III. CRITICALITY SAFETY OF NUCLEAR FACILITIES

outside the reactor, criticality prevention is a must

Great care is taken to avoid a chain reaction in all facilities where nuclear materials are handled, other than inside the reactors themselves. We cannot however exclude the possibility of a chain reaction being initiated by a favorable neutron balance in a fixed facility or during transportation, perhaps following an operator error or a failure to follow the correct procedure: this is the risk of criticality. This risk is prevented by applying basic principles which are simple in themselves but whose implementation requires rigorous design and constant vigilance. The most recent serious criticality accident, which took place in Japan in 1999, clearly illustrated how failing to apply the principles could cause such an accident; the events leading up to the accident, its causes and its consequences are discussed in this chapter. While prevention involves constraints, a strict evaluation of the risk of criticality will also give us more flexibility in how we manage the materials used in the nuclear industry, which can help us control costs safely. Two articles illustrate the progress made in this area by researchers and the nuclear industry.

CEA

Handling non-irradiated fissile material at the CEA/Cadarache. The material is packed in drums and stored on centered cages to protect against the risk of criticality.

THE RISK OF CRITICALITY AND ITS PREVENTION IN NUCLEAR PLANTS AND LABORATORIES AND DURING TRANSPORTATION

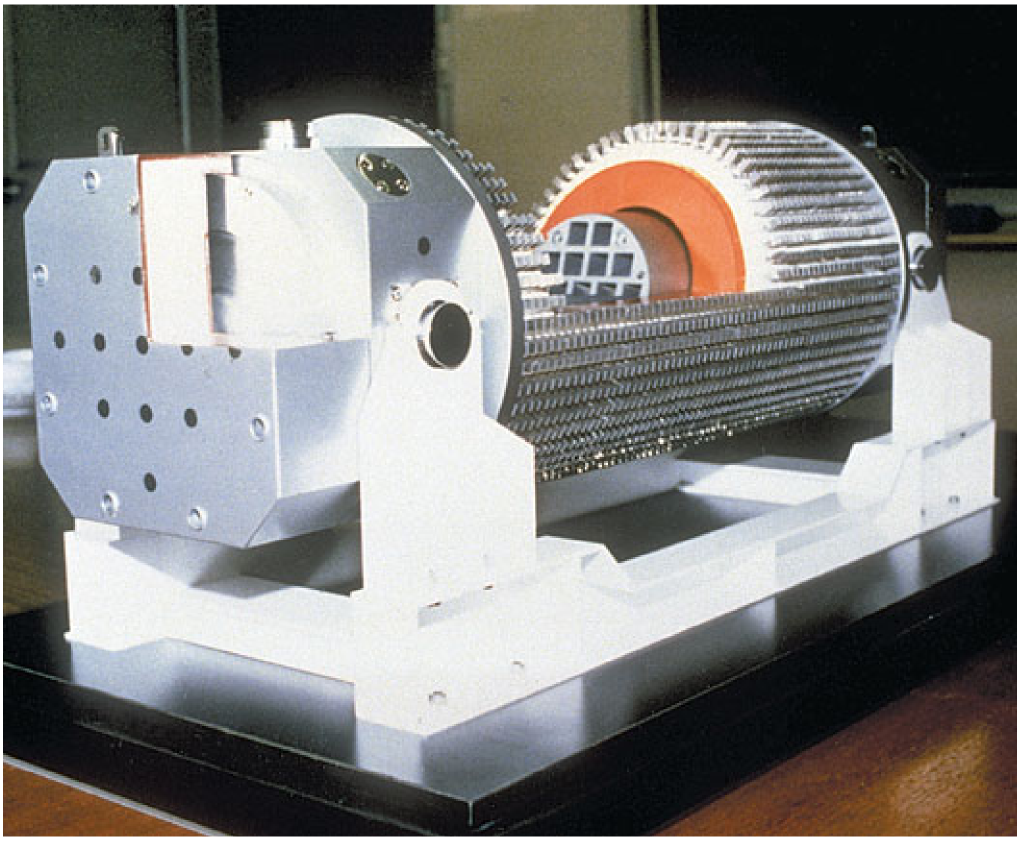
The use of nuclear reactors for energy production is based on the ability of certain fissile nuclei, such as uranium-235 and plutonium-239 and 241, to maintain fission chain reactions. This property is also the direct origin of a risk specific to the nuclear industry: criticality.

Joly/CEA

Glove box titration during MOX fuel handling.

There is no need for a complex machine or very large quantities of **fissile** material to trigger a **fission chain** reaction. Just over 0.5 kg of plutonium or about 60 kg of the type of uranium used to manufacture **fuel** for EDF power plants is enough when mixed with water, as long as the geometry is favorable. If such a chain reaction occurs while handling fissile material in a laboratory, a manufacturing facility or during transportation, it is accompanied by a release of energy, just as it would be in a reactor. This means that the fissile medium is heated significantly and that **radiation** is released (gamma and **neutrons**), which in the most serious cases can cause a major or even fatal irradiation of anyone close to the equipment concerned, as the 1999 Tokaï Mura accident

TN 12 spent fuel shipping container.



