REPORT

IRSN
INSTITUT
DE RADIOPROTECTION
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Enhancing nuclear safety

ANALYSIS GUIDE

NUCLEAR CRITICALITY RISKS AND THEIR PREVENTION IN PLANTS AND LABORATORIES

DSU/SEC/T/2010-334 - Index A

PLANTS, LABORATORIES, TRANSPORTS
AND WASTE SAFETY DIVISION
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Requested by	
Request reference	
Action Sheet Number	AF10.29
Report reference	DSU/SEC/T/2010-334 - Index A

ANALYSIS GUIDE

CRITICALITY RISKS AND THEIR PREVENTION IN PLANTS AND LABORATORIES

This report is intended to provide support for the implementation or assessment of a criticality risks analysis. After a brief description of these risks and the principles of prevention in plants and laboratories, and a reminder of the French Basic Safety Rule (BSR) No. I.3.c, it presents in diagrammatic form (i) the methodology recommended by this BSR, and (ii), for the reference fissile medium and for each criticality control mode, the parameters to be considered in the analysis, the failures to be investigated, and the typical scenarios associated with these failures without claiming to be exhaustive.

This report is the translation of the French version of the nuclear criticality guide referenced IRSN/DSU/SEC/T/2010-105 - Index A.

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Dates	2011-09-06	2011-09-06	2011-09-06	2011/09/12	2011-09-15
Visas	[signature]	[signature]	[signature]	[signature]	[signature]

*report under quality assurance

ISSUE: Free ☒ Internal ☐ Limited ☐

REVISIONS

Index	Date	Author(s)	Pages or modified paragraphs	Description or comments
A	2011-09-15	C. GALET I. LE BARS		The following persons contributed to creating this guide: Patrick Cousinou, Véronique Rouyer, Christophe Barrière, Régis Cousin, Gilles Daumen, Fabien Duret, Stéphanie Kanamori, and Julien Rannou.

ABSTRACT

KEYWORDS

Nuclear criticality, prevention, guide, analysis, basic safety rule

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[2] Que sais-je ? La neutronique – Paul Reuss – Puf - 1998

[3] LA-13638 – A Review of Criticality Accidents (2000 Revision) – Los Alamos

0. FOREWORD

This report first describes the nuclear criticality risks and the prevention principles adopted in plants and laboratories, and reminds the French Basic Safety Rule (BSR) No. I.3.c. Diagrams are then used to introduce (i) the methodology recommended by this BSR, and (ii), for the reference fissile medium and each criticality control mode, the parameters to be considered "**conventionally**" in a analysis, the "**typical**" failures to be investigated, and the "**standard**" scenarios associated with these failures.

These diagrams, developed by IRSN and subject to change as feedback is received from experience in operating facilities or in implementation analyses and assessments, constitute a guide to the analysis of nuclear criticality risks, whether this is for compiling safety documents or for assessing them.

As regards the possibility of modifying this guide, a sheet to be used for suggesting changes, intended for users of the guide, is provided on the last page of this report.

Lastly, this guide is nothing more than the compilation of the "conventional" and "essential" precautions for preventing nuclear criticality risks. Although these precautions must always be kept in mind, the reader should never forget that each configuration is a special case and that there may be scenarios that apply only to this particular case. It is therefore appropriate to remind here that all criticality accidents are the result of failures and incident scenarios that have not been considered in the analysis.

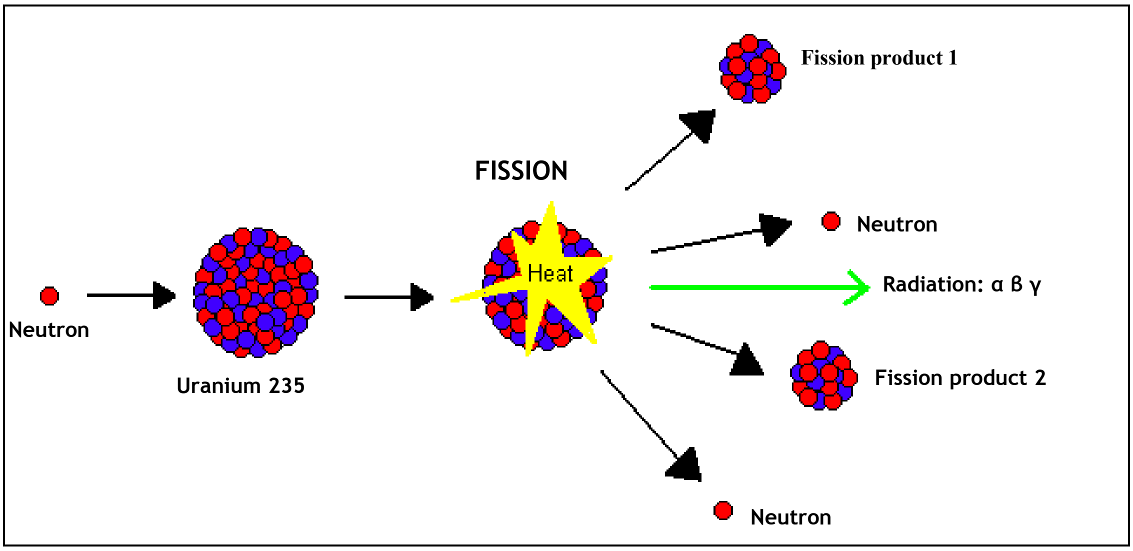
This guide is therefore a tool which is not intended to be exhaustive, and does not replace the necessary analysis to adapt to every situation.

1. NUCLEAR CRITICALITY RISKS

Some nuclides, such as the uranium-235 isotope or the plutonium-239 and -241 isotopes, have the property of being fissionable, i.e., they can split into two fragments, called fission products. This nuclear reaction may be "spontaneous", or "induced" by a particle (for example a neutron) interacting with the atom.

A fission reaction leads to a release of energy, the production of gamma radiations and the emission of neutrons (two or three neutrons on average) which may in turn induce new fissions (see Figure 1). Materials composed of these elements may thus be the site of fission chain reactions.

Figure 1: The fission reaction of ^{235}U



When each fission leads to an average of more than one other fission, the number of fissions, and thus the ionizing radiations, increase exponentially: we then speak of a divergent chain reaction. If such a phenomenon occurs accidentally in a nuclear facility (a plant or a laboratory) or during the transport of fissile materials, it can expose persons in the vicinity of the involved equipment to severe or even lethal radiations. Thus, we speak of a criticality accident, which moreover leads to the production of fission products, including fission products in gaseous form. These fission products may lead to a radioactive release into the environment which is generally of limited extent.

So, it is therefore imperative to avoid reaching conditions that could lead to a divergent fission chain reaction (i.e., a supercritical configuration). The area of nuclear facility safety associated with the prevention of criticality risks is commonly referred to as "nuclear criticality safety".

The nuclear criticality risks must be considered at every stage of the fuel cycle involving plutonium, uranium, and/or certain minor actinides (like for instance curium, americium, etc.). This includes uranium enrichment and conversion plants, plants for plutonium- and/or uranium-based fuels manufacture, spent fuel reprocessing plants, research laboratories involving fissile materials, effluent-treatment and waste-packaging facilities and storage and transport of fissile materials (fuels, radioactive wastes, etc.).

It is not necessary to have a complex process or large quantities of fissile materials to initiate a divergent fission chain reaction. About 0.5 kg of plutonium 239 or 48 kg of uranium like the ones used to manufacture the fuel for PWR or BWR power plants may be enough, in a spherical geometrical configuration with the presence of water. By way of comparison, a 17 x 17 PWR fuel assembly contains more than 400 kg of uranium in a specially-designed geometrical configuration. On the other hand, it is possible to handle relatively large quantities of fissile materials as long as there is strict compliance with a set of parameters ensuring that the criticality conditions will not be met.

The goal of nuclear criticality risks analysis is to define the necessary and sufficient provisions (design and operational) to avoid the triggering of a divergent fission chain reaction when fissile materials are present.

Simply expressed, the nuclear criticality risks analysis consists of connecting (i) the possible configurations of the fissile materials, in light of the actions that might be taken during operations and the changes that might be caused by possible failures (error, failures of a component, etc.) or by accidental situations (fire, earthquake, etc.), and (ii) the margins between these configurations and potentially critical ones. Nuclear Criticality Safety depends on the strict control of these actions.

So, the nuclear criticality risks are mastered by preventive provisions implemented to control the configurations in which the fissile materials are placed. These provisions are expressed in practice by operational constraints which, for example, consist of limiting the quantities of handled materials, the dimensions of the equipment containing fissile materials, and/or the concentrations of fissile materials in liquid media or by employing special materials known as neutron absorbers (or poisons).

In addition, depending on the particular nature of facilities, criticality detection and alarm systems may be installed to enable the prompt evacuation of personnel. However, these systems are triggered only after the initiation of a chain reaction and do not prevent the emission of the radiation associated with the first moments of the accident (which may lead to lethal doses for nearby operators). On the other hand, the consequences for the environment of such an accident are limited in range. The releases of radioactive fission products comprise only a few rare gases and very small amounts of iodine. Furthermore, the radiations are attenuated by walls and other radiation protection shields, and decrease when distance increases.

The following paragraphs of this guide describe the principal features of an analysis of the nuclear criticality risks prevention.

Users of this guide may obtain more information by consulting the documents listed in references [1] to [3], or other sources.

