Research reactor in the event of an earthquake: Safety targets, technical approaches and work carried out

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The Institut Laue-Langevin is an international research organisation and world leader in neutron science and technology. Since 1971 it has been operating the ILL High Flux Reactor, the most intense neutron source in the world.

In 2002, at the end of the second reactor safety review opened in 1995, the safety authorities asked the ILL to present an analysis of the safety of its installations in the event of an earthquake, with a definition of the Safety Related Equipment in the event of an earthquake (the "SRE-S") and an assessment of the operational and associated technical requirements. The Safety Authorities also requested the demonstration that these requirements were being met, and an analysis showing that no damage would be caused to the SRE-S by non-SRE-S structures situated nearby.

A team was set up at ILL to work on this programme. Its mission was to identify and implement solutions best meeting the requirements of the Safety Authorities.

This article provides details on the organisational framework established for the programme and the methodology employed. It also outlines the safety targets set for the event of an earthquake, the technical approaches adopted, and the work carried out since the end of 2002, as regards:

- the reactor building,
- the equipment assuring critical seismic safety functions, i.e. control of sub-criticality, cooling of irradiated fuel, and containment of the installation,
- the buildings close to the reactor building, in need of reinforcement or partial dismantling, depending on their purpose.

1. Context

The Institut Max von Laue - Paul Langevin is a pan-European research organisation and the world leader in neutron science and technology. Since 1971 it has been operating the ILL High-Flux Reactor (HFR), the most intense continuous neutron source in the world.

The ILL is governed by an intergovernmental Convention between France, Germany and the United Kingdom, which was signed in 1967; since then several other countries have joined the ILL as Scientific Member countries: Italy, Spain, Switzerland, Russia, Austria, the Czech Republic and Sweden. The fourth ten-year extension to the agreement was signed at the end of 2002, thus ensuring that the Institute will continue to operate until at least the end of 2013.

Thanks to the reliability of the HFR since its very first years of operation, scientific output at the ILL has developed in a spectacular fashion, allowing the Institute to become the world's foremost neutron facility in terms of scientific publications.

The Millennium Programme, a 20 M€ development plan, was set up in 2000 with the aim of launching an accelerated but sustainable programme of instrument renewal which will maintain the ILL's leading position. Over the next 10 years, a further 100 M€ of investment is foreseen for the Millennium Programme. By way of comparison, the annual ILL general budget is around 75 M€.

In 2002 the facility underwent a general safety review, including an assessment of the impact of a safe shutdown earthquake. The Refit Programme for upgrading the installations and improving safety levels is now under way, in order to allow the ILL to operate for at least another 20 years.

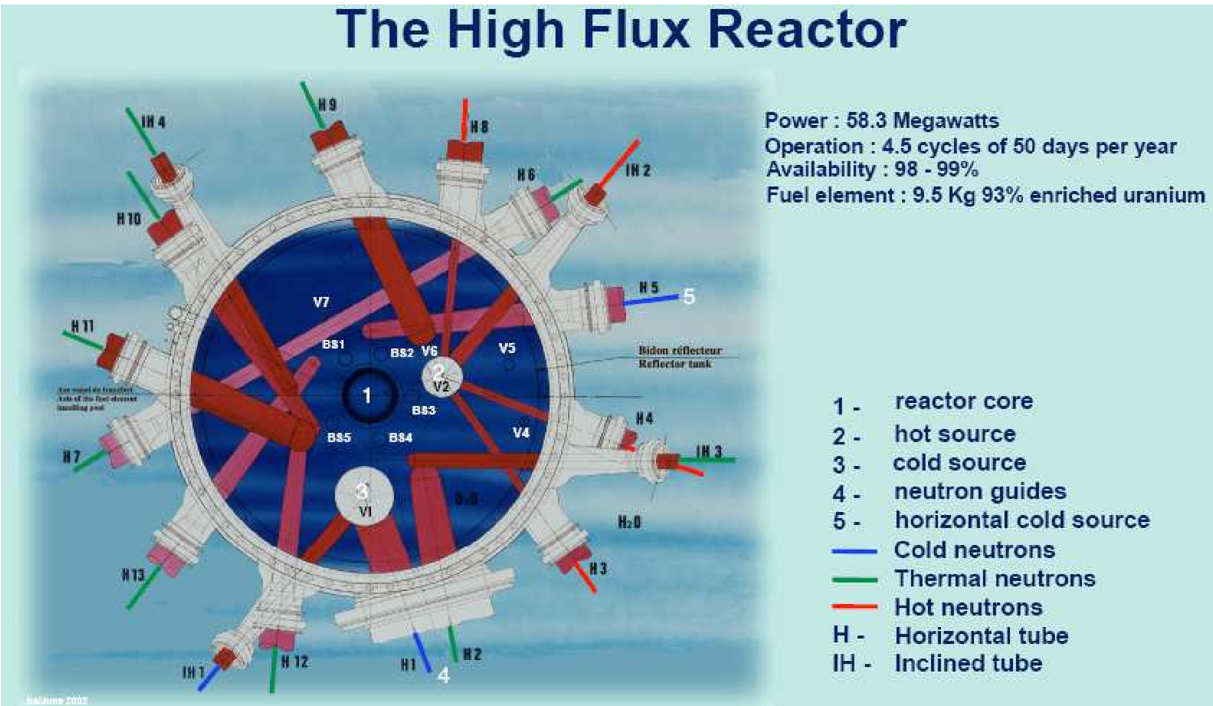
2. HFR operations and scientific experiments

The ILL High-Flux Reactor is an intense source of thermal neutrons for conducting experiments in the fields of solid-state physics, chemistry, biology, nuclear physics and neutrons. The Institute's main activities are:

- operating the neutron source (High-Flux Reactor - HFR),
- designing and building scientific equipment and instruments,
- providing support (logistics, preparation of experimental samples) to experimentalists and visiting scientists,
- conducting experiments, processing and analysing scientific results,
- operating the heavy water detritiation facility.

