Vincent ROUX
INB 101 – Orphée reactor
CEA – Paris-Saclay, France

IGORR 18

ABSTRACT

Findings and results of safety reassessments and safety improvements on the ORPHEE research reactor

The Orphée reactor is a 14 MWth research reactor located at the CEA site in Saclay, France. The main function of the reactor is to supply neutron beams for fundamental research. The reactor first went critical on December 19th, 1980.

Periodic safety review (PSR) and post-Fukushima stress tests have been conducted on the reactor over the past few years. Since the commissioning of the reactor, the Orphée reactor has gained experience in conducting PSRs and implementing safety improvements. The second PSR was released in 2009. The on-going third PSR will be submitted to the ASN in 2019.

The safety reassessments are realized to verify that the reactor is operated with a good level of safety, meaning that the reactor is in conformity and that the safety cases still meet the requirements even after the evolution of regulation and safety analysis standards. For the Orphée reactor, the findings from the conformity analysis and the safety reassessments have resulted in the implementation of both operational improvements and safety related equipment.

After the Fukushima accident, in respect with the regulatory requirements, the safety margins to reach and maintain safe state have been evaluated for extreme external hazards and relevant cumulative losses. For the Orphée reactor, a hard core of robust equipment has been defined for the monitoring of a safe state in extreme situation. The robust design of the Orphée reactor enables to withstand long time loss of heat sink or loss of electrical power thanks to passive residual heat removal design and important inertia of the water capacities. Regarding external hazards, the site of Saclay has a low seismicity risk. The safety improvements mainly consisted in the implementation of reactor emergency shutdown on seismic signal, implemented to strengthen the control rods drop in case of extreme seism. An ultimate emergency control panel with the report of minimal information for the monitoring of safe state has been installed in a local with sufficient seismic margins.

This paper describes the relevant findings from the periodic safety reassessment and post-Fukushima stress tests in relation with external hazards, and safety improvements that were implemented on Orphée reactor to fulfill the requirements of safety levels from the regulatory body.

Vincent ROUX
INB 101 – Orphée reactor
CEA – Paris-Saclay, France

FINDINGS AND RESULTS OF SAFETY REASSESSMENTS AND SAFETY IMPROVEMENTS ON THE ORPHEE RESEARCH REACTOR

Figure 1: Orphée reactor in Saclay

I. Introduction

Since the commissioning of the reactor in 1980, periodic safety reviews (PSR) are performed. The first of them was done in 1995. Over the past few years, the PSR and post-Fukushima stress tests have been conducted. The safety reassessment released in 2009 was realized to verify that the reactor is operated with a good level of safety, meaning that the reactor is in conformity with the safety report and that the safety cases still meet the requirements even after the evolution of regulation and safety analysis standards. In 2012, after the Fukushima accident and in respect with the regulatory requirements, the safety margins to reach and maintain safe state have been evaluated for extreme external hazards and relevant cumulative losses.

The findings from these safety reviews have resulted in the implementation of both operational improvements and safety related equipment.

This paper describes the relevant findings from the periodic safety reassessment and post-Fukushima stress tests in relation with external hazards, and safety improvements that were implemented on the Orphée reactor to fulfill the requirements of safety levels from the regulatory body, especially regarding seismic hazard.

II. Presentation of the Orphée reactor

The main function of the Orphée reactor is to supply neutron beams for fundamental research. Neutron spectrometry provides data on material structures and energy levels in condensed matter that is unobtainable by other methods.

The Orphée reactor is a pool type research reactor with a rated power of 14 MWth. It generates a maximum thermal flux of 3.10^{14} $n.cm^{-2}.s^{-1}$ in a heavy water that acts as a moderator (by slowing neutrons) and a reflector. This makes possible a wide range of neutron spectrometry experiments. It is used by researchers in a number of fields, e.g., chemistry, metallurgy, physics, as well as for neutron radiography, activation analysis and the irradiation of various samples. The reactor first went critical on December 19th, 1980.

It was designed taking into account the experience accumulated by the CEA in the construction of research reactors and, in particular, that of the Haut Flux reactor in Grenoble.