DR/Cogema

showed (see *The Tokaï Mura criticality accident*). On the other hand, the consequences for the environment are slight, since the release of **radioactive fission products** is limited to a few noble gases and a small amount of iodine.

This risk of criticality, specific to the nuclear industry, has since the beginning been taken into account by the CEA and by the nuclear industry through appropriate preventive measures. In practice these involve applying consistent constraints, for example limiting the quantities of material handled, the dimensions of the equipment containing fissile material or the concentration of fissile material in a liquid medium, or using special materials called **neutronic poisons** (see *Neutronic phenomena*). Each situation needs to be analyzed according to the context and the materials involved. Criticality engineering does just this by studying the measures which are most appropriate, necessary and adequate to prevent a chain reaction from starting while manipulating fissile material. A brief look back at the key aspects of **neutronics** will help explain the origin of the phenomenon (see box F, ***Criticality accident: a question of neutron balance***).

Parameters influencing the neutron balance

The preceding articles (see *Neutronic phenomena*) showed the key role played by neutrons in triggering induced fission reactions, and showed how chain reactions maintain themselves by neutron multiplication (where each reaction consumes a neutron but produces more than one, about 2.5 on average in the case of uranium-235 fission). Neutrons will be produced, and if no compensation occurs in the form of a sufficient loss of neutrons, this will lead to a criticality accident. Since different parameters influence the terms of this neutron balance, it is possible to prevent the risk of criticality by respecting the following inequality:

absorption + leakage > production

The production of fission neutrons

Neutrons, particles with no electrical charge, move freely through matter. They carry kinetic energy *E*, linked to their mass *m* and their speed *v* by the relationship $e = {}^1/_2mv^2$, generally expressed in electronvolts (eV). At the

Criticality accident: a question of neutron balance

F

The **criticality** conditions of a medium in which fission chain reactions are taking place (see box A) result from the balance between neutron PRODUCTION by fission and their LOSS by capture* and by leakage (ABSORPTION + **LEAKAGE**). The state of the fissile medium is characterized by the multiplication factor k_{eff}, which can be defined as the ratio between the number of neutrons in two successive generations: where N is the number of parent neutrons (generation n-1) that have disappeared by absorption or leakage, and N' is the number of child neutrons produced (generation n):

$$k_{eff} = \frac{N'}{N} = \frac{production}{absorption + leakage}$$

- if $k_{eff} < 1$ the reaction is inhibited. This is the ***subcritical*** state which characterizes the state of safety that we seek in the operation of nuclear facilities;
- if $k_{eff} = 1$, the reaction is under control. This is the exactly *critical* state for which the neutron population remains constant, which is the aim in an operational reactor but which in other nuclear facilities should never be reached (except in special experimental circumstances);
- if $k_{eff} > 1$, this is the ***supercritical*** state, a situation which leads to a criticality accident. A fission chain reaction starts, resulting in a major PRODUCTION of neutrons which is not compensated by the neutron LOSSES.

Two simple principles are used to remain in a *subcritical* state:

- limit as far as possible the likelihood of any fission reactions and so limit the production of neutrons;
- promote as far as possible the disappearance of neutrons by their leakage from the fissile medium or by their absorption by non-fission capture.

All criticality risk prevention is encapsulated in the practical implementation of these two principles so that the “absorption + leakage” sum is greater than the production of neutrons.

* Note that capture may involve capture by a stable nucleus (in which case k_{eff} is reduced) or capture resulting in a fission reaction (k_{eff} is increased).

moment of their birth following a fission, neutrons have a variable energy, averaging 2 million electronvolts (2 MeV). In this state they are not at their most effective for triggering fission reactions (see *Neutronic phenomena*). But as they move through matter, neutrons gradually lose their energy during collisions with other nuclei in the medium, and this makes them more effective at provoking fission when they impact with fissile nuclei. This slowing phenomenon is called **moderation**.

When the neutrons impact with nuclei in the medium, as a general rule the lighter the nuclei, the more energy the neutrons give up. The “champion moderator” is thus hydrogen, whose nucleus contains a single proton with the same mass as a neutron. This explains the key role played in neutronics and criticality by water, which contains two hydrogen atoms in its molecules.

Almost all criticality accidents in fuel cycle facilities took place in aqueous solution. In the presence of water (and thus hydrogen), which promotes fission reactions by slowing down neutrons, the mass at which $k_{eff} = 1$ is 0.51 kg of plutonium, whereas the mass required is 4.5 kg in the absence of water. For uranium, the limits depend on how **enriched** it is in its ^{235}U **isotope**: 0.87 kg for highly enriched uranium (93.5%), 5.2 kg for 20% enrichment and 91 kg for 3% enrichment. For certain fissile materials such as slightly enriched uranium (less than 6.6% of the 235 isotope), just keeping the medium rigorously dry (anhydrous) and generally free of any hydrogen-containing material is enough to prevent any risk of criticality, even in the presence of large quantities of material.

