Inadvertent Boron Dilution Events during shutdown states in French PWR

Detection means efficiency and necessary improvements

Delphine PLASSART, Aude TAISNE, *Olivier DUBOIS*

Institut de Radioprotection et de Sûreté Nucléaire (IRSN) – PSN-RES/SEMIA

Fontenay aux Roses, 92262, France

Abstract:
In French PWRs, inadvertent homogeneous boron dilution events during shutdown states are supposed to be detected by 2 or 4 source range neutron flux channels (SRNFC) located around the reactor vessel. Yet, the analysis of a new set of rules aiming to prevent criticality risks, named "Criticality Requirements Reference State", has brought to light that, during refuelling (i.e. in dissymmetric core configuration), the functional capacity of the nuclear instrumentation system is non-efficient (at the beginning of refuelling) or limited (only one source range channel is able to detect dilution from half-refuelling on). In order to find a solution for this incapacity, EDF has considered as a possible strategy the use of already in-place instrumentation (Boron Concentration Measurement System - BCMS) or manual boron concentration measurements to detect inadvertent boron dilution events during shutdown states. The IRSN evaluation concluded that the BCMS reliability and manual measurements frequency were insufficient, pointing out the need to strengthen existing features by an extra boron dilution detection system which would be redundant, diversified and independent of the present BCMS.

1 Introduction

The criticality accident which occurred at the Tokai-Mura nuclear fuel plant on September 30, 1999 led EDF to a technical review on criticality risks related to fuel operation processes on French nuclear power plants. This work led to the creation of the "Criticality Requirements Reference State" in 2003. This document is the application of the French regulations concerning criticality risks mentioning that:

"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."*

The Criticality Requirements Reference State describes the modalities of criticality risk considerations during operations in the fuel building and in the reactor building when the reactor vessel is open, and stipulates requirements for criticality studies such as acceptance criteria, studies rules and methods, uncertainties considerations, validation of computer codes.

Among the criticality risks analyzed in this document, the inadvertent boron dilution events during shutdown states are considered.

2 Safety analysis of inadvertent boron dilution events during shutdown states

Four shutdown states are distinguished:

- State 1: state during refuelling operations;
- State 2: state with the core completely loaded but the vessel opened;
- State 3: state with the core completely loaded and sub-critical, the vessel is closed but the control rod system is not yet available;
- State 4: state with the core completely loaded and sub-critical, the vessel is closed and the control rod system is available.

NB: In France, only dilutions in states 2 and 4 are analyzed in the Safety Analysis Report. Dilutions in state 1 are taken into account in the Criticality Requirements Reference State and dilutions in state 3 are considered in a document named Operation Technical Specifications.

The decrease of the boron concentration in the water of the primary cooling system induces an insertion of reactivity in the reactor core which is initially sub-critical.

During states 1, 2 and 3, the dilution cannot be stopped without human intervention: when the neutronic flux, Φ, increases by a factor n, operators are warned by the alarm delivered by source range neutron flux channels measuring the neutron leak flux, located around the reactor vessel. It shall therefore be demonstrated by the licensee that the time-frame between alarm emission and reaching critical conditions is large enough to allow the operator to inject boron and to isolate the dilution source. The analysis principle is illustrated in Figure 1Figure 1Figure 1. Note that the alarm emission occurs when the core sub-criticality, ρ, has been decreased by a factor n, assuming that $\rho.\Phi$=constant.