The very compact reactor core is cooled with a demineralized light water primary coolant circuit and is immersed in a pool, also filled with demineralized light water. The water of the reactor pool provides protection against radiation while allowing easy handling. The core is composed of 8 parallel-plate fuel assemblies. The fissile material of the fuel plates is an alloy of aluminum and enriched uranium in ^{235}U, cladded in aluminum.

1. Core
2. Heavy water reflector
3. Transfer canal
4. Primary cooling system
5. Hot source
6. Cold source
7. Pool
8. Heath exchanger
9. Pump
10. Neutron guide
11. Spectrometer

Figure 2: vertical cut view of the reactor core

Its experimental potential consists of:

- 9 horizontal channels allowing the use of 20 independent neutron beams:
    - 8 beams receive thermal neutrons,
    - 8 beams receive neutrons previously slowed down by 2 cold sources at the temperature of the liquid hydrogen, six of the 8 beams fed with neutrons slowed down, channeled by "neutron guides", leave the reactor building to be used in the adjoining hall of guides,
    - 4 beams receive neutrons warmed by a hot source.
- 9 vertical channels allowing activation analysis and irradiation activities.

The neutron sources are mainly used by the Léon Brillouin laboratory (LLB) the neutron beams inside and outside containment in the hall of guides through 25 experimental areas.

III. Findings of the periodic safety review

III.1. Methodology

The periodic safety review (PSR) of the reactor is performed every 10 years, according to the existing regulation. The last PSR was released in 2009. The review is realized following a methodology in agreement with the requirements of the safety authority. The safety review consists in the three following main steps:

- Lessons learned
  The experience gained from the operation of the reactor is analyzed. It is also analyzed the possibility of drawing lessons relevant for the future of the facility, from significant events occurred since the previous safety review on similar facilities in France and foreign countries.
- Conformity analysis
  The purpose of the conformity analysis is to verify that the facility, as operated at the time of this review, complies with the regulations and the safety standards. That is, the facility verifies all the safety requirements defined in its design, during the previous safety reassessments and following modifications to the installation. The conformity review is conducted based on the operating

documents (periodic tests and control programs, operating procedures, instructions, plans), and ageing assessment.

- Safety reassessment
  The objective is to conduct an assessment and, if necessary, update the safety demonstration in the light of the evolution of regulatory requirements, safety practices and good practices and, where applicable, safety rules and guides. The analysis covers the incidents and accidents from internal events based on a graded approach, the analysis of internal and external hazards, and the organizational and human factor analysis.
  This analysis can conclude in the need for upgrade the safety demonstration or implement safety improvements.

III.2. Overall conclusion

The conformity verification of the facility has shown the overall good state of conservation of the utility. A few minor non conformities were identified and required corrections. The main works have concerned the polar crane, civil work, fuel storage casks and piping supports for which minor repairs have been made. These have been implemented without major difficulties.

The major evolutions due to the safety reassessment consisted in the operating situations analysis, including incident and accidents studies, performed with a graded approach. These studies have concluded to the good level of safety of the reactor. The operating situation analysis resulted in one main improvement. In case of failure of the heavy water cooling system, the reliability of the shutdown of the reactor has been improved by the implementation of an automatic shutdown of the reactor. These studies have been added to the nuclear safety rule set.

As regard to internal and external hazards, important works have been conducted to improve the protection against the effects of fire and flooding, and to upgrade the protection against the effects of lightning.

The new approach of organizational and human factor analysis conducted to several improvements, both in procedures and material improvements, especially for fuel handling operations.

Finally, the PSR concluded that the operation of the reactor could carry on with a good level of safety.

III.3. Focus on findings related to seismic effects

For the safety reassessment, the behavior of the main safety function under seism has been verified with calculations and mechanical studies.

The seismic risk was taken into account during the design of the reactor on the basis of a maximal security seism (SMS) intensity V on MSK scale. The standard spectrum of the NRC Regulatory Guide 1.60 was considered at the time to represent SMS. This spectrum was ranged to peak ground acceleration (pga) of 0.025g.