Criticality is then controlled
by restricting the moderation.

Neutron leakage

As they move through matter, a certain number of neutrons manage to escape the fissile medium which produced them. In this case they no longer take part in maintaining the chain reactions. This neutron **leakage** is increased if the medium contains a low density of the material or consists of nuclei which do not tend to interact and when the distances to the boundary are small. Just by keeping the fissile material in a volume of sufficiently small dimensions may be enough to prevent any risk of criticality.

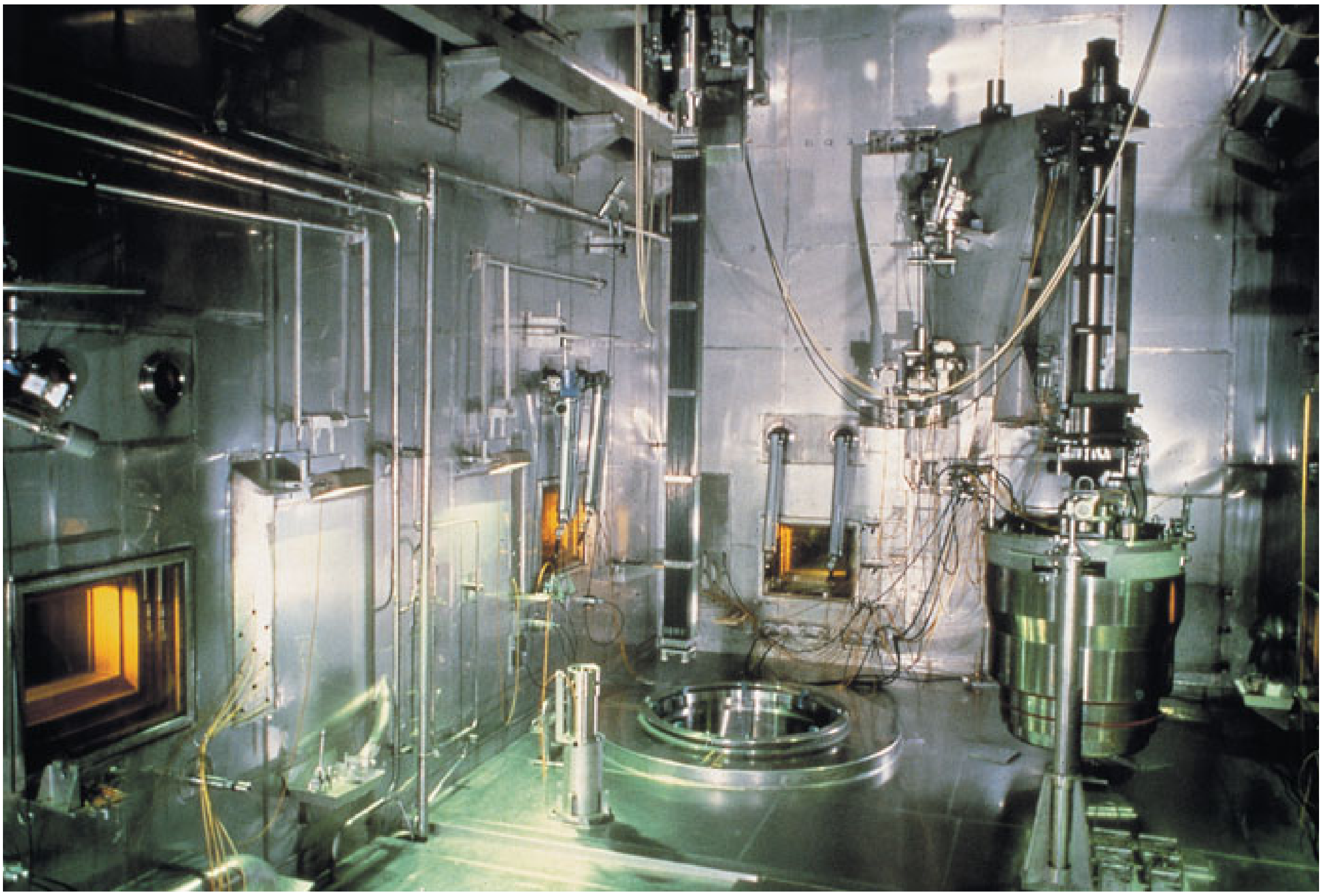
Criticality in this case is controlled by
restricting the geometry.

Neutrons that have escaped from a fissile medium may continue their trajectory in adjacent materials and, after colliding with the nuclei in these materials, be either **captured** or sent back to the original fissile material: this phenomenon is called neutron *reflection*. Walls, machines and even people in nuclear facilities act as reflectors which may reduce neutron leakage and which must also be taken into account.