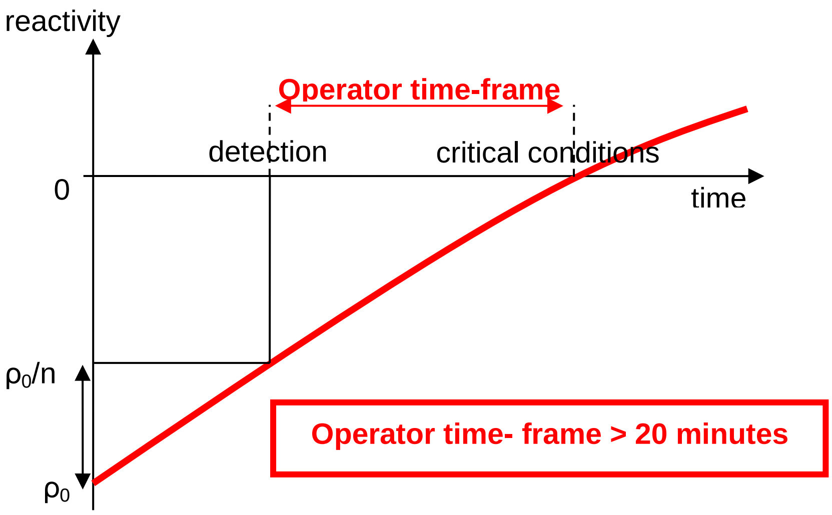

Figure 1 : Safety demonstration principle for dilutions occuring during states 1, 2 or 3

During state 4, the safety control rod system is operational. In case of boron dilution, SRNFC give the signal to activate the scram in order to shut down quickly the reactor and to proceed automatically to the borication. This signal is emitted when the instrumentations measure a certain level of neutronic flux. At this level, the core reactivity, ρ_{scram}, is positive. Safety demonstration is based on the control rods efficiency, $\Delta\rho_{scram,}$ which has to be higher than the supercriticality at the scram occurrence, ρ_{scram}, plus the insertion of reactivity due to the residual dilution, $\Delta\rho_{dilution}$ (while the dilution is not effectively stopped). The analysis principle is illustrated in the Figure 2Figure 2Figure 2.

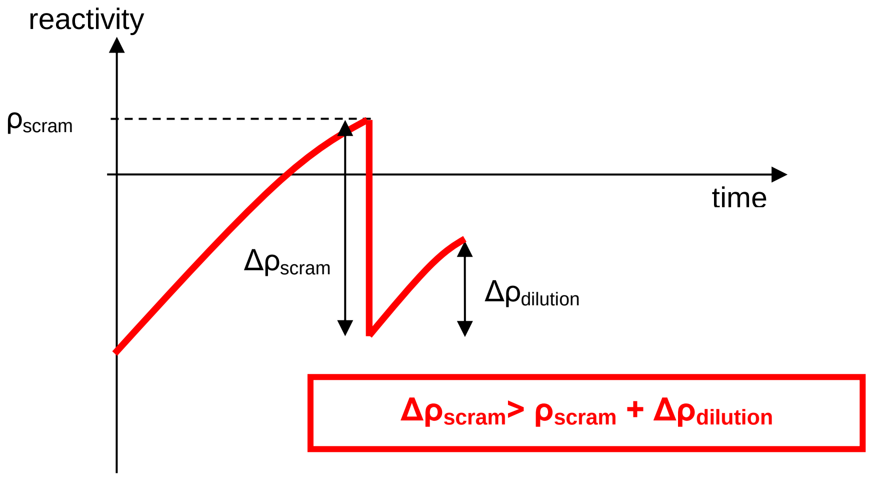

Figure 2 : Safety demonstration principle for dilutions occuring during state 4

3 Source range channel nuclear instrumentations deficiency

In 2001, an error during the refuelling sequence led to a situation close to criticality in a French reactor core. Although the accident has been avoided, SRNFC failed to detect an abnormal neutron flux increase. This observation led EDF to query the capacity of the SRNFC to detect a possible dilution. A thorough assessment of the SRNFC revealed that the approximation "$\rho.\Phi$=constant" resulting from the use of the scattering equation in a homogeneous medium considering a single energy group (0D model) was adapted to simulate the global core response, but not the SRNFC response.

A 2D modelling of the SRNFC response allows a more accurate analysis of the real neutron flux. It appears in Figure 3~~Figure 3Figure 3~~ that, when the alarm occurs, the core reactivity is higher than expected by the 0D model. Consequently, the operator time-frame is over-estimated with a 0D model if a dilution occurs in states 2 or 3.