2. PARAMETERS AFFECTING THE NEUTRON BALANCE

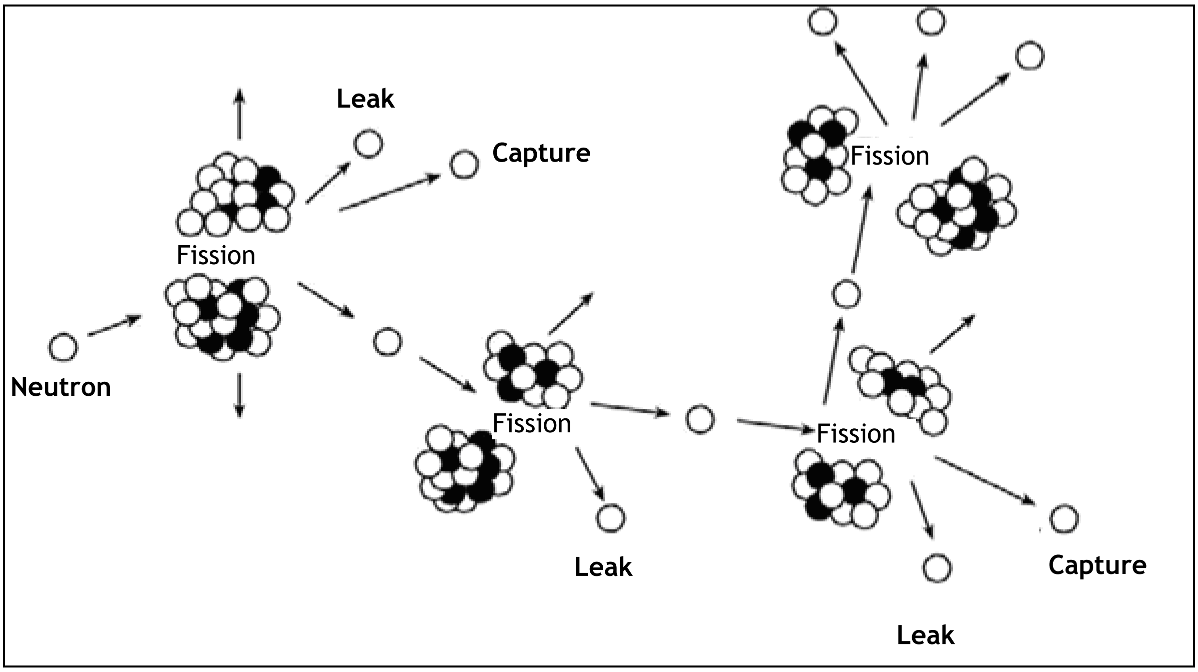
2.1 Neutron balance

One of the most important steps in the nuclear criticality risks analysis is the definition of the worst-case configuration for the fissile material in light of the configurations to be encountered and the actions and operations likely to occur. The identification and precise definition of this configuration is of course dependent on an understanding of the basic phenomena of neutronics.

The fission of the nuclide (uranium 235, plutonium 239, plutonium 241, etc.), caused by a neutron, liberates several neutrons, two or three on average. Neutronic phenomena (associated with the interactions of neutrons with matter) concern a very large number of nuclides and involve notions of probability (or of cross-section, that is the probability of interaction of the neutron for a given reaction). Neutrons emitted in this way, after diffusion into the material, have three possible fates (see Figure 2):

- to be absorbed by fissile nuclides and cause new fissions (can be qualified as fissile capture);
- to be absorbed by nuclides and "stay" in the nuclide, which then changes its atomic number. In some cases, this reaction may lead to the production of a fissile nuclide, as in the case of uranium 238, which - following several nuclear reactions - is transformed into plutonium 239 (this is qualified as fertile capture). In most cases, the reaction leads to the production of a non-fissile nuclide: for example, boron 10 (20% of natural boron) which is transformed into boron 11 (this is described as sterile capture);
- to escape from the concerned system (neutron leakage), for example from the tank containing the fissile solution.

Figure 2: Neutron balance



Thus, neutrons cause fissions which generate neutrons which in their turn cause other fissions (fissile captures), and so on. This production of neutrons, if it is not offset by a sufficient loss (by fertile or sterile captures and/or leakage) leads to an exponential increase in the number of neutrons and to a criticality accident.

The characteristic value of the "neutronic" state of a configuration is the balance between its abilities on the one hand to produce neutrons by fission, and on the other hand to lose them by fertile and sterile captures and/or by leakage. This balance is expressed by the neutrons' effective multiplication factor (usually denoted by keff), which indicates the factor by which the number of fissions is multiplied from one generation of neutrons to the next one.

$$keff = \frac{N'}{N} = \frac{Production}{Absorption + Leakage}$$

where N is the number of "neutrons fathers" (generation n - 1) having disappeared by absorption or leakage and giving birth to N' "neutrons sons"(generation n).

- If keff < 1 (Production < Absorption + Leakage), the configuration is sub-critical; this is the wanted safe state for nuclear facilities (excluding reactors).
- If keff = 1 (Production = Absorption + Leakage), the configuration is critical; this is the equilibrium state encountered in a nuclear reactor (controlled reaction), which must not be reached in other nuclear facilities.

- If keff > 1 (Production > Absorption + Leakage), the configuration is supercritical; this state corresponds to a criticality accident.

This neutron balance depends both on the characteristics of the fissile medium (in particular the physico-chemical nature and its isotopic composition which determine the fissile and fertile captures) and on the geometry of the medium (which determines the proportion of neutrons able to escape).

For example, for uranium, the limits depend on the content of isotope 235. Thus, the minimum mass in a spherical shape that could lead to a criticality accident (under conditions favorable to the reaction) is 0.87 kg for highly-enriched uranium (93.5% ^{235}U), 5.2 kg for an enrichment of 20%, and 48 kg for an enrichment of 4%.

2.2 Production of fission neutrons

The production of fission neutrons depends on the quantity of fissile nuclides present in the given fissile medium, which will directly affect the overall probability of the capture of neutrons by a fissile nuclide. As shown in the previous paragraph, there is a mass below which a self-sustaining fission reaction is no longer physically possible. The criticality of a medium may therefore be controlled by **limiting the mass of fissile material**.

In practice, this criticality control mode is applicable at the scale of an equipment, a glove box, a cell, or even a whole laboratory employing small quantities of fissile materials. The mass limits for fissile materials associated with this criticality control mode, considered by itself (i.e., not in combination with a geometry or a moderation limit), are generally incompatible with facilities of an industrial nature.

Compliance with the mass limits associated with this criticality control mode implies the establishment of procedures that impose strict operating constraints (fissile material accounting, controlled transfers of materials, and control of fissile material accumulations) and has the disadvantage of being vulnerable to "human factor".

Since most fissile nuclide have a fission cross-section (equivalent to a probability of fission) that is larger for low-energy incident neutrons, any process that tends to diminish the energy of the neutrons will favour fission reactions. At their moment of "birth" following a fission, neutrons have an energy of about two million electron volts (2 MeV) and their probability of capture by a fissile nuclide to produce a fission is relatively low. As they move through the material, the neutrons progressively lose their energy during collisions with nuclides in the medium, which increases their probability of being captured and thereby causing fissions. This process of neutrons slowing down by diffusion without capture, during successive collisions with the nuclides of the given medium, is called thermalization or **moderation,** in the technical jargon.

The energy lost by the neutrons during their collisions with the nuclides in the medium is greater when these nuclides are lighter. One of the "champion" moderators is hydrogen, whose the nucleus consists of a single proton which has the same mass as a neutron. This explains the special role played by water in the prevention of nuclear criticality risks: its molecule contains two hydrogen atoms.

By way of illustration, in the presence of water (and therefore of hydrogen), the minimum mass - under the most favorable conditions for reaction - able to provide a "keff" of 1 is about 0.5 kg for plutonium 239, whereas it is 4.5 kg in the absence of water. For certain fissile materials, such as uranium enriched to at least 6.6% of isotope 235 in oxide form, simply keeping the material rigorously free of materials containing hydrogen (or any other moderating material) is enough to eliminate any danger of nuclear criticality, even in the presence of large quantities of fissile material.

The nuclear criticality of a material can thus be controlled by **limiting the moderation**, i.e., mainly by limiting the quantity of hydrogen.

It should be noted that other "light" nuclides such as carbon and beryllium can also provide significant neutron moderation. However, they are less common in the fissile materials encountered in facilities, and the required quantities are generally greater.

2.3 Neutron leakage

During their move through the material, some neutrons may escape from the fissile medium which gave them rise. In this case, they no longer take part in sustaining chain reactions. This neutrons leakage is favoured by:

- a low density of the fissile medium and the presence of nuclides (in the medium) that interact weakly with neutrons (in both cases, the neutrons can move greater distances without a collision);
- low average distances to be crossed by the neutrons to reach the borders of the fissile medium.

Simply keeping the fissile material in equipment with dimensions that are small enough in at least one direction may be enough to eliminate any nuclear criticality risk (equipment with a small diameter, low thickness, etc.).

In this case, the nuclear criticality is controlled by **limiting the geometry of the equipment**.

This criticality control mode is preferred when the constraints on dimensions are compatible with the processes. It is not sensitive to the "human factor", but must be adopted at the design stage of the equipment (dimensioning for earthquakes, corrosion, accidental deformations due to increases in pressure and temperature, etc.). Note that provisions must be taken when modifying or changing equipment, to ensure the correct geometry. Any connections between safe geometry equipments and unsafe geometry equipments must also be carefully controlled.

The neutrons that escape from a fissile medium continue their trajectories in the surrounding materials and, following collisions with the nuclides of these materials, they are captured or sent back to the fissile source medium: **this latter phenomenon is called neutron reflection**. In plants, the rooms walls, the equipments walls and also persons constitute reflectors capable of limiting neutrons leakage. The nuclear criticality safety analyses must take this phenomenon into account.