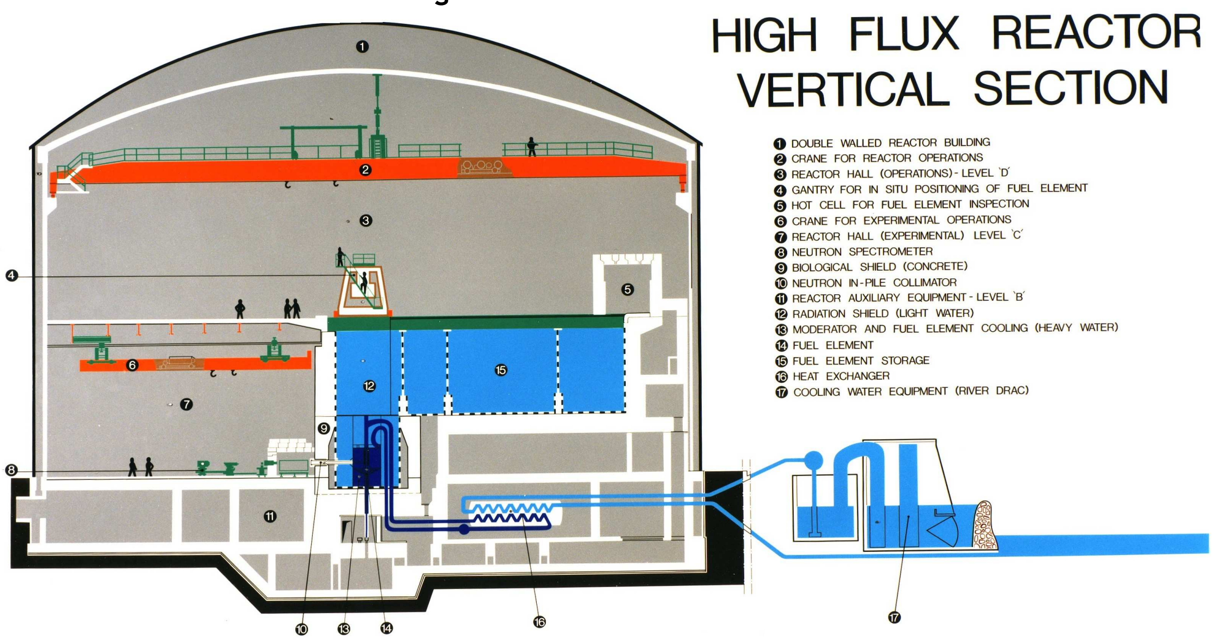
The High-Flux Reactor produces neutrons, which are then directed towards the experimental areas via 15 horizontal beam tubes and 4 vertical beam tubes. The reactor block houses 2 cold sources and 1 hot source, thus guaranteeing a wide range of neutron energies.

View of the heavy water tank

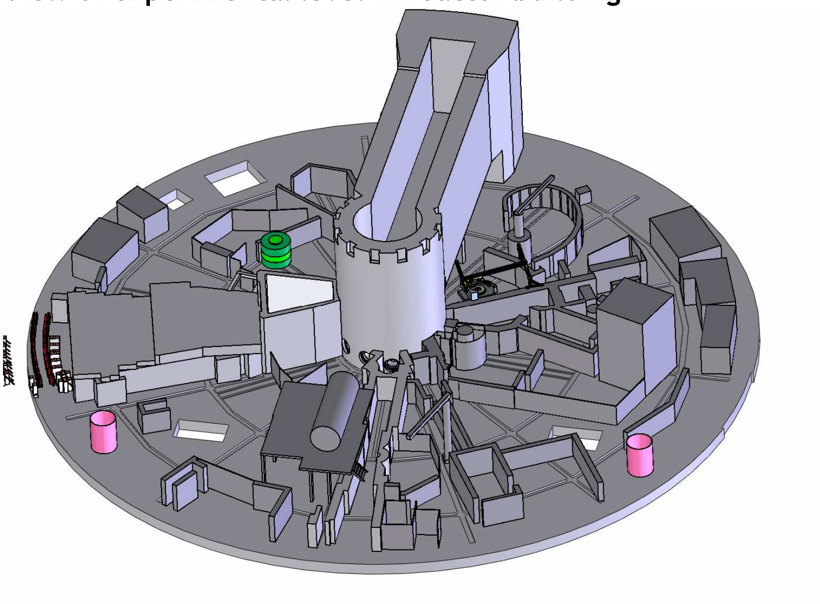


The beam tubes distribute neutrons to 15 instruments in the reactor building (60 m in diameter): 14 situated in the experimental hall (Level C) and one multi-instrument set-up using ultracold neutrons situated in the reactor operations hall (Level D).

