Identification and implementation of a hardened core in a research reactor in light of the lessons learned from the Fukushima Daiichi accident. The JHR case.

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Abstract.
The JHR reactor is a new high performance MTR (Material Testing Reactor) working as an International User Facility in support to Nuclear Industry, Public Bodies and Research Institutes. This new facility of a maximum power of 100 MWth will allow to reproduce on a small scale real power plant conditions and in some cases, more severe conditions for Material screening (comparison of materials tested under representative conditions),Material characterization (behavior of one material in a wide range of operating conditions, up to off-normal and severe conditions) and fuel element qualification (test of one / several fuel rods (clad+fuel)). Its construction began in 2009 after getting the authorization by French Regulatory Body (ASN) with the best safety design specifications of the moment.
Following the Fukushima Daiichi accident as a consequence of the earthquake and tsunami occurred on 2011March 11th, the French government asked all French nuclear facilities to perform complementary safety assessments to meet objectives under extreme situations exceeding licensing basis (with focus on “cliff-edge” effect prevention). JHR, which was under construction, provided its report on 2011 September 15th. The complementary safety assessments basically confirmed the sound design bases of the JHR. Nevertheless ASN asked CEA to propose a so called “Hardened Core” of material and organizational dispositions that can ensure the following three objectives in extreme situations exceeding the current licensing basis:

-prevent a severe accident or limit its progression,
-limit large-scale releases in the event of an accident which is not possible to control,
-enable the licensee to perform its emergency management duties.

After analysis of the consequence of postulated failure of components under extremely severe conditions, some were proposed to be part of the hardened core of material and a selected needs for extra equipment were identified. As an answer to French nuclear regulator requirements, CEA proposed a set of “hardened core” measures This set of “hardened core” measures was assessed by the technical support of the French Regulator (ASN) in 2011 and reviewed in April 2013 by its standing advisory committee. ASN approved CEA proposal and add the containment deflation circuit.
Due to the fact that JHR construction is not yet completed, its situation is rather particular and the Hardened Core is constituted by already designed SSC (Structure, system and component) but also by new SSC. For all Hardened Core SSC the so called Supports to SSC have to be identified. These SSC are the ones requested by Hardened Core SSC to perform its requested function, and identification methods have been developed. All margins on existing SSC designs have to be evaluated regarding the construction codes used for initial design, particular methodologies and new criteria must be defined in case of lack of margin. All new SSC are designed using the classical codes of construction with more severe operating conditions resulting of post Fukushima situations.
The completion of Hardened Core implementation on JHR will be performed without start up schedule modification.

1-The JHR reactor :

1-1-Context :

The large majority of Material Test Reactors (MTRs) is nowadays more than 50 years old, this is leading to the increasing probability of some shutdowns for various reasons (life-limiting factors, heavy maintenance constraints, possible new regulatory requirements…). Such a situation cannot be sustained in the long term [1].
Anyway, associated with hot laboratories for the post irradiation examinations, MTRs remain key structuring research facilities for the European Research Area in the field of nuclear fission energy.
MTRs address the development and the qualification of materials and fuels under irradiation with sizes and environment conditions relevant for nuclear power plants in order to optimize and demonstrate safe operations of existing power reactors as well as to support future reactor design.
Consequently, and in its specific position of new MTR under construction in Europe, the JHR research infrastructure has been identified on the ESFRI Roadmap since 2008.

1-2-Highlights of the JHR project

JHR will offer modern irradiation experimental capabilities to study material & fuel behavior under irradiation. JHR will be a flexible experimental infrastructure to meet industrial and public needs within the European Union related to present and future Nuclear Power Reactors.
JHR is designed to provide high neutron flux (notably twice as large as the maximum available today in the currently operating French MTR OSIRIS, and at the best standards worldwide), to run highly instrumented experiments, to support advanced modelling giving prediction beyond experimental points, and to operate experimental devices giving environment conditions (pressure, temperature, flux, coolant chemistry, …) relevant for water power reactors (PWRs, BWRs, VVERs), but also in support of non-water reactors R&D (Sodium cooled fast reactors…).
As an associated objective, the JHR will also contribute to secure the production of radioisotopes for medical applications.

JHR, as a future international User Facility, is funded and steered by an international consortium gathering industry (Utilities, fuel vendors…) and public bodies (R&D centers, TSO, Regulator…) which is the following: CEA (France), EDF (France), AREVA (France), European Commission-JRC, SCK-CEN (Belgium), UJV (Czech Republic), VTT(Finland), CIEMAT(Spain), STUDSVIK (Sweden), DAE(India), IAEC (Israel), NNL (UK).
There also exists an implementing agreement between CEA and JAEA (Japan) with a view to access to JHR.