Lastly, when several fissile assemblies are close to each other, a factor called *interaction* may affect the neutron balance. A fraction of the neutrons leaving one set of equipment may enter adjacent equipment, itself containing fissile material, and so may cause fissions to take place there. This *neutron coupling* increases the **reactivity** of the system. When calculating the criticality of a set of equipment, account has to be taken of their exact layout and of the presence of any possible reflective materials nearby.

Neutron absorption

While eliminating neutrons in any manner, for example their **capture** by nuclei of the medium, tends to favor **subcriticality** of a fissile medium, there exists a wide diversity in the way nuclei (natural and artificial) interact with neutrons: some of them are almost “trans-



S. Jezequel/Cogema

Equipment in the T0 dry unloading shop cell at the Cogema UP3 fuel reprocessing plant at La Hague.

parent” to neutrons while others behave as fully-fledged neutron poisons. Four relatively abundant natural elements are particularly good at capturing neutrons thanks to the absorbent power of at least one of their **isotopes**. These are **boron** (through the ^{10}B isotope present in natural boron), **cadmium**, **hafnium** and **gadolinium** (through its ^{155}Gd isotope). These are commonly used for their neutron-absorbing properties in criticality risk prevention.

Criticality is then controlled using “poisoning”.

Other nuclei frequently encountered in common fissile media may also contribute to neutron capture and so to reducing the risk of criticality. The main ones include uranium-238 and plutonium-240.

As well as the four “champion” neutron absorbers, many other nuclei have a significant ability to capture neutrons. They have to be taken into account accurately when establishing the **neutron balance**. The more effective among the common elements include chlorine, nitrogen, iron, and hydrogen itself. This means that aqueous solutions containing low concentrations of fissile materials remain subcritical, even for very large volumes, because of poisoning by hydrogen in the water.

Criticality is then controlled by limiting the concentration of fissile material.

Lastly, when we consider the risk of criticality in spent fuel storage, transportation and reprocessing operations, several stable fission products present in these fuels (including samarium-149, samarium-152, gadolinium-155, cesium-133, neodymium-143, ruthenium-103 and molybdenum-95) strongly favor the subcriticality of the medium through their neutron-absorbing properties, which are the subject of a considerable amount of research.

So we can see that in practice a wide range of solutions exists to maintain a system containing fissile materials in a subcritical state. Each solution has a corresponding set of constraints or restriction parameters which have to be precisely defined. Where subcriticality is achieved by limiting just one parameter, this limitation constitutes a *criticality control mode*.

Criticality control modes and reference fissile media

The preceding paragraphs highlighted the range of means available to prevent the risk of criticality. Just restricting one or more "operational" parameters, such as concentration of fissile materials in a solution, equipment dimensions, the quantity of fissile material and of moderator materials, together with the possible use of neutron-absorbing poisons, may be enough to maintain a system containing fissile material in a subcritical state. This step consists of choosing one or more *criticality control mode(s)*. We then have to choose a method of specifying the limits imposed on the control parameters. This involves carrying out a *safety analysis* to investigate the combination of parameters most unfavorable to criticality and deducing their boundary parameters for safety purposes. We then define a boundary fissile medium called the *reference fissile medium* whose critical parameters for the chosen criticality control mode are necessarily more restrictive than those of all the fissile media likely to be encountered in the facility during operation.

The *criticality control mode* and its corresponding *reference fissile medium* form an indissociable pair used to define the safety conditions for a facility with respect to the risk of criticality, known as "nuclear criticality safety".

Analyzing nuclear criticality safety

Even at this preliminary stage of the safety analysis, we have to consider not just operating conditions described as normal, but also the various malfunctions that might be envisaged. In this context it may be useful to refer to the Fundamental Safety Rules (RFS)(1) which provides safety analysts and facility designers and operators with a methodological reference work for criticality risk prevention. The RFS states as a general principle that a "*criticality accident must in no case result from a single anomaly: failure of a component or of a function, human error (e.g. the failure to observe an instruction), accident situation (e.g. a fire)*"… and that "*if a criticality accident may result from the simultaneous occurrence of two anomalies, it shall then be demonstrated that* (1) the two anomalies are rigorously independent, (2) *the probability of occur-*

(1) The Fundamental Safety Rules, issued by the French nuclear safety authority (the Directorate for Nuclear Facility Safety, DSIN) set out the conditions that the operator of a basic nuclear facility must comply with to demonstrate that the facility meets the current regulations. The rules are regularly updated, in particular in the light of recommendations issued by a "permanent group" comprising members chosen for their expertise in the relevant domain.


S. Jezequel/Cogema

Rail transportation of irradiated fuel containers.

Fire resistance test of a plutonium shipping container.