Elevation view of reactor building

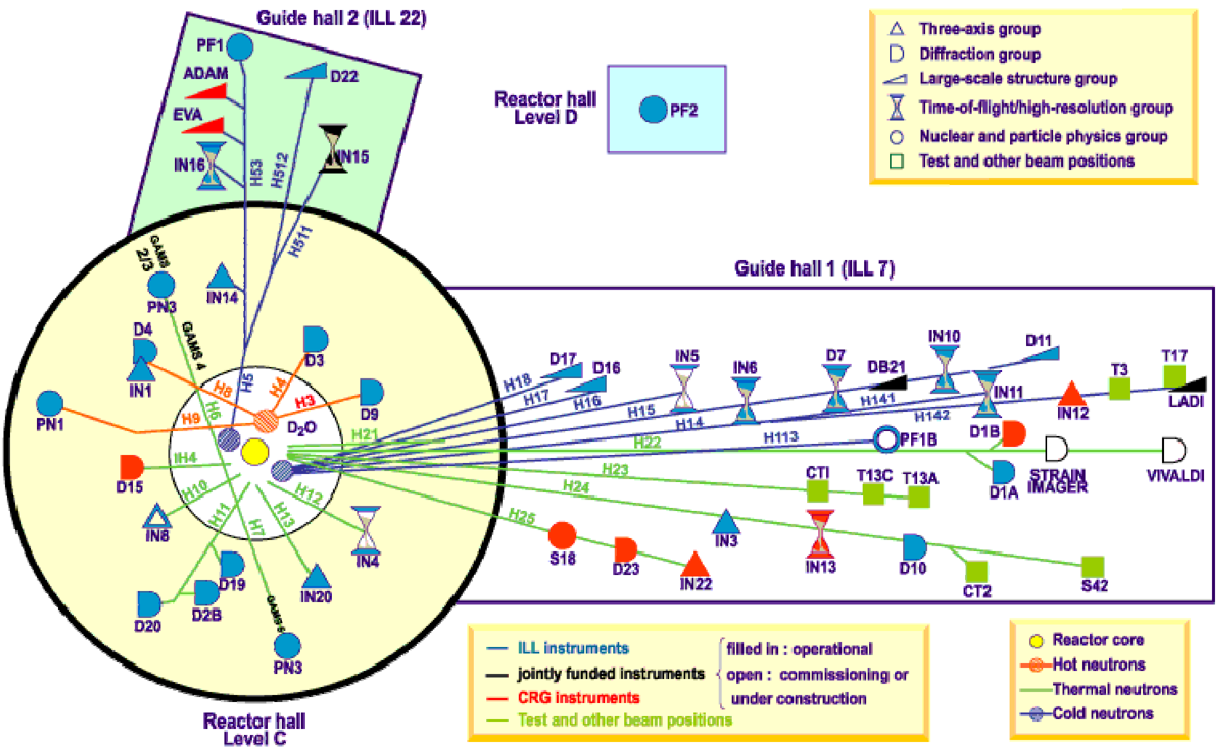


View of experimental level in reactor building



Beam tubes and neutron guides also deliver neutrons to 29 neutron instruments and 6 tests positions for neutron characterisation. These are located in the 2 guide halls adjoining the reactor building.

Diagram showing the layout of the instruments in the reactor building and the 2 guide halls.



The instrument suite at ILL allows 40 experiments to be carried out in parallel during the reactor cycles (225 days per year).

3. HFR operations – Safety

3.1. Operation at nominal power

The HFR is a pool-type reactor, cooled and moderated by heavy water.

The core of the reactor is a single fuel element comprising 280 fuel plates made of an enriched uranium (93 % ^{235}U)-aluminium alloy, clad with an aluminium alloy. The core is cooled by a forced downward flow of heavy water with a speed between the plates of 17 m/s ; the pressure of the heavy water is 14 bar when it enters the core and 4 bar when it leaves the core.

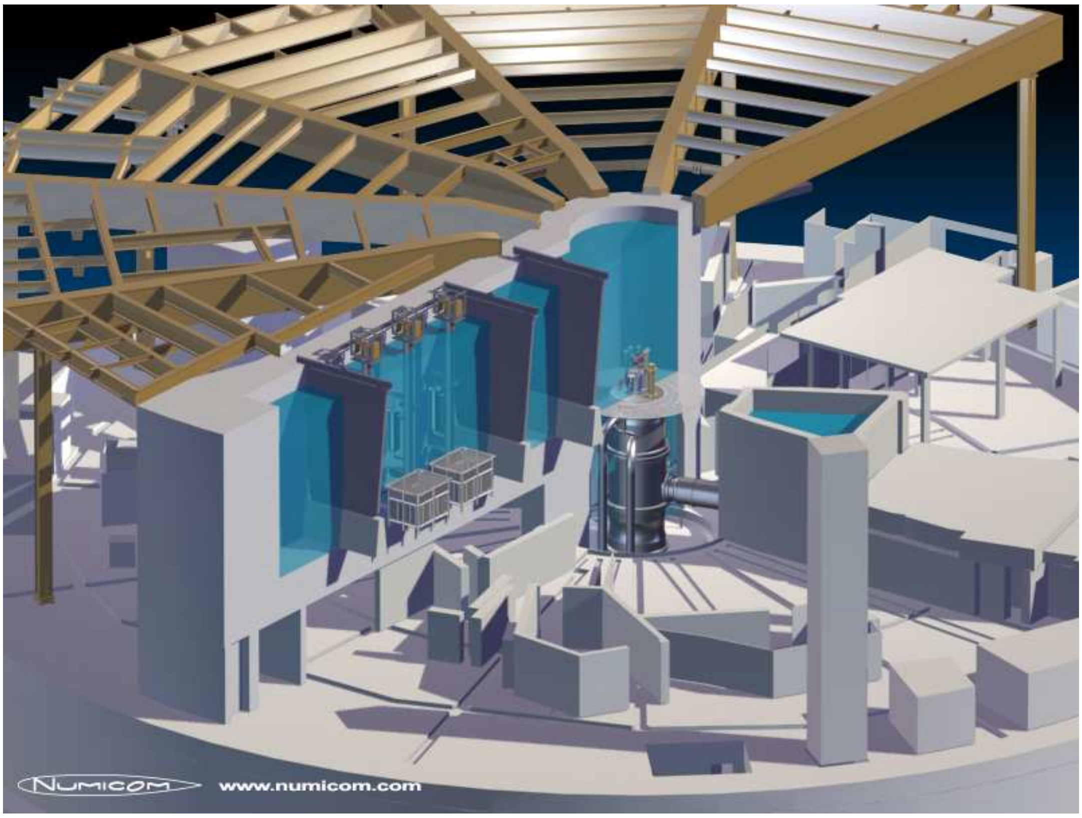
A secondary circuit ensures heat transfer from the heavy water via heat exchangers.

One reactor cycle lasts 51 days at a nominal power output of 58.3 MW. At the end of the cycle, the fuel element is unloaded and stored temporarily in a transfer canal. After it has been cooled for a minimum of 240 days in this canal, the decay heat has fallen sufficiently to allow the spent fuel element to be cooled in air.