A more extensive and in-depth JHR facility description including development of the first experimental capacity can be found in the proceedings and presentations of recent RRFM and IGORR conferences (ref [2], [3], [4] and [5]).

1-3-JHR general description

As a short description, the JHR layout is as follows:

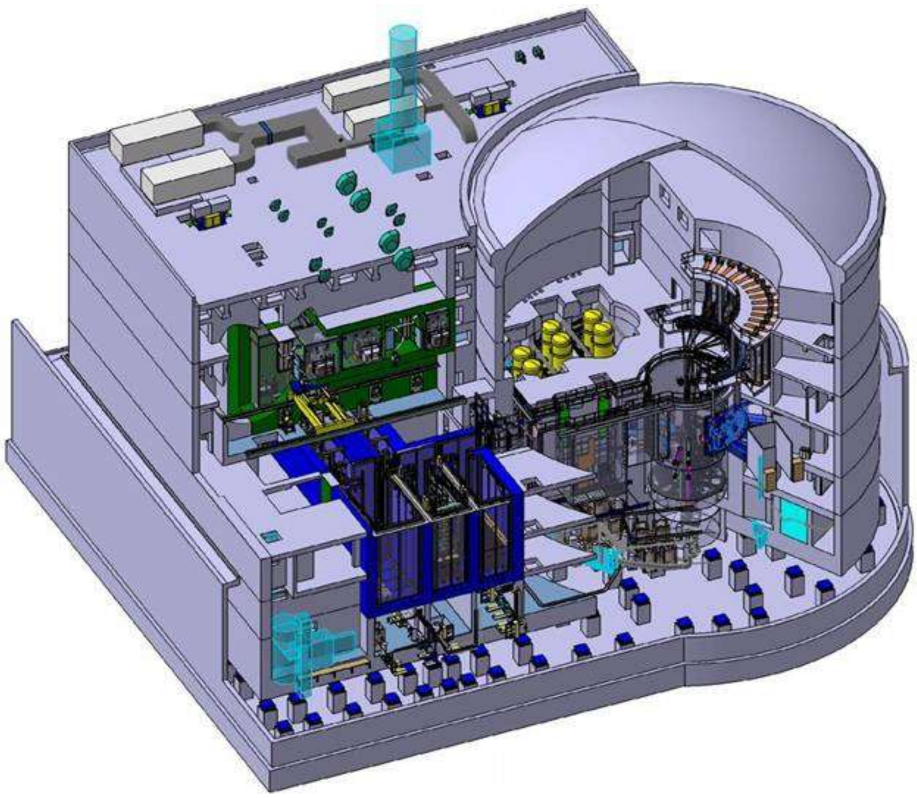


Fig. 1 : The JHR reactor

The nuclear unit of JHR consists in a reactor building and a nuclear auxiliary building.
The reactor building is made in pre-constraint concrete with a diameter of 37 m. The nuclear auxiliary building consists in 3 storage pools for spent fuels, irradiated experimental devices and in 4 hot cells for preparation, conditioning of experiments and non-destructive examinations on irradiated samples. A transfer channel between the reactor building and the nuclear auxiliary building allows the underwater transfer of spent fuels and experimental devices between the two buildings.

In support to the nuclear island, one can quote the following:

- 1 support building for cooling
- 1 support building for the fluids and ventilation
- 2 emergency diesel generators buildings
- 1 building for assembly and test of experimental devices before entering the nuclear island (“cold workshop”)

2-JHR Stress Tests:

Following the Fukushima Daiichi accident as a consequence of the earthquake and tsunami occurred on 2011 March 11th, ASN, the appointed organization responsible for the regulation of the French nuclear installations, requested on 5 May 2011, that all operators undertake complementary safety assessments to meet objectives under extreme situations exceeding licensing basis (with focus on “cliff-edge” effect prevention) of their installations [6]. This initiative also met the Prime Minister's demand that the French nuclear installations be subject to a safety audit, and the European Council's March 2011 requirement for “stress tests” to be conducted on the European nuclear reactors. These assessments were carried out in addition to the safety review approach performed permanently as part of the French regulatory process. JHR, which was under construction, provided its report on 2011 September 15th.