Lastly, when several pieces of equipment containing fissile materials are close to one another a final factor **called interaction** is liable to become involved. A fraction of the neutrons escaping from a piece of equipment may enter an adjacent apparatus that also contains fissile material, and cause fission there. This neutronic coupling thereby can increase the reactivity (or "keff") of the studied system.

2.4 Neutron absorption

The disappearance of neutrons, following non-fissile captures, leads to a decrease of the "keff", which is favourable to maintain the sub-criticality in a fissile medium. Nuclides that are frequently encountered in fissile materials may lead to the fertile capture of neutrons and thereby limit the risk of nuclear criticality. The main examples include the uranium-238 and the plutonium-240 isotopes (in the thermal spectrum). Their content in the fissile material, as long as it can be guaranteed, can be taken into account in determining **the reference fissile medium** (see definition § 3).

In addition, four natural elements are particularly effective for capturing neutrons (sterile captures). These are boron (isotope ^{10}B), cadmium, hafnium, and gadolinium (isotope ^{155}Gd).

They are commonly used in the equipments either in a homogeneous form (dissolved in fissile solutions) or in a heterogeneous form (as a screen) because of their neutron-absorbing properties, to ensure that the nuclear criticality risks are averted.

The control of the nuclear criticality is then carried out by "**poisoning**".

Apart from these four strongly neutron absorbing materials, other nuclides may lead themselves to sterile captures. It may be useful to consider them when determining the neutron balance. Among the common elements, we note chlorine, nitrogen, iron, etc. and in certain circumstances hydrogen. This is why aqueous solutions containing low concentrations of fissile materials (and therefore large quantities of hydrogen) are sub-critical, even if they are present in very large volumes, due to the "poisoning" provided by the hydrogen in the water.

The control of the nuclear criticality is then obtained by **limiting the concentration** (of fissile materials).

Hydrogen has the properties of a moderator (which can increase the reactivity) and also of a neutron absorber (which decreases it). Since the probability of a neutron being captured by a nuclide increases with the moderation, the reactivity of a medium varies with the quantity of hydrogen present and has a maximum value. This maximum is called **the optimal moderation**.

Lastly, for operations involving "spent" (irradiated) fuels, it is possible to take into account the absorption of neutrons by certain fission products, as long as their presence can be guaranteed. Stable and non-volatile isotopes like samarium-149, samarium-152, gadolinium-155, cesium-133, neodymium-143, rhodium-103, and molybdenum-95 make significant contributions to sterile captures and could be used to provide evidence of the sub-criticality of a configuration. However, the validation of the basic data associated with these fission products and the calculation biases evaluation methods incorporating them are still the subject of considerable development work.

3. THE PREVENTION OF NUCLEAR CRITICALITY RISKS (CRITICALITY CONTROL MODES AND REFERENCE FISSILE MEDIA)

The previous paragraphs present multiple means to prevent the nuclear criticality risks. They indicate that by simply limiting one or more "operating" parameters it may be possible to keep a system containing fissile materials in a sub-critical state.

These parameters may be the concentration of fissile materials in solutions, the dimensions of the equipments, or the quantities of fissile and moderating materials. Neutron-absorbing materials (or neutron poisons) may also be used.

In a safety analysis, the first step - depending on the process, the type of fissile materials, and the maximum flows of considered materials - consists of selecting the parameter(s) that will enable sub-criticality to be ensured in a particular working unit (or criticality unit[1]). This step ends with the choice of a **criticality control mode** (geometry, mass, moderation, concentration, poisoning) and one or more reference fissile media. In general, this choice is largely determined by the employed process, its dimensioning (capacity), but also by the need to limit the operating constraints.

The reference fissile medium is a "bounding" fissile medium which, compared to fissile media likely to be encountered in the operating facility (in normal or abnormal conditions), leads to the lower limits, taking into account the adopted criticality control mode. For a given part of equipment, a reference fissile medium may differ according to the analysed scenarios (especially if these scenarios involve a change in the physicochemical form of the fissile material).

[1] A criticality unit is all or part of a facility for which overall limits are defined, in order to prevent criticality risks (common criticality control mode)

The reference fissile medium and the criticality control mode are defined for a criticality unit, e.g., a glove box, a set of glove-boxes, a cell, a transport container, etc.

In practice, **to determine the imposed limits on the parameters associated with the criticality control mode and the reference fissile medium, it is necessary (i) to find the most disadvantageous combination of parameters, in light of the selected scenarios regarding nuclear criticality risks and (ii) to deduce the associated bounding safety parameters. Parameters that are not chosen with regard to the criticality control mode may take any credible value.**

The determining of a criticality control mode, a reference fissile medium, and a criticality unit then automatically leads to the implementation of adapted means of control to comply with the parameter limits associated with the criticality control mode (weighings to check the mass, chemical analyses to check the concentration, acidity measurements to avoid any precipitation, etc.).

4. NUCLEAR CRITICALITY SAFETY ANALYSIS

A nuclear criticality safety analysis considers not only the so-called normal operating conditions, but also the conceivable malfunctionings. In this regard, the Basic Safety Rule (BSR) No. I.3.c constitutes the reference methodology in France for the prevention of nuclear criticality risks, both for the designers and the operators of facilities.

This BSR states as general principle, called “double contingency", that a "criticality accident should in no case result from a single anomaly: failure of one component or one function, a human error (e.g., non-compliance with an instruction), an accident situation (e.g., fire)" ... and that "if a criticality accident can result from the simultaneous appearance of two anomalies, it shall then be demonstrated that:

- the two anomalies are strictly independent of each other,
- the probability of occurrence of each of the two anomalies is sufficiently low,
- each anomaly is identified by appropriate, reliable monitoring systems, within an acceptable time-frame that allows response ."

This BSR further recommends that, for each criticality unit (working unit, etc.), the criticality control mode, the reference fissile medium, and the provisions concerning each of them be set out, and be consistent with the failures analysis carried out in accordance with the above-mentioned " double contingency" principle.

The text of this BSR is included in Appendix 1.

The block diagrams (based on the principles defined in the BSR) included in Appendix 2:

- summarize the analytical approach of BSR No. I.3.c;
- present, for the reference fissile medium and for each criticality control mode:
  - the associated parameters,
  - the types of failure to be analyzed and, according to the current state-of-the-art, the corresponding incidental scenarios.

These diagrams constitute a guide to the analysis of nuclear criticality risks, whether this is for compiling safety documents or for assessing them. They are developed by IRSN and subject to change as feedback is received from experience in facilities operating or in analyses and assessments of nuclear criticality risks implementation. They are presented as a list of standard questions that should be raised by the criticality expert, but are not intended to be exhaustive.

5. SAFETY MARGINS AND DESIGN CRITERIA

Safety margins are essential for ensuring the safety of facilities. In the case of nuclear criticality risks, the safety analysis must therefore define the upper safety values for each parameter, the critical state constituting a limit that must never be reached.

It is not possible to make the simplistic assumption that this safety margin can be expressed only by an "administrative" margin, predefined between the maximum value of the effective multiplication factor ("keff") of the studied configuration and the value 1 (corresponding to the critical state). The "keff" associated to some fissile materials can indeed vary very rapidly as a function of certain parameters. This applies for instance to materials comprising plutonium or highly-enriched uranium.

For this reason, the BSR does not give any regulatory criterion for a specific numerical safety margin that must be applied with regard to the "keff" value. The assessment of the safety margins for a configuration or a situation mainly addresses four criteria:

- an evaluation of the sensitivity of variation of the "keff" to the considered parameters,
- the level of conservatism involved in calculation model (simplifications of the geometry, the composition, the reflector, and the moderating material),
- the more or less probable nature of the scenario corresponding to the bounding situation adopted for the incidental and accidental (abnormal) situations,
- the level of confidence in the employed calculations techniques (here the BSR refers to a validation based on experiments).

The validation of the used calculation packages must be closely examined when the configuration being studied has a relatively high "keff". This is mainly based on comparisons of calculations with experiments. The obtained differences are then interpreted to determine the origin of the observed biases (approximations, calculation options, nuclear data) and then to transpose them to the actual configurations under consideration. For this, it is necessary to assess the representativity of selected experiments from the industrial configuration of interest. The determined bias is highly dependent on the representativity of the selected experiments and on the quality of these experiments, the experimental values always having an uncertainty associated to them.

The acceptability criteria and the criticality parameters must then be established in light of the status of the validation of these calculation packages for the studied configurations. This can potentially incorporate "fixed" margins that the expert considers adequate.

6. LIMITING THE CONSEQUENCES OF A CRITICALITY ACCIDENT

The provisions to avoid nuclear criticality risks in a facility make an uncontrolled divergence highly unlikely. Nevertheless, in view of the employed fissile materials, a criticality accident is still physically possible (if several provisions are no longer effective).

About sixty criticality accidents have occurred worldwide since 1945. About forty of these accidents took place in research reactors or in laboratories on "critical assemblies". Twenty-two accidents have occurred so far in fuel cycle facilities, in spite of safety margins that are inherently larger in this type of facility. These accidents have not caused any significant releases of radioactivity into the environment, but their substantial irradiations quickly led to twenty deaths, ten of them in fuel-cycle facilities.

Another special feature of criticality accidents is their duration, which ranges from some tenths of second to several dozen hours. In some cases, special actions (injection of a neutron poison, etc.) had to be undertaken to bring the accident to the end.