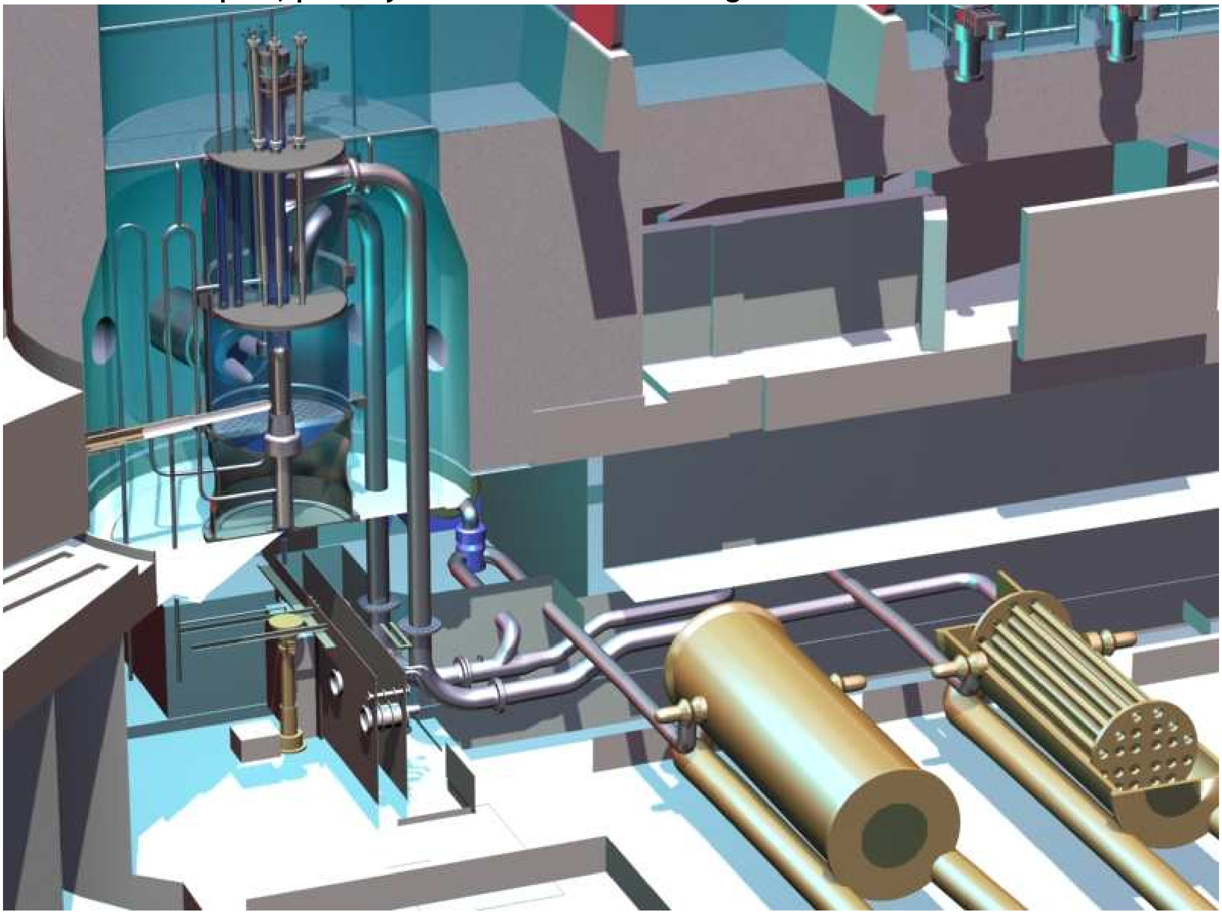
The confinement of the reactor building is provided by a double-wall containment (inner concrete wall and outer metal wall). The space between the two walls is maintained at an overpressure of 135 mbar compared to the inside of the building.

The presence of this overpressure means that, in the event of an accident involving a core meltdown in air, it is possible to delay by at least 12 hours any release outside the reactor building and therefore greatly limit the radiological impact on the surrounding populations.

View of reactor pool, reactor block and transfer canal



View of reactor pool, primary circuit and heat exchangers



3.2. Automatic reactor shutdown – Transition to natural convection

The reactor is shut down by 5 safety rods (which are dropped in less than 1 second); 2 safety rods are sufficient to guarantee the safe shutdown of the reactor. The rods are dropped by cutting the power supply to the electromagnets which hold them in the raised position. This power cutoff function is provided by two redundant circuits.

After the reactor has been shut down and when the pumps on the primary circuit have stopped, the fall in pressure between the core entrance and core exit triggers the opening of 4 “flaps”. The opening of just one “flap” creates a by-pass in the heavy water circuit above the reflector tank and allows the fuel element to be cooled by natural convection.

In the long term, the passive removal of the decay heat is achieved through heat transfer between the heavy water reflector tank and the light water reactor pool.

4. Seismic scenario

In May 2002, a safety review was carried out by the French safety authorities. The review focussed primarily on the impact of an earthquake on the safety of the installations and resulted in the following observations:

- The seismic resistance of the civil engineering structures of the reactor building and the adjoining buildings had not been demonstrated;
- The items of equipment important for safety in the event of an earthquake (EIS) had not been defined; consequently, a demonstration had not been provided of their sound behaviour (i.e. that they satisfied a minimum required performance level, e.g. stability, leaktightness, …).

As a result, in order to guarantee that the ILL received authorisation to operate the reactor, the safety authorities requested that the Institute carry out seismic reinforcement work on the civil engineering structures and provide the necessary demonstrations of sound behaviour for all items of equipment important for safety in the event of an earthquake.

The Refit project was therefore set up in July 2002 with the aim of satisfying these requests while at the same time not reducing too drastically the number of days of reactor operation per year (from 225 days/year to 150 days/year) during the refit work (2003-2005).

4.1. Target equivalent doses for local populations

As the earthquake level (Safe Shutdown Earthquake) used in the seismic resistance calculations is considered to be a severe accident, the ILL has set itself the objective of limiting the radiological impact on the surrounding populations to the values recommended by the French safety authorities in the event of a serious accident involving crisis management from outside a nuclear site.

If these values are exceeded, the safety authorities recommend that the following protective measures be taken:

- Effective dose (whole body) more than 10 mSv: take cover order,
- Effective dose (whole body) more than 50 mSv: evacuation order,
- Dose to the thyroid more than 100 mSv: administration of stable iodine.

In fact, in the event of a design-basis earthquake, which by definition is more severe than the local risk, the above protective measures would not be easy to implement. As a result, the objectives set by the ILL in terms of radiological impact are lower than these values.

4.2. Relevant source terms

The radioactive source terms in the reactor building which may have a radiological impact on the environment are:

- the tritiated heavy water (400 000 Ci maximum) and the tritiated deuterium of the cold sources (2 000 Ci for both sources),
- the reactor startup source, the radioactive check sources, the irradiated samples from experiments and the radioactive liquid effluents,
- the spent fuel elements.