J.-M. Taillat/Cogema

rence of each of these two anomalies is sufficiently low, and (3) *each anomaly is brought to light using appropriate and reliable surveillance methods, within an acceptable time enabling remedial action to be taken"*.

The Rule clearly imposes a requirement to specify which modes of control and reference fissile material are chosen, and specifies the measures applicable to each (see box).

Safety margins and design criteria

Any safety-based approach implies the existence of *safety margins*. In the case of the risk of criticality, the approach will seek to define what the maximum admissible values are for each parameter, with the critical state forming a limit which must never be overstepped. Unfortunately, the subcriticality margin cannot be considered simplistically as expressed only by the multiplication factor k_{eff}. For some fissile media, k_{eff} varies rapidly as a function of certain parameters: examples include media containing plutonium or highly enriched uranium. For other fissile media, such as slightly enriched uranium, k_{eff} varies slowly. For this reason, the RFS does not set a regulatory subcriticality figure. In France, the assessment of the safety

Criticality safety control modes as defined in the fundamental safety rules

The *Fundamental Safety Rules* [RFS, 1.3.c] governing the measures for preventing risk of criticality in nuclear facilities other than reactors has been issued by the DSIN (Directorate for Nuclear Facility Safety), the competent safety body in France for basic civil nuclear facilities. It is applicable to facilities which use fissile material, in particular plutonium and uranium (where this contains more than 1% ^{235}U). The facilities concerned are uranium enrichment plants, fuel element manufacturing facilities, spent fuel reprocessing plants, storage facilities and laboratories.

The RFS stipulates first of all that *for each functional unit of the facility, an appropriate control mode* […] *shall be selected* [and] *defined by an upper limit imposed on one or more of the following parameters: mass of fissile material, geometrical dimensions of the equipment, concentration of fissile material in solutions, moderating ratio for materials which are dry or contain little moisture, taking into account the possible presence of nuclear poisons.*

These limits shall be fixed for a reference fissile medium, taking into account the reflective environment and interactions. The reference fissile medium is that which among all those that may be encountered in the assembly concerned, under normal and abnormal operating conditions, leads to the lowest limits for its content of fissile material, its composition and its dilution law.

The RFS specifies the measures relating to the different control modes:

Control by mass of fissile material

The RFS requires the work unit in which the mass of fissile material is limited to be defined as well as the rules for managing associated materials. *Where this mode of control is adopted, a safe mass of fissile material is fixed per work unit. If it is recognized that the critical mass may be reached following a single anomaly* […] *, the safe mass of fissile material in the work unit in question shall equal at most half of the minimum critical mass for the reference fissile material. This limit may be lowered to take into account any neutronic interaction with the masses of fissile material present in the neighboring work units.*

The total mass of fissile material present in the work unit shall be evaluated in order to check that this mass is at all times less than or equal to the limit set […] .

In practice, this mode of control may be applied at the scale of a set of equipment, a glove box, a cell or even a whole laboratory. It requires strict observance of instructions and so has the disadvantage of being vulnerable to the "human factor".

Control by equipment geometry

This type of control is mainly used where the fissile material is in the form of concentrated solutions. Measures shall be taken to prevent the following situations or to limit their consequences: accidental deformation of equipment […] *, leaks or overflows of solutions of fissile material* […] *, the placing of fissile material solutions in recipients with non-safe geometry, placed on auxiliary systems* […]*, mobile recipients approaching close to equipment: safe geometry mobile recipients, limited in number, surrounded if necessary by a rigid structure which guarantees a sufficient spacing from fixed equipment.*

This mode of control must be preferred where constraints on the dimensions are compatible with the processes. It is not vulnerable to the human factor, but needs to be considered at the equipment design stage and requires particular surveillance of any possible communication between safe geometry equipment and other equipment.

Control by concentration of fissile material in solution

This type of control is mainly used in facilities or parts of facilities in which concentrations of fissile materials in solution are safe, given the geometry of the equipment containing them. It may only apply to homogenous solutions of fissile material.