2-1-Methodology :

Within the initial reactor design, a set of calculations and expert evaluations were performed to evaluate margins of the design for extreme situations in light of Fukushima-Daishi accident:

Earthquake beyond SSE (1.5)
Flooding beyond design and flooding caused by earthquake
Natural phenomena at a higher level than the one observed for the site (wind, tornado, lightning etc)
Loss of inner and external electrical supply
Loss of cooling sources
Cumulating of both loss of power and cooling
Accident management in such situations

In order to define dispositions to prevent extreme consequences especially for environment and population, the studies had to identify the possible situations that may cause a severe degradation of the scenario (cliff edge effect). The safety analysis had previously identified two major risks :

-Underwater fusion with loss of containment
-fusion in air

These situations have to be considered as well for fuel element as fuel samples in experimental devices. Underwater fusion might occur for irradiated materials in the core, in case of loss of cooling. Because a similar situation is already taken into account in the safety analysis, underwater fusion is not considered as a cliff effect if containment keeps its integrity.
Fusion in the air might occur for core and reflector in the pools of the reactor building in case of fuel material become uncovered by water, this may be caused by water evaporation consecutively of a loss cooling or a decrease of the water level due to a loss of tightness of pools, pipes or penetrations. But this kind of fusion could not happen to experimental devices which are out of the core and reflector and which observe a fast decrease of its decay heat after irradiation. This fusion could not occur neither in the cooling pools because transfer of the fuel is allowed only when decay heat is sufficiently low to withstand a loss of water without melting.
Evaluation of the impact on environment and population is the most important to demonstrate the installation acceptability versus post-Fukushima situations. This impact is estimated on the base of radiological releases: On the standard safety analysis the Borax accident which is an hypothetical situation, is supposed to lead to underwater fusion. Dose calculations on the reference population and environment show it can be mitigated by acontainment isolation during 12 hours.

2-2-Essential equipment and structures:

Cliff edge effect can be prevented by several dispositions each being self-sufficient. In the applied methodology only structures and equipment required are identified to be essential.
To prevent underwater fusion, Scram System (SS), Ultimate Cooling Pump (UCP), Natural Convection Valves (NCV) and Ultimate Supply Batteries (USB) are identified. In these studies no hazard that may affect simultaneously several essential devices has been found. To prevent fusion in air, scram system, pools and dispositions to maintain their tightness are identified. In this case hazard that can affect these devices during a severe earthquake are civil works of containment, the polar crane, main poll platforms which could fall and degrade tightness of the pools.

3-Hardened Core Identification:

The complementary safety assessments basically confirmed the sound design bases of the JHR. Nevertheless ASN asked CEA to propose a so called "Hardened Core" of material and organizational dispositions that can ensure the following three objectives in extreme situations exceeding the current licensing basis:

-prevent a severe accident or limit its progression,
-limit large-scale releases in the event of an accident which is not possible to control,
-enable the licensee to perform its emergency management duties.

After analysis of the consequence of postulated failure of components under extremely severe conditions, some were proposed to be part of the hardened core of material and selected needs for extra equipment were identified.

As an answer to French nuclear regulator requirements, CEA proposed a set of “hardened core” systems including:

- An ultimate recirculation pump on the reactor main cooling circuit
- A circuit constituted by pipes and valves for an ultimate pool water supply from outside the containment building (REW circuit),
- Natural circulation valve and its actuation system
- Dedicated sensors to independently measure water level in the pool, pressure and radio-activity level in the containment building,
- Specific ultimate power set for the above-mentioned equipment : Ultimate Battery, Ultimate Electrical Panel and relevant wiring
- Remote shutdown panel with natural convection valves indication of position, water level and temperature of the reactor pool

This set of “hardened core” measures was assessed by the technical support of the French Regulator (ASN) in 2011 and reviewed in April 2013 by its standing advisory committee. ASN approved CEA proposal and add the containment deflation circuit.

3-Hardened Core Implementation:

3-1- definitions:

The Hardened Core SSC (HC SSC) are structures systems and components resistant to extreme events and are vital to assure safety functions of the installation. The SSC strictly required for the fulfillment of the HC SSC performances in post-Fukushima situations are called Support to SSC (S SSC). To guarantee the efficiency of this set of SSC it is required to identify SSC which can have a negative impact during post Fukushima situation (I SSC) as for instance SSC behaving as missiles during an earthquake beyond SSE

3-2-SSC performances:

First HC SSC performances are defined upon the safety analysis in post-Fukushima situations, then S SSC performances are also defined upon safety analysis in post-Fukshima situation but depending on their respective HC SSC. Finally the I SSC performances are limited to an absence of impact on the performances of HC SSC and S SSC. (chock, fall of load, fire, flooding, explosion)

3-3-HC SSC identification:

They were identified during stress test studies, proposed by operator to the Nuclear Safety Authority, approved and completed by this body and its list published in an Act [7]

3-4- S SSC identification:

The methodology consists in two steps :

1-definition of the HC SSC performances
2-functionnal analysis in order to identify S SSC required or the ones which failure who degrade or impair HC performance.