Of all these sources, only the spent fuel elements can cause a greater radiological impact on the public than the objectives defined in the previous paragraph. This level of radiological impact would only be possible if an earthquake were to cause a fuel element meltdown to occur in air and at the same time the fission products released in this way were not contained. With respect to the other radiological source terms, whose radiological impact is significantly lower than the above objectives, no specific protective measures have been defined in the event of an earthquake.

4.3. Radiological impact

If an earthquake were to cause a meltdown in air of the reactor core and the immediate filtered release of the inventory of volatile fission products via the installation's exhaust stack, the radiological impact on the most exposed populations would be around 10 mSv (whole body).

In order to obtain additional margins with respect to its objectives in terms of radiological impact in the event of an earthquake, the Institute decided to provide the necessary demonstrations and carry out the necessary work in order to guarantee the safety functions presented below.

4.4. Safety functions to be guaranteed in the event of an earthquake

The items of equipment important for safety in the event of an earthquake (EIS) were identified by considering the fuel element in the various phases of its lifetime (new, in the reactor block, in the fuel handing device and in canal n° 2) and identifying those items which play a role in the safety functions in the event of an earthquake. Given the low probability of an earthquake occurring, only those phases with a significant duration were taken into account.

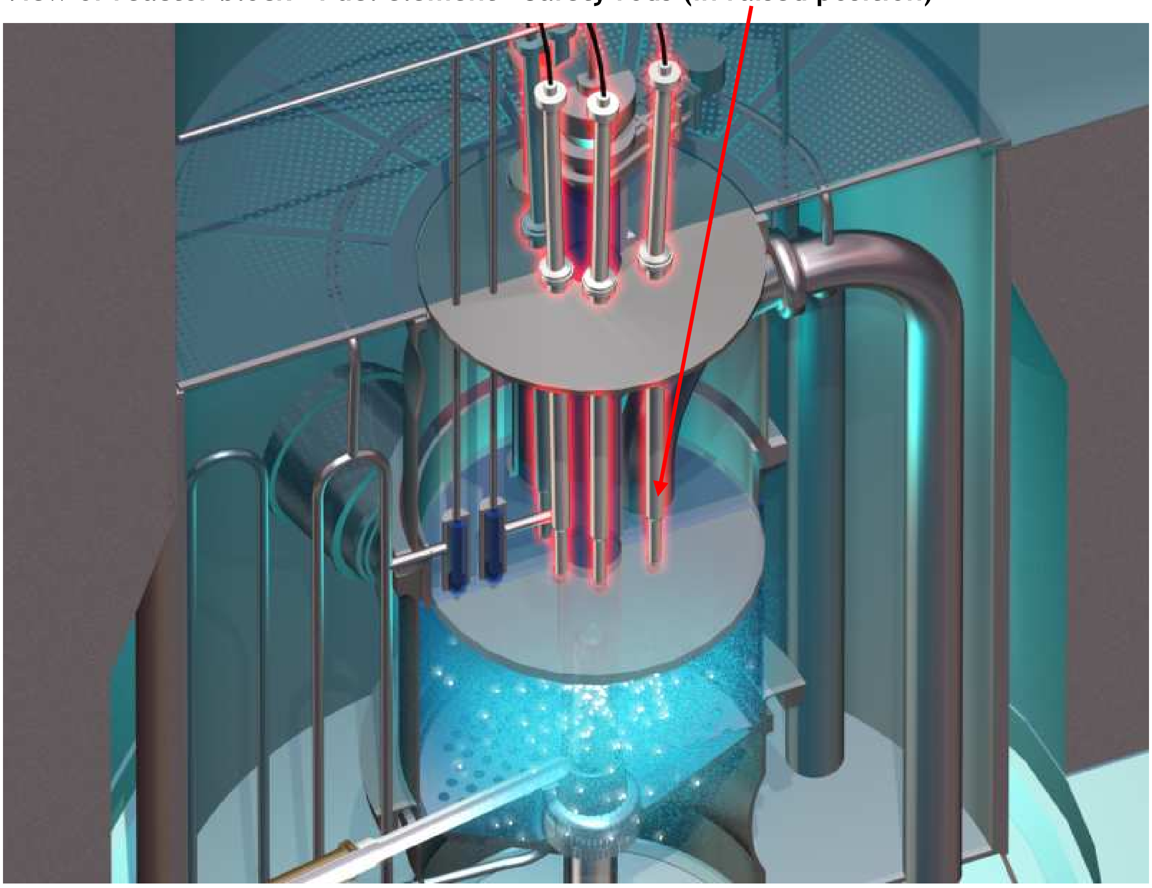
4.4.1. Controlling reactivity

In order to control the reactivity of new and spent fuel elements, the civil engineering structures of the reactor building and the various metal support structures must be stable:

- New fuel elements: storage boxes,
- Fuel element in core: reactor block in reactor pool,
- Spent fuel elements: storage rack in the transfer canal.

Other prerequisites for controlling the reactivity of the reactor are the proper functioning of the safety rods and the early detection of seismic signals, so that the automatic shutdown of the reactor (achieved in less than one second) can be triggered before the strong phase of the earthquake.

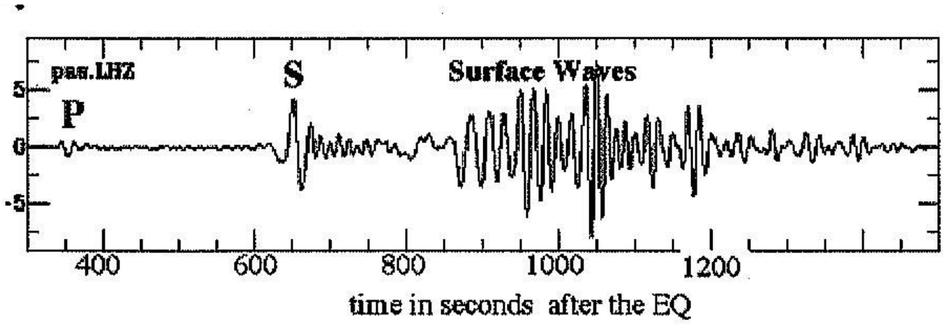
View of reactor block – Fuel element – Safety rods (in raised position)



This early shutdown option is justified by the fact that:

- it is extremely difficult technically to achieve seismic qualification for all the mechanisms which make up the HFR emergency shutdown system, given the complex path taken by the system within the installation,
- the thermohydraulic studies performed on average-size leaks in the core's heavy water cooling circuit as a result of an earthquake have concluded that there is no damage to the reactor core if the reactor is shut down at the same time as the seismic event occurs.