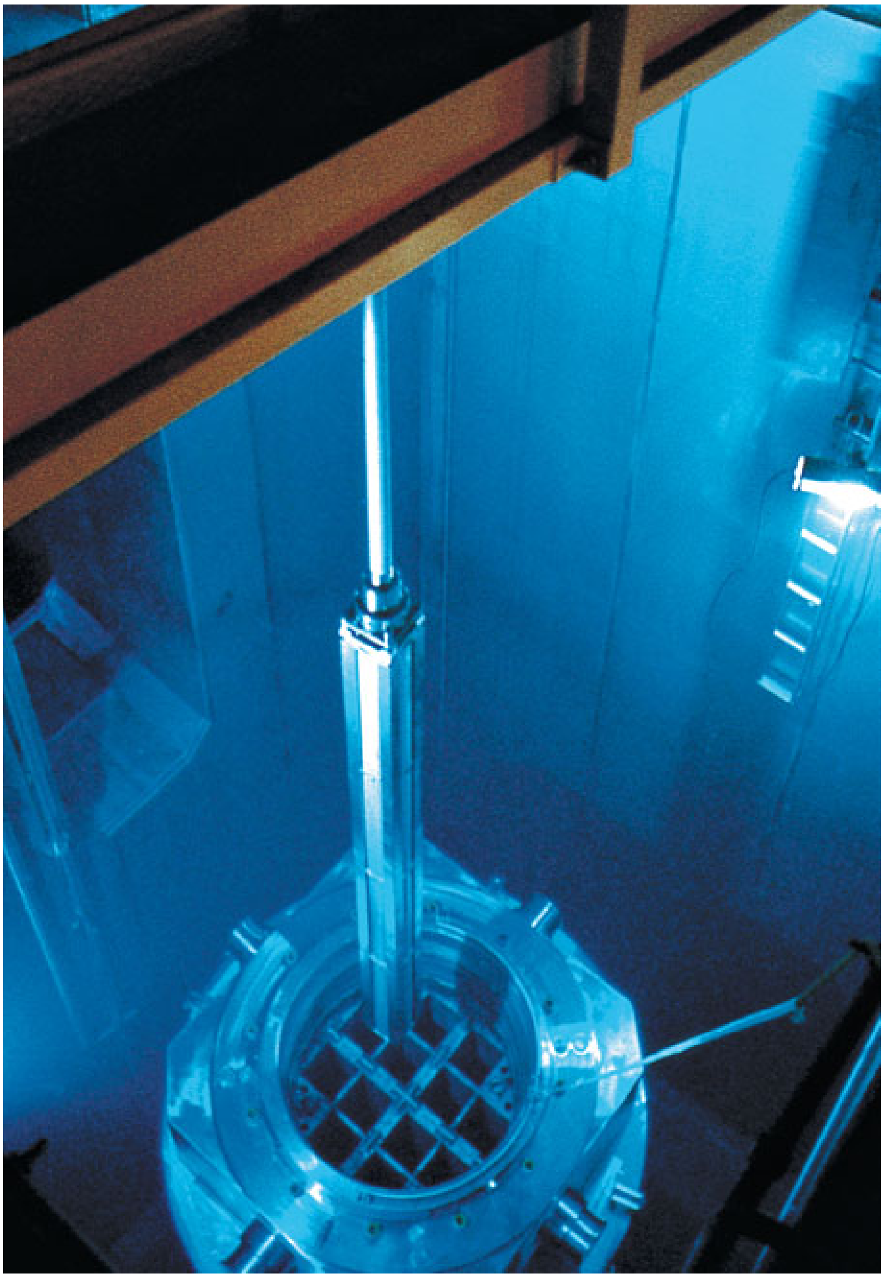
Consequently, the appropriate measures shall be taken to avoid precipitation, polymerization, crystallization, extraction in another fluid (e.g. a solvent) or increasing the concentration of the fissile material by evaporation.

Control by moderation

This mode of control is generally used (together with control by mass) in fuel element manufacturing facilities or parts of such facilities. It is generally reserved for products which are dry or contain little moisture and which are non-hygroscopic. Two "barriers" whose integrity shall be monitored, shall be interposed between the fissile material and hydrogen-containing fluids. In certain cases, just one barrier may be tolerated if special measures are taken […]*, notably concerning its quality. The risks of accidental moderation of external origin (e.g. floods) or internal origin (e.g. leaks) shall be take into account.*

Neutron poisoning

Neutron poisoning is used when the process requires the use of large volume equipment, which cannot be made with a safe geometry, or where sets of equipment have to be isolated neutronically from each other. The presence in sufficient quantity of neutron poison shall be guaranteed […].



Loading a PWR spent fuel assembly into a TN 12 shipping container under water.

M. Crepin/Photothèque EDF

margins is left in the hands of experts. This assessment takes four criteria into account: the evaluation of the variation of k_{eff}, the degree of conservatism linked to the calculation model (simplification of geometry and of composition), the likelihood of the scenario which corresponds to the *boundary situation* chosen for accident situations and lastly the qualification rating for the calculation software for the case studied (the RFS here refers to qualification *on an experimental basis*).

Limiting the consequences of a criticality accident

The preventive measures taken, however perfect, only make it improbable and not impossible to encounter an uncontrolled chain reaction in a facility in which the quantity of fissile material is potentially supercritical: this is where a criticality accident occurs (see *Studying the phenomenology of criticality accidents* and *The Tokaï Mura criticality accident*). Additional measures have to be taken aimed at limiting as far as possible the consequences of any accident for the facility workers, for nearby members of the public and for the environment.

These measures focus on three main aspects: early detection of the accident, organizing the rapid evacuation of personnel concerned, and intervention aimed at stopping the accident where necessary.

