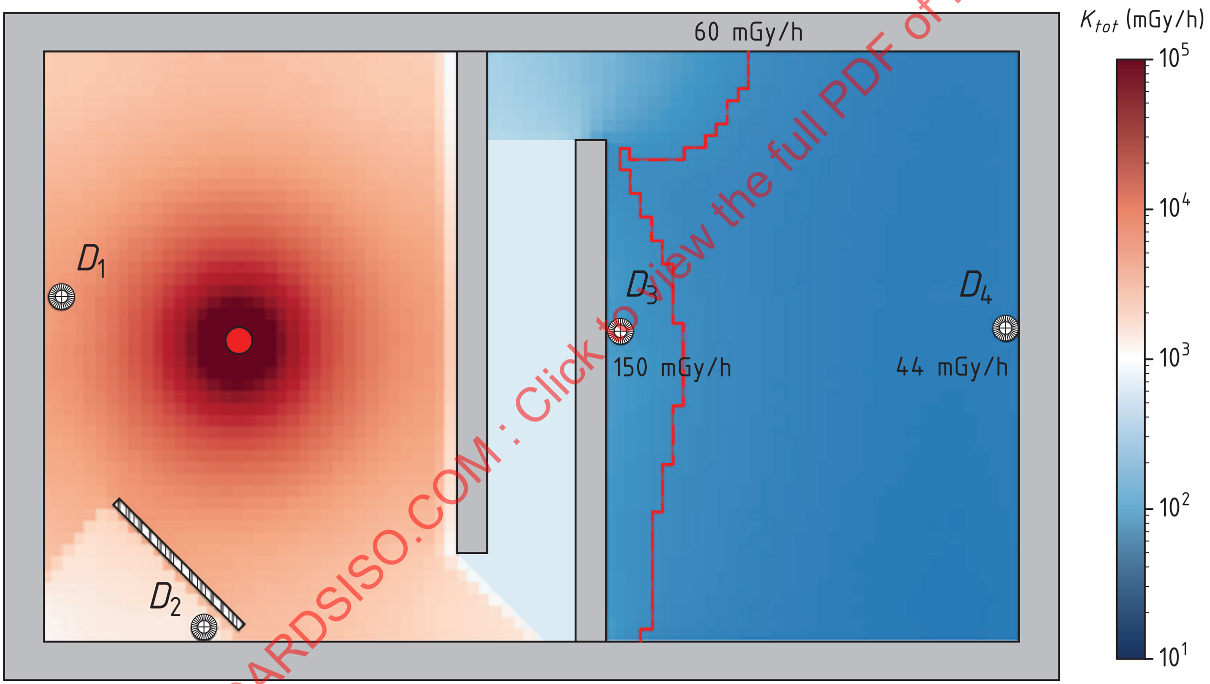
— *Numerical simulation approach:*

Using the neutron and gamma sources defined in the MAC description (B.3), numerical simulations may be run so as to compute total kerma rate maps in Rooms 1 and 2. Monte Carlo codes are a common choice to perform such calculations, as they include accurate modelling of relevant phenomena such as scattering; other options are available, each having a different precision/cost balance.

To serve that purpose, rooms may be divided in voxels in which the total kerma rate is calculated as the sum of contributions from gamma, neutron, and secondary gamma resulting from interactions of neutrons with matter. Calculation options should be chosen carefully for this kind of simulation.

In this example, calculations have been performed using MCNP6[19].

An X-Y view of the total kerma rate map obtained is presented below in Figure B.4, at 1,5 m height, which is the height where the MAC occurs. This map also pictures the computed iso-kerma rate line at 60 mGy/h. Note that the total kerma rate value calculated at detector 3 is 150 mGy/h, many orders of magnitude greater than the simplified methodology result of 0,016 mGy/h.



Key

D_1 detector 1

D_2 detector 2

D_3 detector 3

D_4 detector 4

concrete

steel

air

MAC

Figure B.4 — Total kerma rate K_{tot} map