The early automatic shutdown of the HFR is achieved thanks to highly sensitive seismic sensors (2/3 logic) capable of detecting the occurrence of p-type waves (which occur before S-type waves), as illustrated in the diagram below.



4.4.2. Cooling of fuel elements

The non-release of the fission products contained in the spent fuel elements is guaranteed by the presence of water. We have considered the three most penalizing cases set out below:

Reactor shutdown transient in the event of an earthquake; case of a leak in the primary circuit

The main part of the heavy water circuit (reactor block, circuit in reactor pool, circuit in basement, including primary pumps and heat exchangers) must not sustain a major breach. A leak on the other parts of the circuit is acceptable (no melting of fuel plates).

Cooling of spent fuel element in reactor block

In addition to the fact that the reactor block must be stable and at least one of the 4 “flaps” must be function properly, there must be heavy water in the reflector tank (to allow the thermosiphon to function) and light water in the reactor pool (long-term heat removal) up to the top of the reflector tank. The penetrations of the light water circuit at the bottom of the reactor pool, the isolation mechanisms of the neutron beam tube penetrations around the edge of the pool and the stainless steel coating of these penetrations must therefore all be leak-tight.

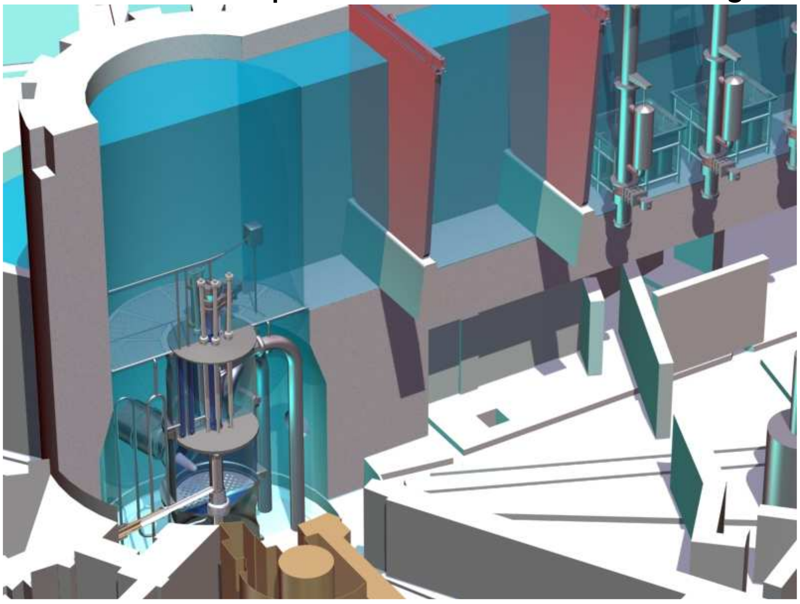
Cooling of the spent fuel element in the transfer canal

After the shutdown of the reactor, the spent fuel elements are cooled for 50 days in the fuel handling device (thermosiphon) located in the transfer canal, after which time they are lowered to the bottom of the canal, where they remain for around 1 year. As a result, the following two conditions must be satisfied:

- the stability of the fuel handling device,
- the presence of light water up to the top if its heat exchanger (long-term heat removal).

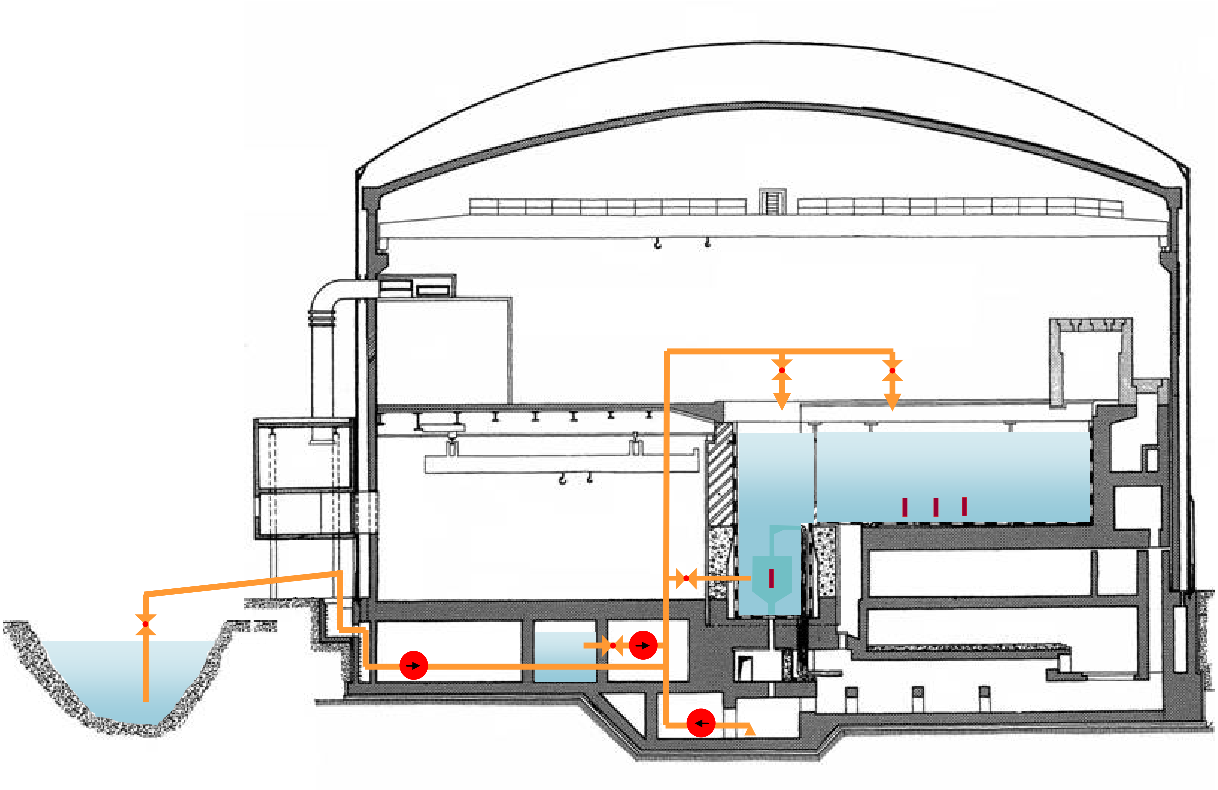
The walls of the transfer canal, the gates and the penetrations at the bottom of this canal must therefore be leak-tight.