Criticality detection and alarm

There is no measurable precursor of a criticality accident. The detection systems use the fact that a chain reaction is accompanied by a significant flux of neutrons and gamma (γ) radiation. Detectors judiciously located in the personnel circulation zones give a signal which triggers a set of visual and audible alarms when the total dose (neutrons + γ) and the **dose rate** reach predetermined levels ($2.5 \cdot 10^{-5}$ Gy and $1 \cdot 10^{-2}$ Gy/h respectively for the French "EDAC" system described in the following article)(2).

These systems are designed to reduce the risk of false alarms as far as possible and can also provide useful information on the accident (its location, dose evaluation) to help during any subsequent remedial action.

Evacuating personnel

Limiting the radiological consequences for personnel of a criticality accident depends largely on the ability to evacuate the affected zone quickly. Personnel must therefore have been trained to evacuate the site toward assembly points *via* previously determined and signed routes. The layout of detectors and evacuation routes is optimized by studying accident scenarios specific to each facility.

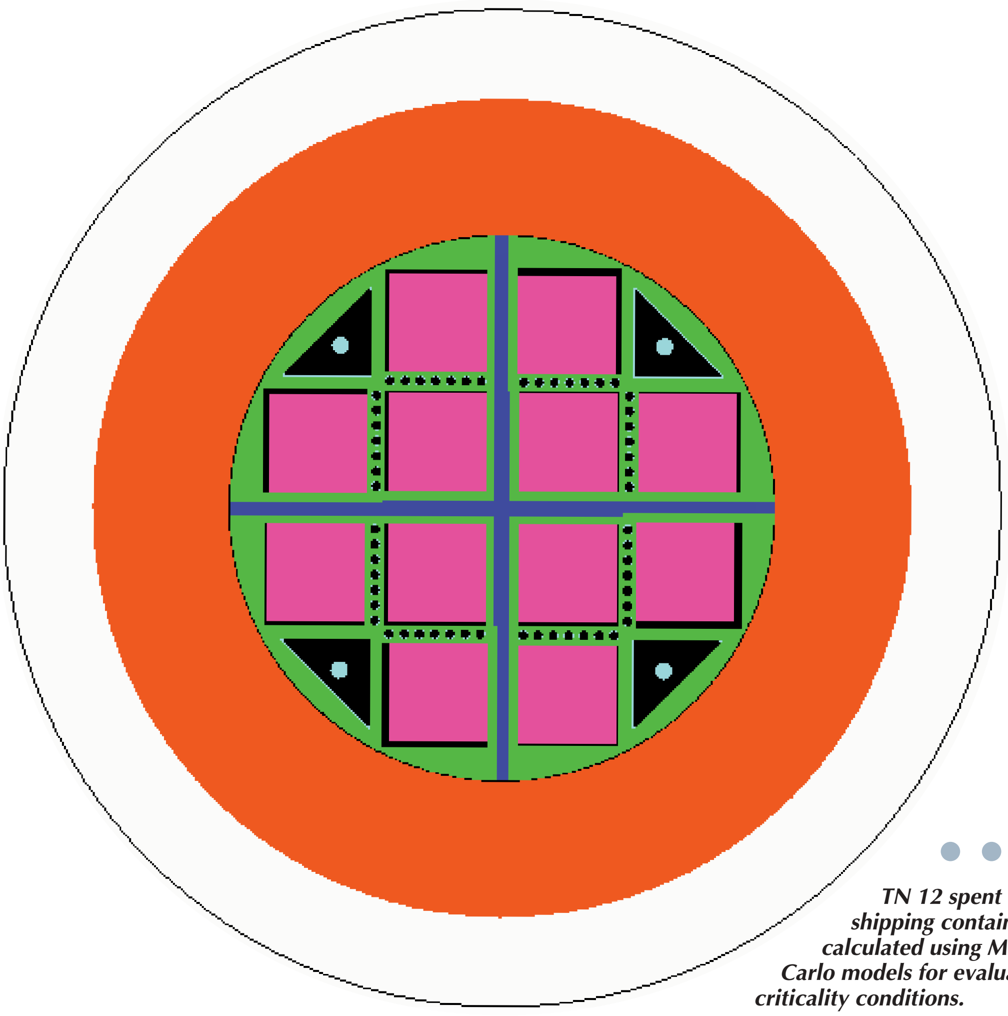
Intervention in the event of a criticality accident

Experience drawn from previous criticality accidents, in particular the most recent in Japan in 1999, shows that it may be necessary to intervene to stop an accident if it will not stop quickly enough on its own. This may consist in "poisoning" the fissile medium by adding a solution or powder containing neutron-absorbing material, transferring a fissile solution which is the seat of the accident to a geometry which guarantees a subcritical state, or eliminating a neutron reflector (by draining the water from the cooling circuit in the case of the Tokaï Mura accident). In the light of this last accident, the French safety authorities asked all operators of facilities concerned by the risk of criticality to re-examine the means they had of detecting an accident and of intervening to bring it to an end, and to propose any necessary improvements.