The PSR in 2009 was conducted taking into account the reference seismic response spectra ranged to pga of 0.1g specified in the applicable safety rule RFS 2001-01 (see figure 3 below), so called *séisme forfaitaire* (SF).

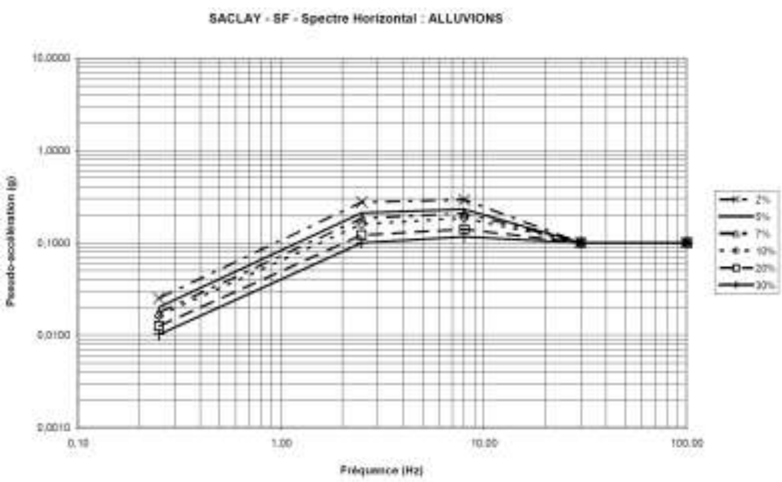

Figure 3: reference seismic response spectra for the site of Saclay

The good behavior of the civil work of the containment building, internal structures and heavy water building has been verified, as well as the capacity of the control rods to drop during a seism of this higher intensity. The integrity under seism of the main piping of the primary cooling system and the operability for opening after seism of the natural convection check valves was verified.

Limited weaknesses were identified on the polar crane and the fuel storage casks. So, improvements have been implemented.

IV. Findings of the post Fukushima accident stress tests

IV.1. Methodology of the stress test

At the request of the french nuclear safety authority (ASN), the CEA carried out an additional assessment of the safety of the Orphée reactor, in view of the accident at the Fukushima power plant. The robustness of the utility was assessed regarding the considered extreme external hazards and the postulated losses of electrical power supplies or heat sink. The objective was to identify possible weaknesses that could possibly result in cliff effect and to determine the existing margins with regard to these situations.

For the Orphée reactor, the events likely to result in a risk of cliff effect are defined as:

- the dewatering of the fuel assemblies loaded in the reactor or stored in the pool, that would result in fuel melting,
- the ruin of the containment building coupled with a release of radioactive products.

The analysis resulted in the definition of a set of structures, systems and components (SSC), so called *hard core*, dedicated to:

- prevent the occurrence of a severe accident, or limit its progression,
- limit massive releases of radioactive products into the environment in case of an accident,
- enable the utility to carry out the operations and the management of an emergency situation.

The mission of the hard core is, in case of extreme situation resulting from an extreme external hazard event, to prevent a cliff effect in the radiological consequences of an accident, and allow the crisis management in extreme situation.

The essential SSCs identified as necessary to reach and maintain safe state are related to the reactor reactivity control (availability of emergency shutdown chains and associated equipment), the cooling capability of the core and spent fuel, and the containment. These materials are:

- the equipment allowing the control rods drop,
- the natural convection valves,
- the concrete walls and steel liners of the reactor pool and the transfer canal.
- the reactor, which supports the core and the heavy water tank, guides the control rods and maintains the cooling channels of the core in natural circulation, is also considered essential equipment.

In addition, the equipment identified as necessary for monitoring the safe state of the utility is the I&C allowing knowing:

- the low position of the control rods,
- the opened position the natural convection valves,
- the level and temperature of the water in the pool and transfer canal.

The behavior on the reactor was studied and the existing margins were assessed in the following extreme external hazards situations: seism, strong wind and snow, heavy rain and flooding, lightning, hail.

The main findings of the analysis are presented in the next chapter. The safety related improvements implemented from these findings are presented in the chapter V.