View of the reactor pool and the fuel element handling devices in the transfer canal



As an additional guarantee, in the event of a leak in the reflector tank, the reactor pool or the transfer canal, an emergency water makeup system would allow internal and external water reserves to be injected into these vessels. This circuit would also make it possible to reinject the water recovered from the bottom of the reactor building.

Diagram of the layout of the emergency water makeup system



4.4.3. Controlling reactor containment

Following an earthquake, any release of air must be via the exhaust stack after filtration. The main openings in the concrete containment wall (air locks, doors, isolation valves of circuits which penetrate the containment) must be leak-tight and the containment walls and exhaust stack must be stable.

However, the overpressure of 135 mbar between the two containment walls does not have to be maintained.

Moreover, it is planned to install a seismically qualified containment air filtered extraction system.

4.4.4. Post-accident actions

The emergency control room (PCS), which is separate from the reactor control room (whose operation is not guaranteed after an earthquake) is equipped with a diesel generator set and enables subcriticality and the water levels in the reflector tank, the reactor pool and the transfer canal to be monitored and the water makeup and containment air filtered extraction systems to be controlled. All PCS equipment and the PCS building itself are seismically designed. All the connections between the PCS and the reactor building (power supplies, instrumentation and control) for equipment which must function after an earthquake are direct and dedicated to this equipment.

4.5. State of installation following an earthquake

Based on the Institute's safety objectives, the general configuration of the installation following an earthquake is described below.

In the event of an earthquake, the reactor is shut down automatically in 2/3 logic as soon as the earthquake is detected (P-type waves); this also triggers the automatic cut-off of power supplies.

It is assumed that there is a possible total loss of power (apart from the seismically designed diesel generator of the PCS), as well as a loss of control and monitoring capability from the building which houses the reactor control room (adjoining the reactor building).

The fuel elements are cooled by natural convection without fuel cladding failure.
The containment is isolated and maintained at a slight negative pressure by means of the filtered extraction system.
The reactor's two safeguard systems can be operated and monitoring can be performed from the PCS.
The reactor can be accessed via the air locks, to allow post-earthquake monitoring of systems.

5. Organisational structures implemented

The Reactor Refit Programme was launched in 2002 in the light of the demands issued following the general safety review. An ILL team was created to manage the project, made up of staff with experience in:

- modelling and dynamics,
- the analysis of civil engineering structures and the seismic reinforcement of buildings,
- instrumentation, control systems and power supply,
- safety analysis.

The team is divided into six dedicated groups; each group is in charge of the tasks relating to a specified domain.

The Refit project team is composed of both external staff, taking part in the project within the framework of technical assistance contracts, and ILL staff temporarily assigned to the project. All group leaders in the Refit project team are ILL staff members (and group leaders within the ILL hierarchy).

This team is supervised and supported by the Refit Programme project leader and by the Head of the Reactor Division. The Project leader reports to the Director on a monthly basis. Twice a year a report is presented to international experts from outside the ILL.

This team was asked to:

- identify solutions for demonstrating the seismic resistance of the installations, involving possible modifications to be made once their principles had been validated,

– present the reinforcement work envisaged to the safety authorities,

– organise and monitor the work,

– maintain reactor operations at a minimum of 150 days/year in order to safeguard scientific activity and continue with ongoing long-term investment in instruments (Millennium Programme).

Initially, the team consulted seismic experts from the French *Commissariat à l'Energie Atomique* (CEA) and from Areva to confirm the general approach it was taking and the preliminary studies; the feasibility of the reinforcement work being proposed was then assessed by outside consultants, and recognised contractors were commissioned to prepare the dossier on the diagnostic survey of the installations in their present state and on the merits of the reinforcement measures proposed.

The Refit budget for the period 2002 to 2006 is around 30 M€.

6. Main work completed or planned

6.1. Buildings

The seismic reinforcement of the reactor building (ILL5 – subject of another article) and the office / instrumentation and control building (ILL4) is ongoing and will be completed within about 1 year.

Regarding the 2 experimental halls (ILL7 and ILL22), the parts of these buildings which are closest to the reactor building are in the process of being dismantled, to ensure that the possible collapse of these buildings does not interfere with the reactor building (subject of another article).

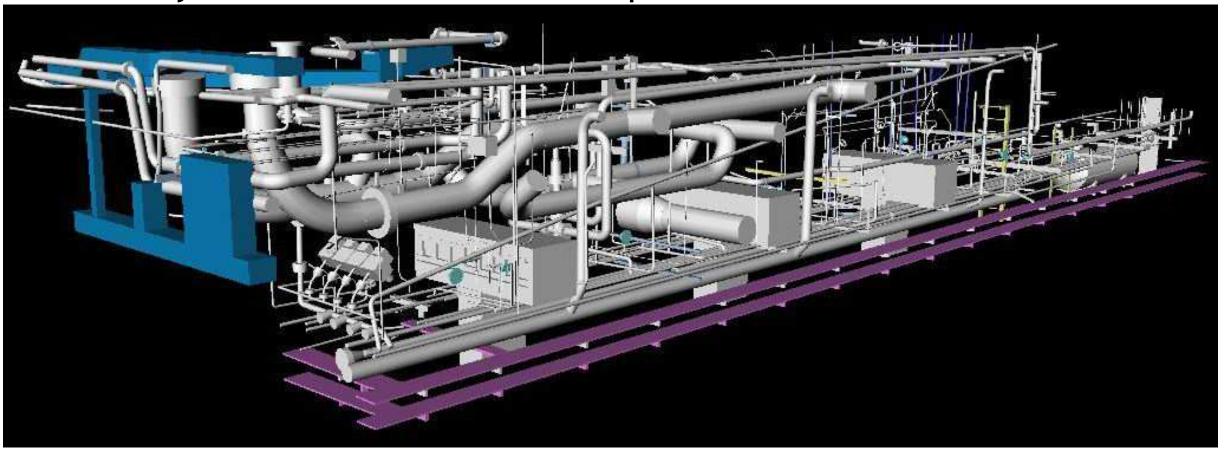
General view of the buildings adjoining the reactor building

6.2. *Equipment inside the reactor*

All the isolation valves of the reactor pool, the transfer canal and the containment are currently being replaced by seismically qualified equipment.