Depending on the particular nature of the facility, it is necessary to take additional provisions aimed at limiting as far as possible the consequences of a possible accident, especially for the personnel working in the facilities and for persons liable to be in the vicinity (public and response staff). These provisions are structured around three main actions: detection of the accident, organization of a prompt evacuation of the involved personnel, and if necessary, response to end the accident.

7. CRITICALITY ACCIDENT ALARM SYSTEM

Because of the kinetics, there is no initiating event of a criticality accident. Detection systems therefore use the emission of an important flux of neutrons and /or gamma ray at the beginning of a criticality accident. As a result, these systems do not allow to avoid the consequences associated with the beginning of the criticality accident which are potentially lethal for operators located nearby.

In France, the criticality accident alarm systems are based on groups of detectors, or sensors, that measure the total (neutron + gamma) dose rate, and a processing cabinet of these measurements, which operates sound and light alarms specifically associated with a criticality accident. These alarms are triggered as soon as the total dose and the dose rate reach predetermined thresholds. The detectors have been designed so as to minimize the risk of false alarm and are moreover able to provide informations about the criticality accident (development over time, evaluation of doses, etc.) that can be used for the emergency response.

8. EVACUATION

Limiting the radiological consequences of a criticality accident depends greatly on the prompt evacuation of the concerned area. The personnel must therefore have been trained to evacuate the site to assembly points, following routes defined and marked out in advance. Optimization of the locations of detectors and evacuation routes results from a study of criticality accident scenarios specific to each facility.

9. RESPONDING TO A CRITICALITY ACCIDENT

Experience acquired from various criticality accidents, in particular the most recent, which occurred in 1999 in Japan, shows that in the absence of a rapid spontaneous shutdown it may be necessary to respond to stop an accident. This response may consist of "poisoning" the medium by adding a solution or powder containing neutron-absorbing substances, transferring the involved fissile medium into a geometry that ensures a sub-critical state, eliminating a neutron reflector (by draining the water in the cooling system in the case of the Tokaï Mura accident), etc.

Responding to feedback from the Tokaï Mura criticality accident, the French safety authorities have asked the operators of facilities exposed to the nuclear criticality risks to review the resources available to them for detecting an accident, and to state the resources that can be used to stop it.

10. CONCLUSION: RIGOUR, COMPLIANCE WITH SAFETY PRINCIPLES, AND VIGILANCE

Management of criticality risks in nuclear facilities is obtained by imposing strict limits on certain clearly-identified control parameters. These limits are defined by the exhaustive study of criticality conditions in all equipments liable to contain fissile materials in normal and abnormal (degraded, incidental and accidental) operating conditions, taking into account their specific environments.

The bounding parameters for these safety studies and the configurations examined must be determined in accordance with the "double contingency" principle set out in Basic Safety Rule No. I.3.c.

The criticality calculations tools have reached a high degree of precision through the progress achieved in the neutron-processing models and in our understanding of basic nuclear data. They now enable identification of the optimum safety conditions for the majority of situations, without undue approximations. Development and validation work currently in progress seek to further improve their precision, for example for calculations concerning spent fuels, to provide a better evaluation of safety margins and, in the case of operators and manufacturers, to optimize the nuclear criticality safety constraints in technical and economic terms.

However, one of the requirements of very detailed calculations models is the need to provide a more specific justification for the validation of criticality calculation packages. This justification often runs up against a lack of criticality experiments relevant to the application in question. Research programs developed by the IRSN are directed towards a better validation of the available calculations tools.

In any event, the criticality calculations results must be used only as supports for nuclear criticality assessments, and must always be seen in perspective and carefully applied.

Finally, regardless of the effort put into the design of the facilities, it should not be forgotten that the nuclear criticality risks prevention is ensured by people !

Failures in the "human chain" observed during criticality accidents around the world show, in this regard, throughout the importance of training and organization in controlling nuclear criticality risks, and the importance of vigilance on the part of every actor, i.e., of the good safety culture.

French Basic Safety Rule No. I.3.c[2]
(October 18th, 1984)

Volume I: Overall concept and general principles applicable to the whole of facility;
Chapter 3: Regulations applicable to the prevention of risks due to ionizing radiations;
c) Criticality risks.

Area of application: Nuclear facilities other than nuclear reactors.

The criticality-safety depends on the implementation of systematic and rational prevention techniques organized on the principle of "defense in depth". It's based specifically on the principle that a criticality accident should in no case result from a single anomaly. All the regulatory recommendations of a general nature, applicable to the criticality risks prevention in laboratories and facilities other than nuclear reactors are subject to the publication of a basic safety rule whose text is reproduced below.

I - Purpose of the rule

This rule is intended to set out the provisions taken to avoid the risk of a criticality accident in nuclear facilities (other than nuclear reactors) in which fissile materials are handled. From these facilities, we can mention uranium-enrichment facilities, fuel fabrication facilities, spent-fuel reprocessing facilities, fuel storages, etc. Excluded from the provisions of this rule are facilities or parts of facilities, in which only uranium with no more than one percent of isotope 235 is used, as long as this uranium is not in the form of a system of rods arranged in graphite or in ordinary water or in water enriched in heavy water. Also excluded, facilities or parts of facilities in which only fuel elements composed of uranium with an isotope 235 content smaller than one percent are handled, as long as these elements have not been irradiated in fast-neutron reactors, or do not undergo a chemical treatment liable to change the proportions of the fissile isotopes present.

Note: The terms used in this basic safety rule are defined in the glossary, attached as appendix 1.

II - General provisions intended to avoid a risk of criticality

II.1 - Definition of control modes

An appropriate criticality-safety control mode shall be adopted for each of the facility's functional units. This control mode shall be defined by an upper limit imposed on one or more of the following parameters:

- mass of fissile materials,
- geometrical dimensions of the equipment,
- concentration of fissile materials in solutions,
- moderation ratio for dry or semi-dry products,

taking into account the presence of neutron absorbers.

These limits shall be set for a reference fissile medium, taking into account the reflecting environment and interactions. The reference fissile medium is the one which, among all those that might be encountered in the concerned unit, under normal or abnormal operating conditions, leads to the lowest limits based on its content of fissile materials, its composition, and its density law.

[2] Original official French version (RFS n° I.3.c) is available on http://www.asn.fr/

II.2 - General principles

The following principles shall be applied both in the design and in the operation of the facilities:

- a criticality accident should in no case result from a single anomaly: failure of one component or one function, a human error (e.g., non-compliance with an instruction), an accidental situation (e.g., fire), etc.,
- if a criticality accident can result from the simultaneous appearance of two anomalies, it shall then be demonstrated that:
  - the two anomalies are strictly independent of each other,
  - the probability of occurrence of each of these two anomalies is sufficiently low,
  - each anomaly is identified by appropriate, reliable monitoring systems, within an acceptable time-frame that allows response.

II.3 - Provisions concerning the various control modes

II.3.a - Control by mass of fissile material

When this control mode is adopted, a safe mass of fissile material is fixed for each working unit. If it is recongnized that the critical mass can be reached as the result of a single anomaly, in accordance with the principle given in Paragraph II.2 - , the safe mass of fissile material in the working unit in question shall be no more than half the minimum critical mass for the reference fissile medium. This limit may be lowered to take into account possible neutron interactions with the masses of fissile material in the adjacent working units.

The total mass of fissile material present in the working unit shall be estimated in order to confirm that this mass is at any time smaller than the established limit.

In order to prevent any excessive accumulation of fissile material, regular inspections of the working unit shall be performed, followed if necessary by cleaning.

II.3.b - Control by geometry of equipment

This type of control mode is mainly used in facilities or parts of facilities where the fissile material is in the form of concentrated solutions.

Provisions shall be taken in order to prevent the following situations or to overcome their consequences:

- accidental deformation of equipment: consideration, at the design stage, of the risk of a rise in pressure or temperature, and of external causes of modification (earthquake, movements of heavy loads nearby, fire, etc.);
- leaks or overflows of fissile materials solutions from equipments: manufacture of the equipments in the appropriate quality class, setting-up, underneath them, of drip-trays capable - under sub-critical conditions - of containing the largest volume of fissile material solution liable to be spilled, and fitted with fluid detectors and with means of recovery;
- transfer of fissile material solutions into unsafe geometry containers, located in auxiliary circuits (vents, vacuum, reagents, heating, cooling, etc.);
- placing of movable containers against the equipments: safe geometry movable containers, in limited numbers, if necessary, surrounded by a rigid structure that ensures sufficient spacing from the fixed equipments.

It may be necessary to establish circuits that allow the transfer of solutions between safe geometry equipments and others with unsafe geometry. There are two possibilities:

- the unsafe geometry equipments are intended, in normal operating conditions, to receive solutions that have no risk of criticality in an infinite medium: if the devices for controlling the correct operation of the process are such that the general principles defined in Paragraph II.2 - are satisfied, and that consequently the risk of inadvertent flow of solutions with a risk of criticality in an infinite medium in the unsafe geometry equipment is negligible, the transfer circuit may be permanent and direct. In the contrary case, the transfer circuit is closed and the solutions may be transferred only after confirmation - by means of two estimates using different methods - that the concentration of fissile material in the solution contained in the safe geometry equipment is satisfactory.
- unsafe geometry equipments are intended to receive solutions resulting from operations of an exceptional nature (e.g., decontamination solutions): the transfer circuit shall be shut off, in normal operating, by appropriate and reliable devices. The connection establishment and the transfer shall be performed according to a written procedure which includes two estimates, using different methods, of the concentration of fissile material in the solution contained in the safe geometry equipment.

II.3.c - Control by concentration of fissile material in solutions

This type of control mode is mainly used in facilities or parts of facilities in which the fissile material concentrations in the solutions are safe, taking into account the geometry of the equipment containing them. It can only be applied to homogeneous fissile materials solutions.