IV.2. Main findings of the stress tests

IV.2.1. Seismic related

The overall behavior of the utility was evaluated in relation to the reference seismic hazard (SF) applicable to the CEA site of Saclay which is located in a low seismicity zone.

The following table presents the seismic margins of the main SSCs to achieve their safety function. The structures of civil work having a key role in maintaining the containement function have been analyzed.

Safety function	Equipment	Seismic margin (times SF)
Reactivity control	gravity control rod drop	2.0
Cooling	natural convection check valves	4.0
	civil work internal structures of the pool and transfer canal	2.3
	reactor and support	1.7
Containment	reactor building	2.0
	heavy water building	1.6
	reactor chimney	1.3
	ventilation building	1.3
	safeguard ventilation system	1.5

The loss of stability under the effect of the earthquake of equipment which could swing towards the pool or the transfer canal could represent a risk of damage to the spent fuel stored for cooling. These surrounding equipment present margins higher than 1.5 for the most relevant of them.

Following the review based in a first time on safety margin analysis, the extreme seism for the site of Saclay, so called *hard core seism* (*séisme noyau dur*: SND), has been defined equal to 1.5 times the maximal security seism (SMS). The figure below gives the response spectra for this hazard.

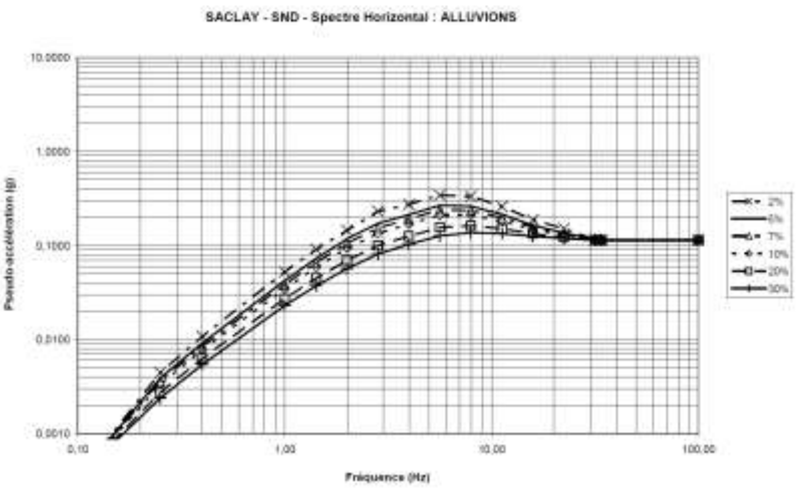

Figure 4: hard core seism (SND) - response spectra for the site of Saclay

On the basis of the upgraded hard core seism, the robustness of the reactor support, including core housing and heavy water tank, and leak tightness of the pool liner has been verified. It was verified these equipment could ensure their safety related function in case of en extreme seism, with margins with respect to the SND.

Cumulative seism and seismic induced event

The cumulative effects of a seismic with the risk of flooding induced by an earthquake do not lead to an increased risk of cliff effect.

The main risks of seismic induced flooding could originate from:

- The large piping and basins of the secondary cooling system (ES), which are guaranteed in the event of a level earthquake equal to 1.3 times the level of the SF.

This risk is attenuated by arrangements to prevent a flooding in the ES subsoil affecting the subsoil adjacent to the building ventilation. These provisions will in particular make it possible to keep available the safeguard ventilation as well as that of the machinery of the material lock.

- A leak on a circuit connected to the pool or transfer channel.
  The additional safety assessment shows that in this case there would be no discharge of contaminated water to the environment.

There is no identified risk of cliff effect from the risk of rupture of other pipes.

As a conclusion of the stress tests, the evaluations carried out showed no risk of cliff effect in the event of an earthquake up to a level of stresses of up to 1.5 times the level of seism to the CEA site of Saclay (SF).

IV.2.2. Other extreme situations

The risk assessment of flooding and extreme weather does not indicate any risk of cliff effect.