Vigilance and observing principles

The risk of criticality in nuclear facilities is controlled by imposing strict limits on certain clearly identified *control*

(2) Unlike certain facilities, where the interruption of a permanent alarm signals the accident.



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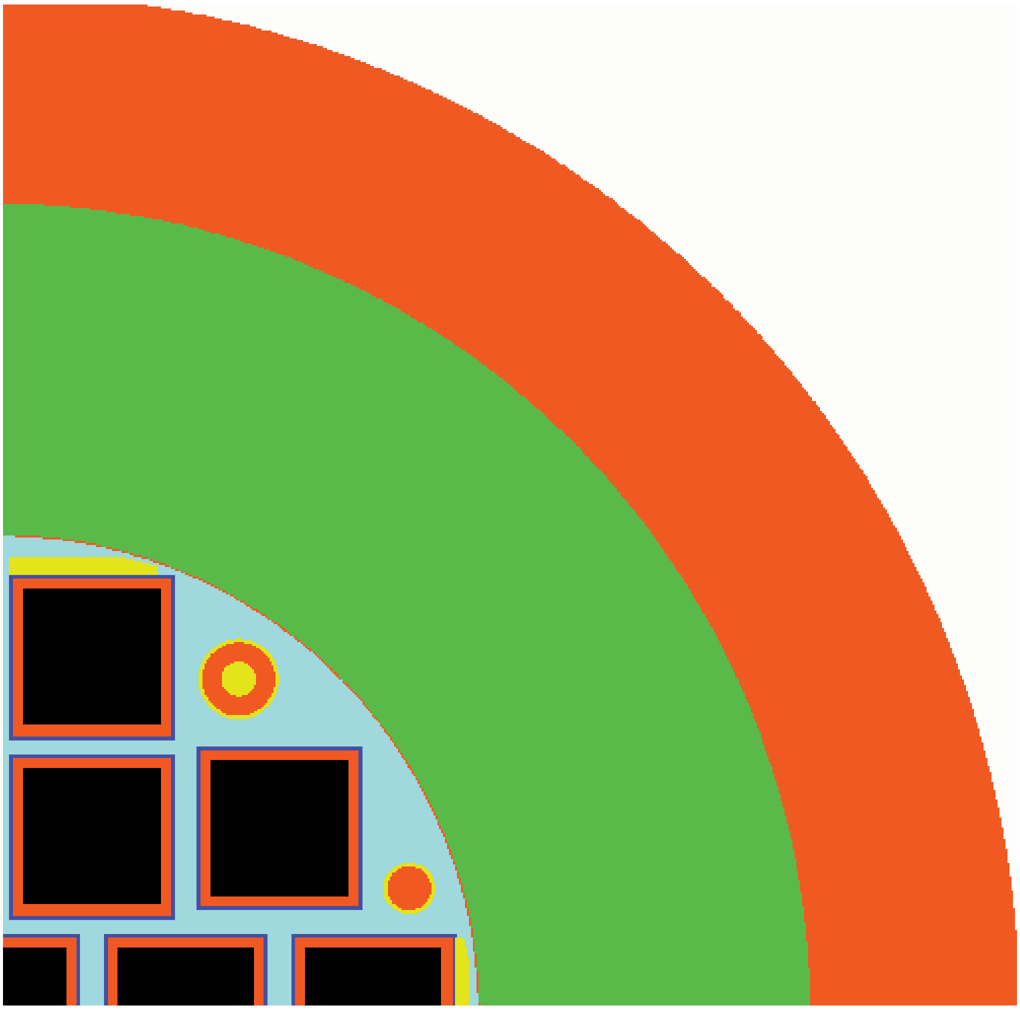
TN 12 spent fuel shipping container calculated using Monte Carlo models for evaluating criticality conditions.

TN 17 spent fuel shipping container calculated using Monte Carlo models for evaluating criticality conditions.



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parameters. These limits are defined by an exhaustive study of conditions of criticality for all equipment that might contain fissile material, taking into account their specific environment, and the safety design boundary parameters must be compatible with the “dual eventuality principle” set out in the Fundamental Safety Rules (box).

The calculation tools used by criticality engineers have already reached a high level of accuracy thanks to progress made in neutron processing models and the knowledge of basic nuclear data. These enable engineers to research the best safety conditions for most situations without making excessive approximations. Developments and qualification work currently in progress will improve their accuracy even further, for example calculating spent fuel criticality (see *Spent fuel criticality*) in order to better evaluate the safety margins and to optimize the safety-criticality constraints from both technical and economic perspectives.

Finally, it must be remembered that the prevention of risk of criticality is carried out by humans. The many failures in the human chain revealed in the Tokaï Mura accident show the importance of training and organization in the control of safety and of all of the factors that promote the vigilance of all parties concerned.

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