Accordingly, appropriate provisions shall be taken to avoid precipitation, polymerization, crystallization, extraction into another fluid (a solvent, for example), and the rise of fissile material concentration by evaporation.

II.3.d - Control by moderation

This criticality control mode is generally used, together with mass control mode, in facilities or parts of facilities for fuel elements fabrication.

It is generally reserved for dry or semi-dry non-hygroscopic products. Two "barriers", whose integrity shall be monitored, shall be interposed between the fissile material and the hydrogeneous fluids. In some cases, a single "barrier" may be accepted if special provisions are taken, particularly as regards its quality. The risks of accidental moderation from external origins (floods, tornadoes, snowfalls, firefighting, etc.) and from internal origins (leaking pipes, oil spatter, etc.) shall be taken into account.

II.3.e - Neutron poisoning

Neutron poisoning is employed when the process requires the use of large volume equipments whose geometry cannot be made safe, or when it is necessary to provide neutron isolation between equipments.

The presence of a sufficient quantity of neutron poison shall be ensured. In the case of homogeneous poisoning, it shall be subject to two estimates employing different methods, and if necessary provisions shall be taken to avoid dilution or precipitation of the poison. In the case of heterogeneous poisoning, the durability of the neutron-absorbing component and, if there is one, of the accompanying moderating material, shall be guaranteed against the risk of fire.

II.4 - Dimensioning criteria

A study as complete as possible of normal or abnormal operating conditions shall enable a control mode to be selected for the various parts of the facility. The calculation assumptions that are the most pessimistic in terms of criticality risk shall be adopted when designing the facility.

The dimensioning of the equipments, the values for fissile materials masses and for neutron-poison concentrations shall be defined in such a manner that the effective multiplication factors (keffs) are less than unity, with a sufficient safety margin. This margin may be adjusted depending on the level of confidence assigned to the calculation techniques, which depends on the validation of these techniques by comparison with results from experiments performed on configurations similar to those studied.

II.5 - Modification procedures

Any modification that is liable to affect the analysis of criticality risk: modification of equipment, of its location, of its environment (biological shield, for example), of operating conditions, etc., shall be carried out according to a written procedure specifically providing for prior consultation with specialists on nuclear criticality safety.

III - Operators training

In view of the importance of the human factor in the prevention of criticality risk, personnel required to work in facilities having such a risk shall receive relevant training (provided by a criticality engineer).

IV - Additional provisions for the prevention of the consequences of a criticality accident

In view of the possible consequences of a criticality accident for the operators and the population, it may be necessary to supplement the preventive provisions by installing a criticality accident detection, alarm and measurement system.

GLOSSARY

I - Critical concentration

Concentration of fissile material of a given isotopic composition for which a homogeneous fissile medium of a given geometrical form is just critical.

I.1 Critical limit concentration: concentration of fissile material of a given isotopic composition for which a homogeneous medium of infinite dimensions is just critical.

I.2 Safe concentration: concentration of fissile material of a given isotopic composition below which the fissile medium is guaranteed sub-critical, with an appropriate safety margin.

II - Neutron poisoning

Reduction in the reactivity of a fissile medium by the presence of neutron-absorbing nuclides (neutron poisons). Homogeneous neutron poisoning is ensured by the presence of a neutron poison dissolved in a fissile material solution; heterogeneous poisoning is ensured by the presence, in a container receiving solutions of fissile material, of structures composed of materials containing neutron poisons (borosilicate-glass Raschig rings, borated steel plates, etc.).

III - Effective multiplication factor (keff or "reactivity")

Ratio of the total number of neutrons produced in a given fissile medium over an interval of time to the total number of neutrons lost by absorption and by leakage over the same interval of time, all other conditions equal (neutrons produced by sources whose intensities do not depend on the chain-reaction process are not considered in this ratio).

IV - Critical geometrical form

Geometrical form of a fissile medium whose dimensions are such that it is critical for a specific composition or distribution of fissile material, taking into account the reflecting environment.

IV.1 Minimum critical geometrical form: geometrical form of a fissile medium of dimensions below which it is sub-critical, regardless of the mass and moderation of the fissile material.

IV.2 Safe geometrical form: geometrical form of a fissile medium guaranteed sub-critical with an appropriate safety margin, regardless of the mass and moderation of the fissile material.

Note: the word "geometry" is normally used in place of the expression "geometrical form".

V - Density law

Relationship between the concentration of fissile material and the moderation ratio.

VI - Critical mass

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

VI.1 Minimum critical mass: mass of fissile material below which the fissile medium is sub-critical regardless of its geometry and its moderation.

VI.2 Safe mass: mass of fissile material below which the medium is guaranteed sub-critical with an appropriate safety margin, regardless of its geometry and moderation.

VII - Fissile material

Material composed of chemical elements, some of whose isotopes are fissile, e.g., ^{233}U, ^{235}U, ^{239}Pu, and ^{241}Pu.

VIII - Fissile medium

Physico-chemical medium containing fissile material among other elements.

IX - Moderator

Materials whose nuclides (moderating nuclides) reduce the kinetic energy of the neutrons they encounter. This slowing down of neutrons is obtained by elastic or non-elastic collisions with these nuclides.

X - Moderation ratio

Ratio of the number of moderating nuclides to the number of fissile nuclides contained in a given volume of fissile medium.

XI - Nuclear criticality safety

Set of provisions designed to prevent the criticality risk.

XII - Working unit

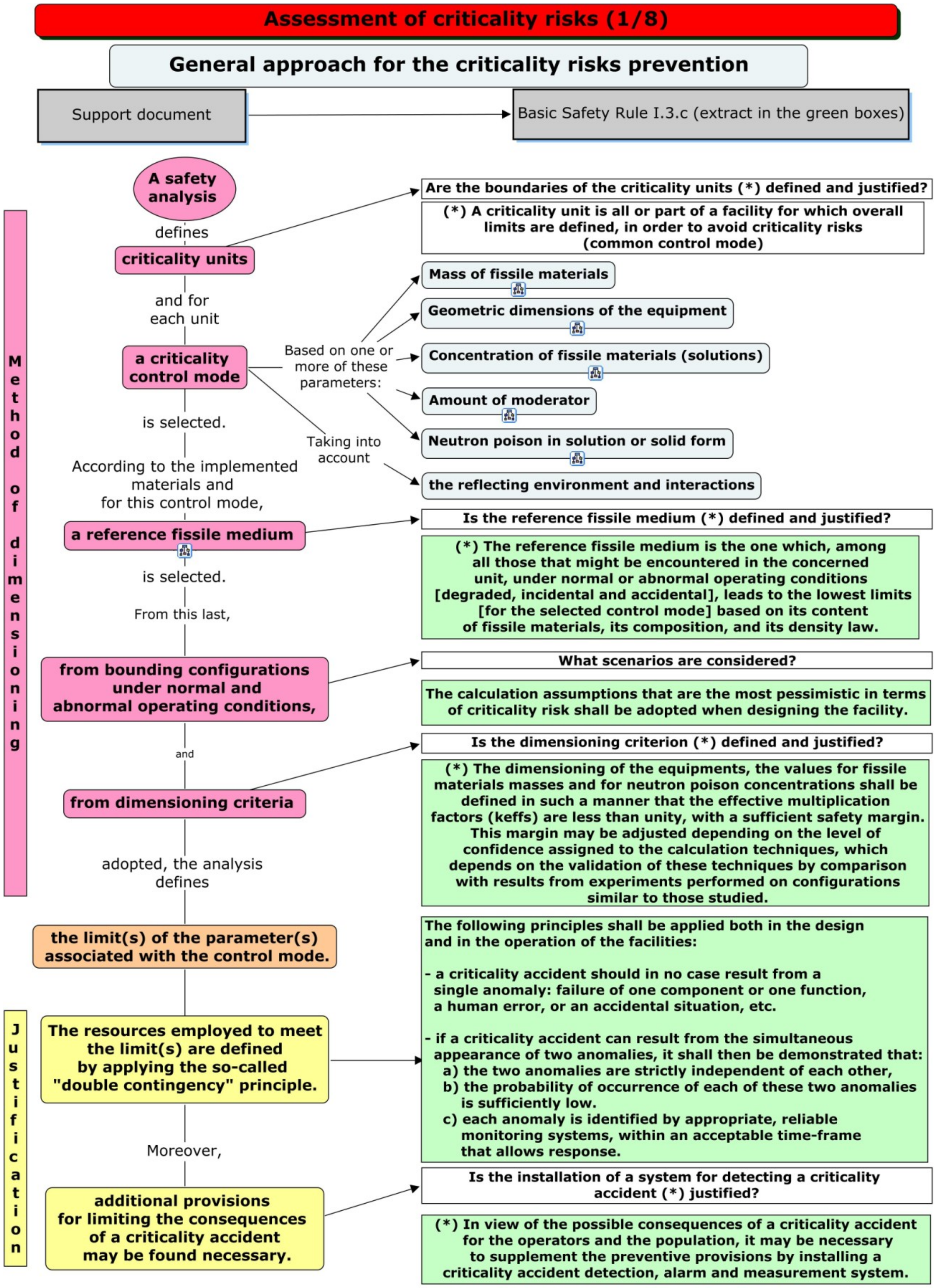
Part of the facility whose outline is physically defined, within which there is a limited mass of fissile material.

Block diagrams of the nuclear criticality risks analysis

The diagrams included in this appendix summarize (i) the methodology recommended by the BSR No. I.3.c (first diagram), and (ii), for the reference fissile medium and each criticality control mode, the parameters to be considered, the failures to be studied and the typical scenarios associated with these failures.