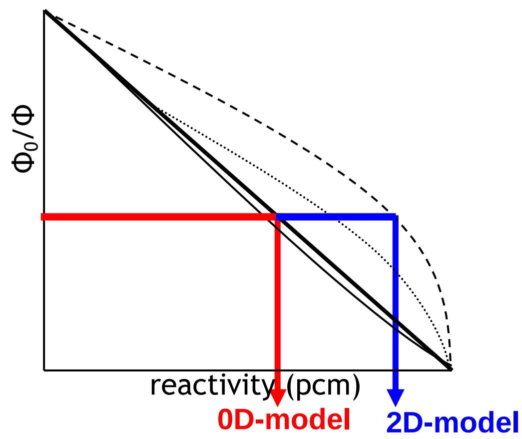

Figure 3 : Correlation between flux measured by SRNFC and reactivity considering 0D-model or 2D-model (considering different fuel managements)

This phenomenon is due to the following reasons:

- SRNFC detects only the fast neutrons flux in fuel assemblies located the closest to detectors;
- for low fluence fuel management, assemblies situated in the core periphery and therefore close to the SRNFC are among the most irradiated. Yet, the more the assemblies are irradiated, the more the effect of the dilution on the neutron flux decreases. During a dilution, a radial flux redistribution occurs and the SRNFC flux measurement is therefore not well correlated with the core reactivity.

Incomplete core configuration (state 1) amplifies the difficulty for the SRNFC to represent, in a reliable way, the core reactivity evolution. Indeed, Figure 4~~Figure 4Figure 4~~ shows that during refuelling operations (state 1) only the SRNFC close to the reloaded assemblies would be able to measure a significant neutron flux. Therefore, there is no redundancy on the detection system which is not acceptable for a safety-related system.

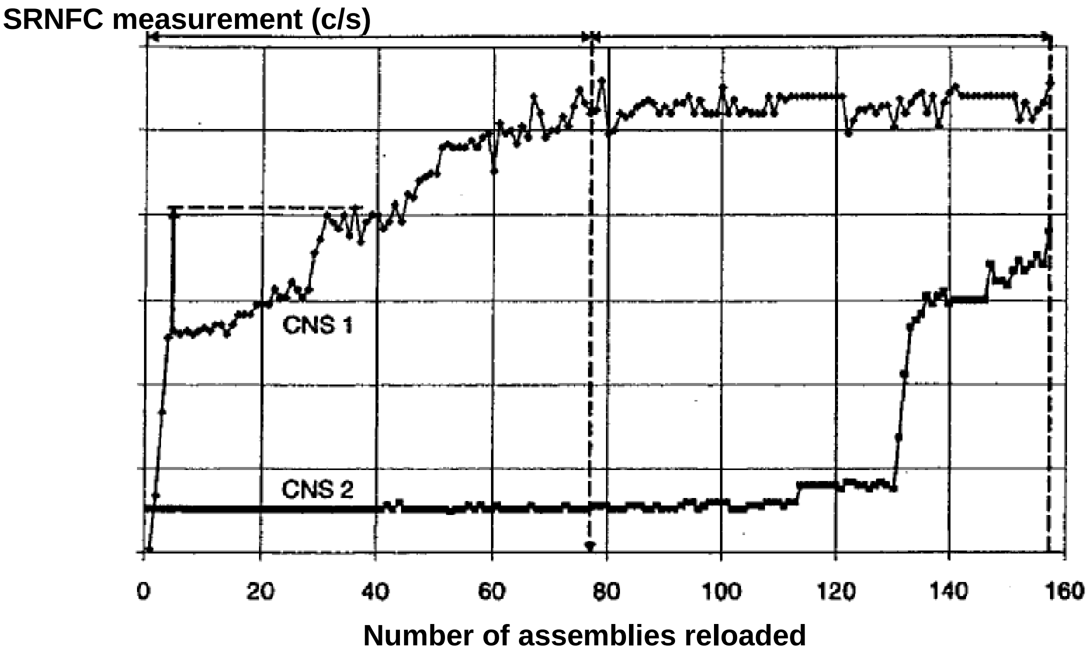

Figure 4 : An example of SRNFC flux measurements during refuelling operations

For state 4, the SRNFC flux measurement is probably correctly correlated with the core reactivity, because the scram occurs when the core is over-critical and thus when the radial flux distribution is homogeneous. Consequently, there must be no SRNFC deficiency for this state.