The supporting elements of the main part of the heavy water circuit will be adapted to seismic conditions.

View of heavy water circuit under the reactor pool and transfer canal



6.3. *New safeguard systems*

Two new seismically qualified safeguard systems are either currently being installed or are scheduled to be installed (cf. previous paragraphs):

- the emergency water makeup system,
- the containment air filtered extraction system.

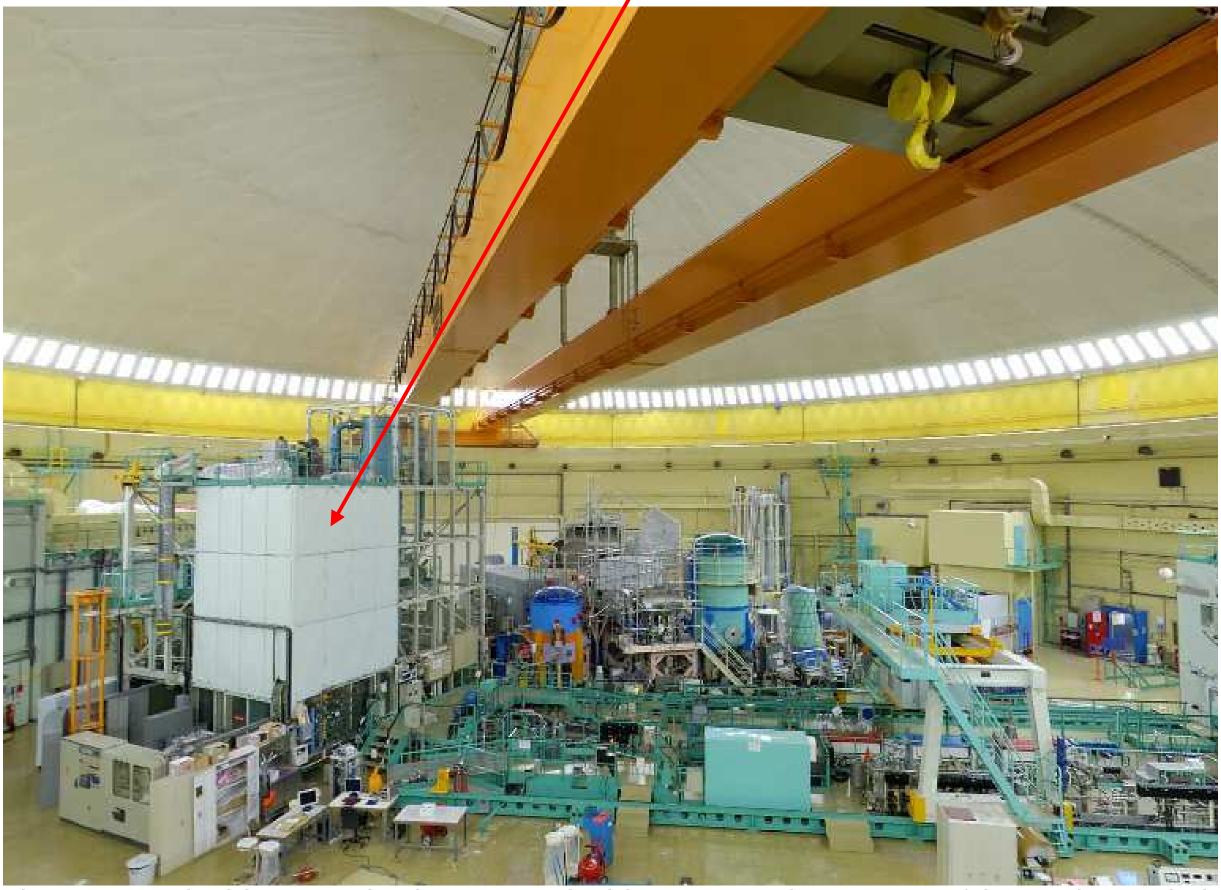
In addition, the safety circuit which is responsible for cutting the power to the electromagnets of the safety rods has been duplicated.

6.4. *Elements which could damage seismic equipment*

All equipment which is not classified as seismic but which could cause damage to equipment important for safety in the event of an earthquake is being studied and, where necessary, reinforced. For example:

- the overhead crane in the reactor building, which is scheduled to be reinforced,
- the upper structures of the vertical cold source, which adjoin the reactor pool.

View of the overhead crane and the upper structures of the vertical cold source



The masonry buildings inside the reactor building are in the process of being dismantled. Since these buildings house the general reactor building ventilation system, a new general ventilation system will have to be installed. (This point is the subject of another article.)

7. Conclusion

The programme of action taken by the ILL in order to satisfy safety requirements in the event of an earthquake was launched, under the management of a special project group, in July 2002, in the light of the conclusions of the safety review of the installations by the French safety authorities.

In the first phase of the project, from July 2002 to the end of 2003, the broad priorities were fixed for the reactor building and each of the adjoining buildings based on existing seismic studies of these buildings or on new studies undertaken in 2002:

- reinforcement of buildings directly involved in reactor operations (office / instrumentation and control building and reactor building),
- deconstruction of those parts of the buildings used for scientific purposes (2 guide halls) which could interfere with the reactor building.

In parallel to this, the items of equipment important for safety in the event of an earthquake were defined, together with their necessary functions in order to guarantee the Institute's safety objectives.

In a second phase, from January 2004 to July 2005, the preparatory work was launched for the dismantling operations in the guide halls and for the building reinforcement work. Studies concerning the seismic behaviour of existing equipment and the 2 new safeguard systems were launched or were completed.

Finally, during the current phase of the project, which will last until the end of 2006, the major part of the work on buildings and equipment will be completed.

Reactor operations have been maintained throughout the entire project, albeit with a reduction in the number of cycles per year from 4.5 to 3 during the period 2003-2006.