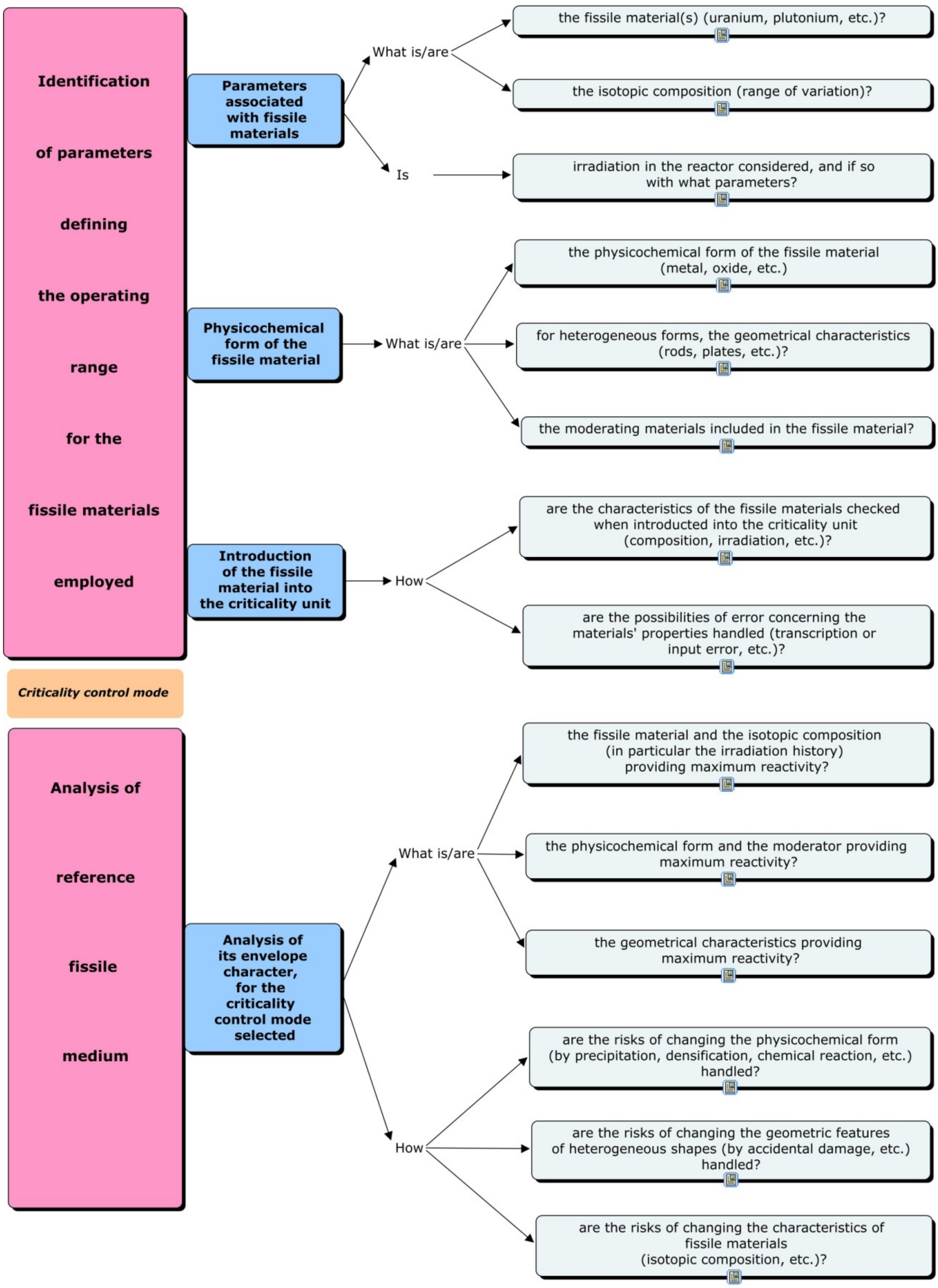
The objective of these diagrams is to provide the most comprehensive support possible for the preparation or assessment of a critical risk analysis. They are meant to identify the points that should be investigated, but do not recommend technical solutions. Such solutions should, to the extent possible, be adjusted to the situation in hand. Thus, for each scenario identified, the goal of the analysis is either to rule out this scenario or to show that it would lead to an acceptable configuration.

Finally, these diagrams may be modified by feedback from experience acquired in the design and operation of nuclear facilities.


Assessment of criticality risks (1/8)
General approach for the criticality risks prevention
Support document
Basic Safety Rule I.3.c (extract in the green boxes)
Method of dimensioning
A safety analysis
defines
criticality units
Are the boundaries of the criticality units (*) defined and justified?
(*) A criticality unit is all or part of a facility for which overall limits are defined, in order to avoid criticality risks (common control mode)
and for each unit
a criticality control mode
Based on one or more of these parameters:
Mass of fissile materials
Geometric dimensions of the equipment
Concentration of fissile materials (solutions)
Amount of moderator
Neutron poison in solution or solid form
Taking into account
the reflecting environment and interactions
is selected.
According to the implemented materials and for this control mode,
a reference fissile medium
Is the reference fissile medium (*) defined and justified?
(*) The reference fissile medium is the one which, among all those that might be encountered in the concerned unit, under normal or abnormal operating conditions [degraded, incidental and accidental], leads to the lowest limits [for the selected control mode] based on its content of fissile materials, its composition, and its density law.
is selected.
From this last,
from bounding configurations under normal and abnormal operating conditions,
What scenarios are considered?
The calculation assumptions that are the most pessimistic in terms of criticality risk shall be adopted when designing the facility.
and
from dimensioning criteria
Is the dimensioning criterion (*) defined and justified?
(*) The dimensioning of the equipments, the values for fissile materials masses and for neutron poison concentrations shall be defined in such a manner that the effective multiplication factors (keffs) are less than unity, with a sufficient safety margin. This margin may be adjusted depending on the level of confidence assigned to the calculation techniques, which depends on the validation of these techniques by comparison with results from experiments performed on configurations similar to those studied.
adopted, the analysis defines
the limit(s) of the parameter(s) associated with the control mode.
Justification
The resources employed to meet the limit(s) are defined by applying the so-called "double contingency" principle.
The following principles shall be applied both in the design and in the operation of the facilities:
- a criticality accident should in no case result from a single anomaly: failure of one component or one function, a human error, or an accidental situation, etc.
- if a criticality accident can result from the simultaneous appearance of two anomalies, it shall then be demonstrated that:
a) the two anomalies are strictly independent of each other,
b) the probability of occurrence of each of these two anomalies is sufficiently low.
c) each anomaly is identified by appropriate, reliable monitoring systems, within an acceptable time-frame that allows response.
Moreover,
additional provisions for limiting the consequences of a criticality accident may be found necessary.
Is the installation of a system for detecting a criticality accident (*) justified?
(*) In view of the possible consequences of a criticality accident for the operators and the population, it may be necessary to supplement the preventive provisions by installing a criticality accident detection, alarm and measurement system.

Assessment of criticality risks (2/8)

Reference Fissile Medium



Assessment of criticality risks (3/8)

Control mode including a limit on the mass of fissile materials

Identification of parameters defining the operating range for the avoidance of criticality risks, and analysis of their relevance

- **Parameters associated with the implemented materials**
  - What is
    - the nature of the fissile materials?
    - the nature of the moderating materials?
    - the parameter used : the total mass of fissile material, the mass of fissile isotopes, or the mass before irradiation?
- **Parameters associated with the environment**
  - What
    - reflectors are present (nature, thickness of materials reflectors, etc.)?
  - How
    - are interactions with other criticality units and movable components handled, under normal and abnormal operating conditions?

Operating range:

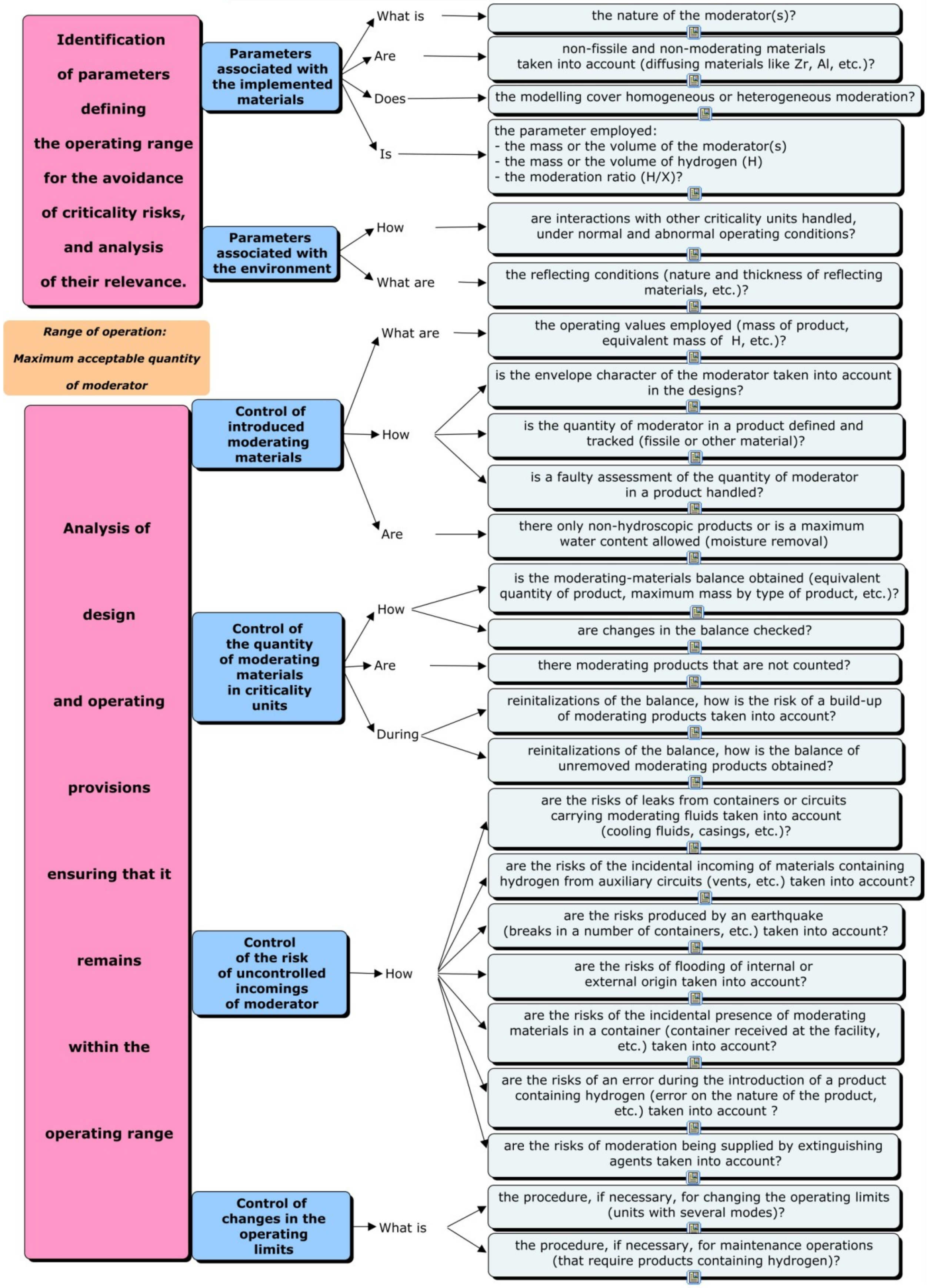
Upper safety mass

Analysis of design and operating provisions ensuring that it remains within the operating range

- **Control of the characteristics of the implemented materials**
  - What are
    - the operating values used in monitoring the mass, to comply with the upper safety mass(es) adopted?
  - How
    - is the absence of a more efficient moderator than the one used in the studies ensured?
  - What are
    - the methods used to estimate the operating values (measurement, estimation, etc.)?
    - the parameters used to provide these estimates (enrichment, spectrum, burnup, etc.)?
  - How
    - is the conservative nature of the estimates ensured (qualification of the method, or uncertainties)?
    - are the characteristics of the materials entering the facility checked?
    - are operations that change the characteristics of a batch of materials handled?
    - is a failure in the methods for estimating the operating values handled (measurement, procedure, etc.)?
- **Control of the mass of material in criticality units**
  - How
    - is the mass balance obtained (input/output figures, cumulative inputs, etc.)?
    - are uncertainties in the evaluation incorporated?
    - are changes in the mass balance checked?
  - How
    - is the risk of loading errors taken into account?
    - is the risk of slow build-up taken into account?
    - is the risk of the sudden incoming of fissile material taken into account?
  - During
    - reinitialization of the balance, how is the residual or retained mass assessed?
    - reinitialization of the balance, how is the unit cleaned (handling of areas with little or no access, etc.)?
- **Control of the risk of error during transfers of materials between criticality units**
  - How
    - is an error concerning the introduced or removed products handled (defective container, etc.)?
    - is an error concerning the destination of a transfer handled?
- **Control of changes in the operating limits**
  - What is
    - the procedure for changing the operating limits (units with several modes)?

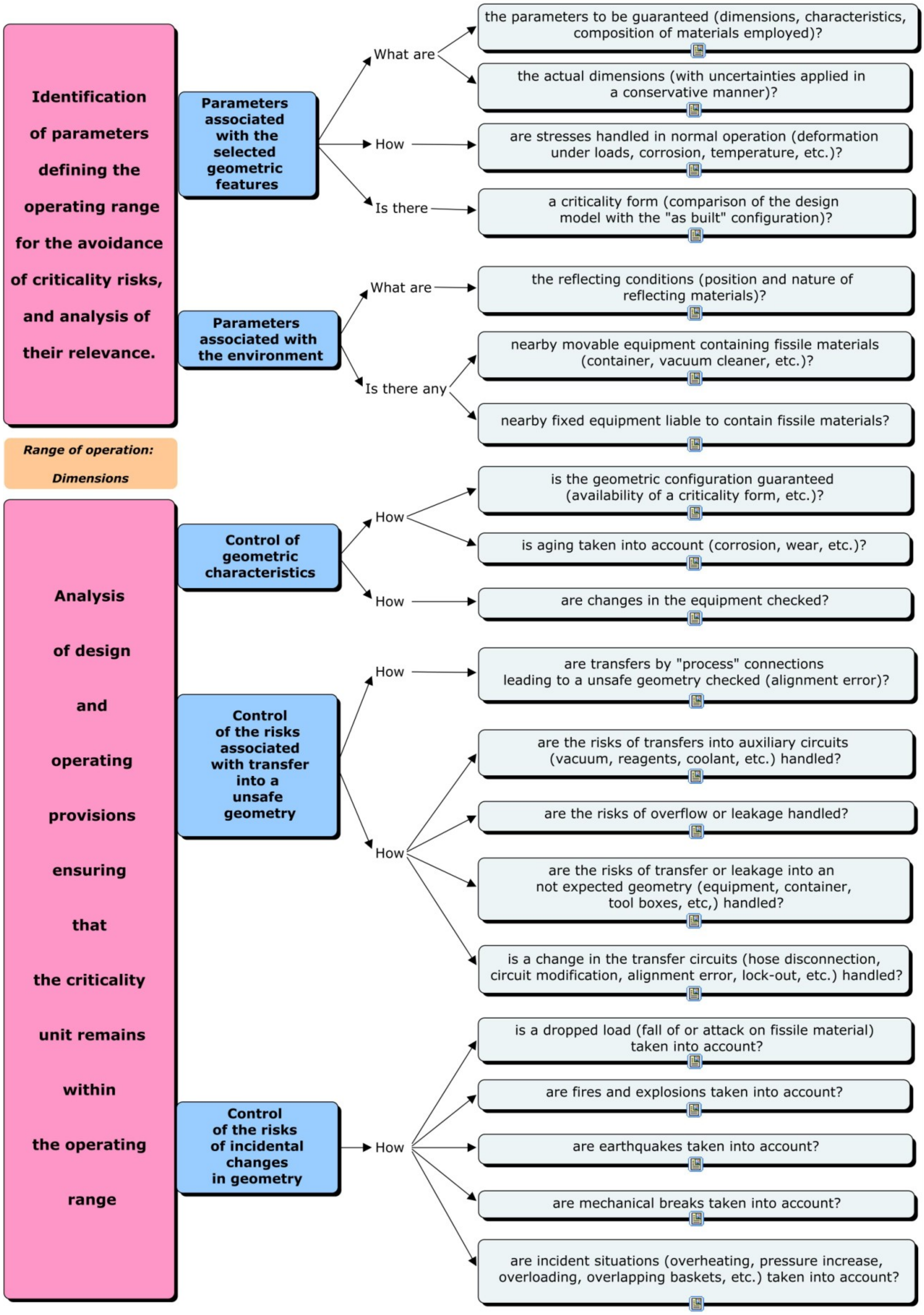
Assessment of criticality risks (4/8)

Control mode including a limit on moderation



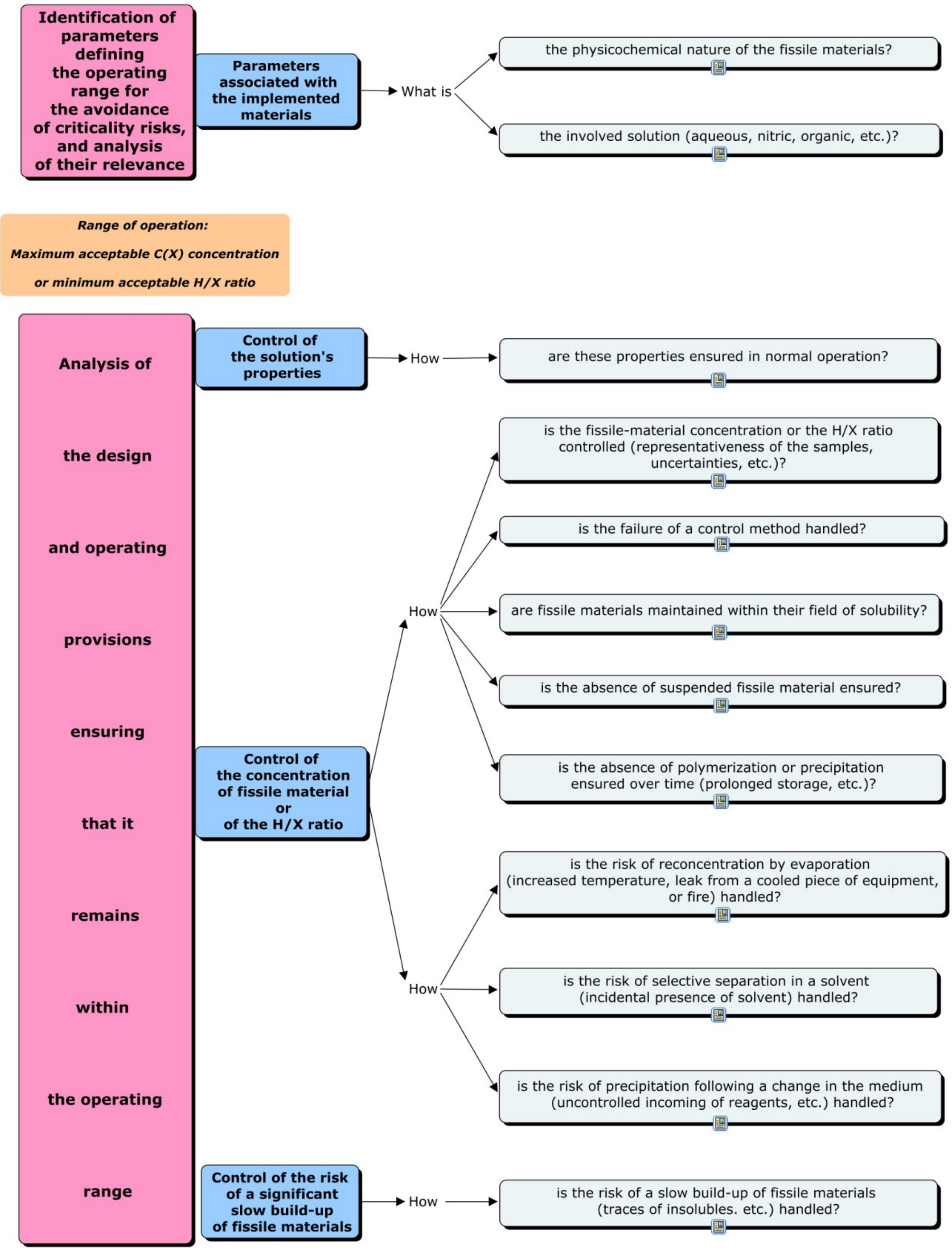
Assessment of criticality risks (5/8)