4 Assessment of possible improvements

Incomplete core

For state 1, because the SRNFC are not able to detect dilution events, EDF has considered the possibility to use boron concentration measurements to detect the dilution: on-line measurements with the Boron Concentration Measurement System (BCMS) situated on the nuclear sample circuit and, in case of BCMS deficiency, manual periodic measurements by a chemist.

Thorough IRSN assessment concluded that the BCMS is not reliable enough to assume the requirements of the “reactivity control” safety function. In particular, the BCMS is not redundant. Furthermore, IRSN considers that the manual measurements periodicity is not sufficient to ensure an early enough detection of a dilution and that the manual measurements are not a long-lasting solution anyway. Finally, IRSN has come to the conclusion that it was necessary to strengthen existing hardware features. EDF is studying therefore an extra redundant, diversified material solution independent from the BCMS, because initially this system was not designed to assume a safety function.

Complete core without scram available

For states 2 and 3, because the SRNFC are not able to detect dilution events early enough, the operator time-frame could be restored by means of a reduction in the threshold of the

SRNFC alarm from $n\Phi_0$ to $N\Phi_0$ with N chosen as a compromise between allowing sufficient time for the operator and avoiding inopportune alarm triggering.

The determination of the SRNFC alarm threshold ($N\Phi_0$) is to be justified. But it appears that this determination will need:

- 3D calculations to quantify the differences between flux evolution seen by the SRNFC and average core flux evolution during the dilution and,
- Operational feedback data concerning flux evolution measurements during dilution in plants operation.

Complete core scram available

For state 4, because the SRNFC scram is not affected by the anomaly, the present demonstration is still available. Nevertheless, IRSN considers necessary to continue the assessment for this state in order to convince itself that the SRNFC scram is not affected by the anomaly.

5 Current situation in some other countries

Some information collected about the situation in other countries on the criticality risk in case of homogeneous boron dilution in shutdown states led to the following lessons:

- for all of them, as in France, the dilution is prevented by administrative measures, such as instructions or specific valves locking, required by the operation technical specifications;
- some of the reactors abroad still rely on SRNFC to detect homogeneous dilutions;
- only few countries use boron concentration measurements to detect dilutions events, in addition to SRNFC.
- a majority of them estimate that if certain dilutions are not detected, this will have no significant safety impact because the consequences of such criticality events are relatively minor. Therefore improvements are not under consideration in those plants.

These informations revealed that there is no convergence of technical nuclear safety practices on this issue because:

- the regulation requirements are not similar; reaching critical condition is forbidden or not during shutdown states.
- the confidence on detection means of the flux increase depends on the country; it may be due to different loading patterns for which the detectors are not blinded by a unfavourable radial redistribution during dilution, or any other reason.

It would therefore be interesting to initiate technical exchanges on these points with each concerned country in order to converge on this issue.

6 Conclusion

Initially, shutdown states were not really considered in the safety demonstration of French PWR. Nevertheless, since the 90's, some design or operational improvements were implemented to reduce risks in shutdown states, and a "Criticality Requirements Reference State" has been introduced in nuclear power plants during their periodic safety review. This Requirements Reference State denotes awareness that a reactor, although intended to become critical, may, in some shutdown states, be treated in a manner comparable to any other nuclear installation with a risk of criticality, especially for workers present in the reactor building during these states. Therefore, in France, even if the consequences of a criticality accident are minor, to bring the reactor to criticality is forbidden during shutdown states.

Dilution accidents are a part of the accidents considered during shutdown states but, the means (SRNFC) designed to detect dilutions events proved to be not sufficiently efficient; the need arose to enhance existing features. This should be done by hardware modifications. One solution under consideration would consist of the implementation of a second BCMS on the let-down line of the volumetric and chemical control system in order to detect dilutions wherever they come from. Until an efficient solution, operators have been asked to pay extra attention to the dilution risk during shutdown states.