3-5- I SSC identification:

This identification is based on the walk down method which allows identifying in situ potential missiles. Because JHR construction is not completed this walk down is realized with the 3D JHR mockup.
These I SSC are identified considering inducted hazard : chock from other SSC, fall of loads, flooding, fire and explosion.

3-5-Exclusion method:

Because degradation is also directly linked to the energy content of I SSC and the ruggedness of HC SSC or S SSC, an exclusion method has been developed, in order to reduce the scope of mechanical calculations to a reduced set of I SSC. This exclusion method defines categories of couples of I SSC/ HC SSC or S SSC and provide an evaluation, based on experience the opportunity, of resistance calculation. For instance ventilation pipes of samll diameter are not considered as I SSC during earthquake beyond SSE.

4-HC SSC and S SSC sizing:

Due to the fact that JHR construction is not yet completed, its situation is rather particular and the Hardened Core is constituted by already designed SSC but also by new SSC.
New HC SSC will be designed with the exactly same methods and codes as the ones used in the initial design but with more severe specifications corresponding to post Fukushima stress levels. But for existing HC SSC the approach is different. These SSC have been already designed, and will not be remanufactured under the new specifications of New HC SSC. The methodology used on JHR is to evaluate robustness, that is to say their behavior under a post-Fukushima stress, in relevant ambient conditions. In most of cases irradiation and temperature stress are not different from the normal or accidental situations evaluated in the safety report. The main difference is related to the seismic stress inducing a higher mechanical stress.

4-1-Robustness evaluation of existing HC SSC:

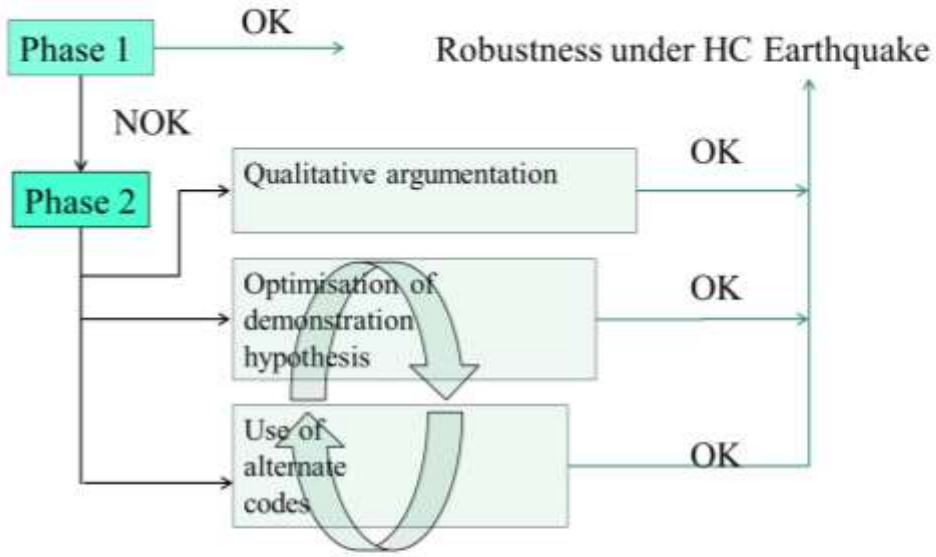
JHR components are designed under RCC-Mx code, or FEM for cranes, and civil works under RCC-G code or Eurocodes. These ones accumulate mechanical margins in order to guarantee the performance of the components and structures, especially by keeping materials in the plastic domain with really conservative margins (usually 200%). In the post Fukushima situation, the mechanical behavior of existing HC SSC or S SSC is evaluated to defined within which domain it remains (most of all in plastic domain) in order to allow a sufficient performance in post-Fukushima situations.

4-2-Robustness methodology / The Polar Crane case:

Fig2 : The JHR Polar Crane

The JHR Polar Crane is not a HC SSC neither a S SSC, but it is identified as an I SSC because its fall could cause the degradation of HC SSC or S SSC as reactor pool for instance, in case of beyond basis design earthquake.
In Post Fukushima situation and particularly after the earthquake taken into account for stress tests (called HCE Hardened Core Earthquake), the Polar Crane expected performances are: absence of fall, integrity of components which guarantee an absence of pool degradation, no fall of the handled load during operation. But the Polar Crane operability is not expected after Post Fukushima situation.