Control mode including a limit on the geometry



Assessment of criticality risks (6/8)

Control mode including a limit on the C(X) concentration or the H/X ratio



Assessment of criticality risks (7/8)

Control mode including a homogeneous poisoning

Identification of parameters defining the operating range for the avoidance of criticality risks, and analysis of their relevance

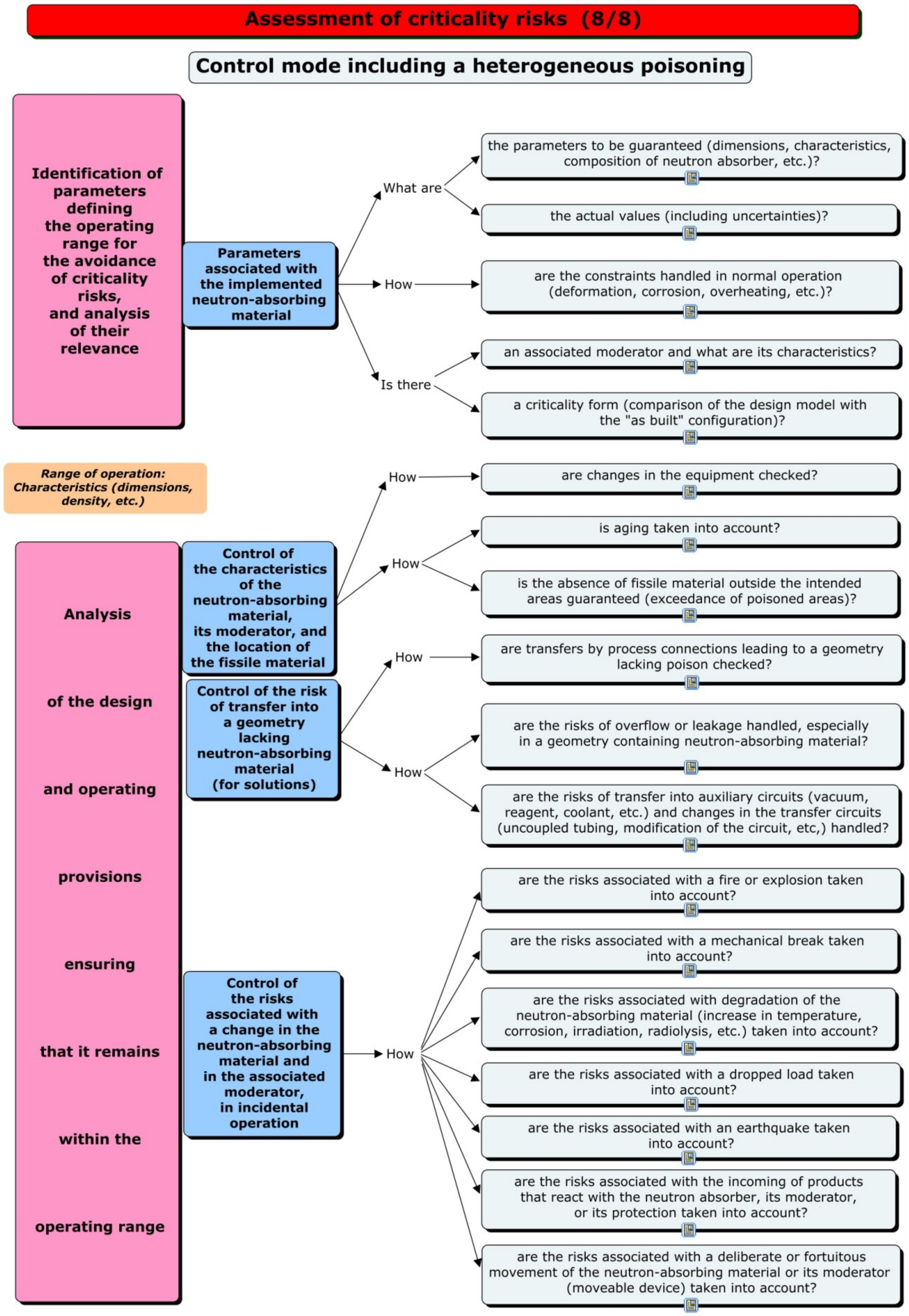
- **Parameters related to the implemented poison** → What is
  - the physicochemical nature of the fissile materials?
  - the neutron-absorbing component considered (its composition)

Range of operation:

Minimum poison concentration

Analysis of the design and operating provisions ensuring that it remains within the operating range

- **Control of the poison concentration** → How
  - is the solubility of the poison ensured under the conditions of use?
  - is the concentration of the poison controlled?
  - is the failure of a concentration-control method handled?
- **Control of the risk of a "loss" of poison** → How
  - are the risks of accidental precipitation of the poison (incoming of reagents, changes in the conditions of use that change the solubility, etc.) handled?
  - are the risks of changes in the poisoning (adsorption, unmixing of the solution, etc.) handled?
  - are the risks of dilution of the poison (incoming of non-poisoned solutions or fluids, etc.) handled?
- **Control of the risk of separation of fissile materials and the poison** → How
  - is the risk of settling of the fissile materials (absence of insolubles) handled?
  - is the risk of selective separation in a solvent (incidental presence of solvent) handled?
  - is the absence of polymerization or precipitation ensured over time (prolonged storage, etc.)?
  - is the risk of precipitation following an incidental incoming of reagents (process circuit, vent, etc.) handled?
  - are fissile materials maintained within their field of solubility?


Assessment of criticality risks (8/8)
Control mode including a heterogeneous poisoning
Identification of parameters defining the operating range for the avoidance of criticality risks, and analysis of their relevance
Parameters associated with the implemented neutron-absorbing material
What are
the parameters to be guaranteed (dimensions, characteristics, composition of neutron absorber, etc.)?
the actual values (including uncertainties)?
How
are the constraints handled in normal operation (deformation, corrosion, overheating, etc.)?
Is there
an associated moderator and what are its characteristics?
a criticality form (comparison of the design model with the "as built" configuration)?
Range of operation: Characteristics (dimensions, density, etc.)
Analysis of the design and operating provisions ensuring that it remains within the operating range
Control of the characteristics of the neutron-absorbing material, its moderator, and the location of the fissile material
How
are changes in the equipment checked?
How
is aging taken into account?
is the absence of fissile material outside the intended areas guaranteed (exceedance of poisoned areas)?
Control of the risk of transfer into a geometry lacking neutron-absorbing material (for solutions)
How
are transfers by process connections leading to a geometry lacking poison checked?
How
are the risks of overflow or leakage handled, especially in a geometry containing neutron-absorbing material?
are the risks of transfer into auxiliary circuits (vacuum, reagent, coolant, etc.) and changes in the transfer circuits (uncoupled tubing, modification of the circuit, etc,) handled?
Control of the risks associated with a change in the neutron-absorbing material and in the associated moderator, in incidental operation
How
are the risks associated with a fire or explosion taken into account?
are the risks associated with a mechanical break taken into account?
are the risks associated with degradation of the neutron-absorbing material (increase in temperature, corrosion, irradiation, radiolysis, etc.) taken into account?
are the risks associated with a dropped load taken into account?
are the risks associated with an earthquake taken into account?
are the risks associated with the incoming of products that react with the neutron absorber, its moderator, or its protection taken into account?
are the risks associated with a deliberate or fortuitous movement of the neutron-absorbing material or its moderator (moveable device) taken into account?

ANALYSIS GUIDE
NUCLEAR CRITICALITY RISKS AND THEIR PREVENTION IN PLANTS AND LABORATORIES

EVOLUTION REQUEST FORM

REQUESTER	
Name: Society: Department: Address:	Date: Phone: Fax: E-mail:
CONCERNED PART	
TEXT	**DIAGRAM**
Paragraph number: Page number:	Title:
REQUEST DESCRIPTION	

Send to Eric LETANG - Head of IRSN/DSU/SEC

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