The loss of power supplies or the loss of heat sink, whether induced by a seism or not, have the same effect concerning the risk of cliff effect. In these situations, the residual heat of the fuel is removed by evaporation of the water of the pool. Without any water supply, the decrease of the water level would present a risk of dewatering the reactor core and the fuel elements stored in the pool. However, the pool and the transfer canal represent a large inertia for passive cooling. The delay before dewatering the fuel elements stored in the reactor pool is varying from about 200 to 700 days, depending on the reactor initial state and the cofferdam position. In this extreme situation, no risk of cliff effect is identified as any risk of fuel melting is discarded after 100 days of underwater cooling.

The Orphée reactor takes advantage of large reserves of water in the pool and the transfer canal. Additional water refill could be possible through the central fire network or the FLS pumping means in the CEA site basins, or even the Saclay neighboring ponds.

V. Focus on seismic related safety improvements

V.1. Improvements issued from the periodic safety review

A number of safety improvements related to seismic hazard have been issued from the PSR of 2009 conducted on the basis of the reference response spectra for Saclay site (SF). This work mainly consisted in structural reinforcement.

fuel storage racks

For the underwater spent fuel racks located in the reactor pool, missing bolts at the level of the anchorage of the rack support were discovered during the conformity analysis. The reinforcement consisted in the setting of an additional maintain of the top of the guiding tubes of the racks. This modification of the racks has been verified to the extreme seism SND.

The fresh fuel storage racks have also been reinforced after the periodic safety review. The storage racks have been reinforced to prevent their tilting in case of seism. The implemented reinforcement has been verified to the extreme seism SND too and has shown sufficient margins.

polar crane

The mechanical studies of the behavior of the polar crane under seism have identified localized and very limited weaknesses of the bolted structure. A number of bolts have been replaced by higher class material to ensure a higher resistance of the bolted joints, and to consolidate safety margins.

V.1. Improvements issued from the stress tests

The conducted safety stress tests have concluded that there was no risk of cliff effects in case of extreme seism up to 1.5 times the reference seismic hazard for the site of Saclay. However, it was enhanced that some dispositions showing an interest for the management of extreme situation could be implemented to improve further the robustness of the utility respect to:

- the effects of a seism induced flooding situation,
- the long term total loss of electrical power,

- the long term loss of water supply to the reactor pool.

With respect to the conclusions of the review, the following improvements have been implemented:

- An emergency shutdown of the reactor on detection of a seismic event. The threshold was set at 0.04g, which is enough for the low seismicity area of the site of Saclay.
- An automatic cofferdam protects the ventilation system from a seism induced flooding resulting from the collapse of the secondary coolant system piping.

Also, a set of equipment, defined as the *hard core*, ensure the monitoring of the safe state of the reactor in case of extreme situation that would have led to the unavailability of the main control room and the existing backup control panel of the reactor:

- An ultimate control panel (PECS) has been installed, displaying the minimal information for monitoring the safe state of the reactor. The panel displays the detection of the inserted position of the control rods, the position of the natural convection check valves, and the level and temperature of the water of the reactor pool and the transfer canal.
  This control panel is power feeded by a dedicated ultimate emergency diesel generator, designed for extreme seism.
  The information is transmitted automatically to the PCD-L. These equipment, and the I&C components for the information control and display are part of the *hard core*.
  This panel provides a backup for the opening of the material lock. A leak tight door for the opening mechanisms has been installed.
- An additional connection device to the emergency water supply system allowing a water make-up to the pool and transfer canal capacities by the means of external firefighter pumping equipment.

Also, the crisis management was assessed, and a batch of emergency procedures have been written and enforced.

VI. Conclusion

This paper has presented the main safety related improvements implemented on the Orphée reactor within the past years consecutively to periodic safety review and post Fukushima advanced safety review. Many improvements have been implemented to meet the regulatory and safety guides evolutions.

In the field of external hazards, the site of Saclay has a low seismicity. Nevertheless, important works and utility modifications have been implemented to reinforce its robustness, and fulfill the evolution of requirements for seismic hazard.

For the next periodic safety review due in 2019, the safety reassessment will be covering the specific activities related to operations to be done during the definitive shutdown of the reactor and in the long term, decommissioning.