Methodology :



Phase 1 consists in the determination of seismic stress (x, y, z accelerations) at the relevant location in the civil works. Demonstration of design has been renewed with these new constraints exactly as it has been done taking into account SSE but with the HCE. Because the polar crane is already constructed and operational, its mass which has been considered has been the measured one and not the predicted one as it has been during its design phase, and as build characteristics were also considered. Unfortunately, phase one concluded that design criteria are not respected for HCE, because the design margins of three parts of the polar crane has been found to be less than one (negative margin).

For phase two, a group of experts has analyzed these three particular points and defined alternate methods to evaluate robustness:

1- The Polar Crane walkway: its design margin under HCE was 0.95, but calculations shown a slight excess of elastic constraint in the guardrail. Because this excess is very local and without incidence on the safety goals it has been considered as robust.

2- The polar Crane structure: margins were above 1 except for local mechanical assemblies. In phase two it has been recalculated allowing stress into plastic domain before rupture. And it has been concluded that Polar Crane structure is robust.

3- The rolling tracks: some assemblies were calculated under FEM code with a negative margin, but for these assemblies Eurocode 3 is also relevant and new margins are positive. It has been concluded that rolling tracks are robust. (Fig. 3)

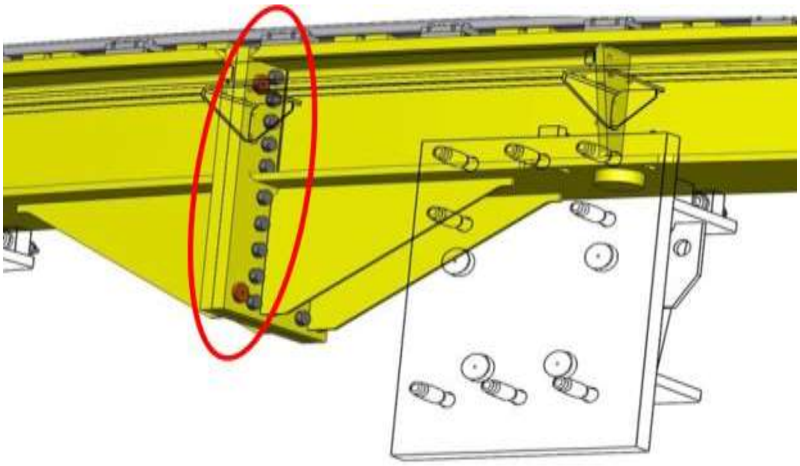


Fig 3 : Localization of excessive stress on the support of rolling track

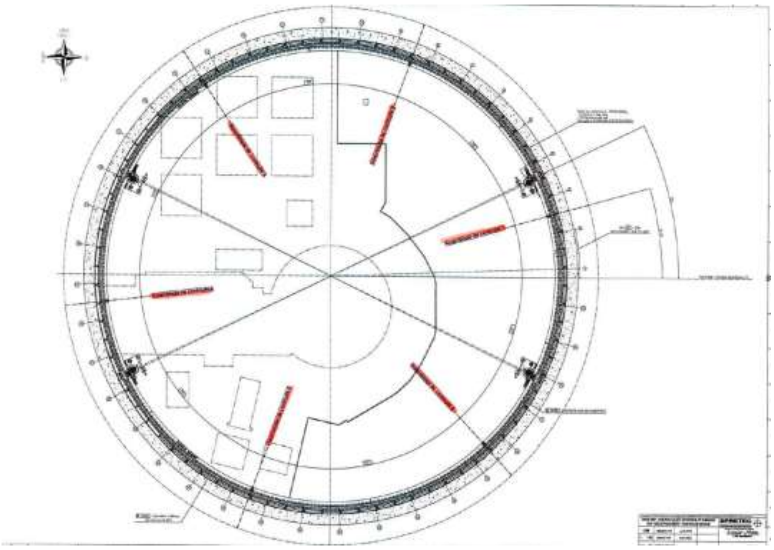


Fig. 4: Localization of excessive stress on the circular Rolling Track

5-Conclusion

JHR, the future high performances MTR under construction in France has taken into account the lessons learned from Fukushima Daiishi accident. After stress test evaluation, a Hardened Core of material dispositions was decided by ASN based on a CEA proposal, constituted by already designed SSC and new SSC. New methodologies have been defined to guarantee Hardened Core SSC operation in post Fukushima situations preventing a severe accident or limiting its progression, limiting large-scale releases in the event of an accident which is not possible to control, enabling the licensee to perform its emergency management duties. The completion of Hardened Core implementation on JHR will be performed without start up schedule modification.

References

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[6] Décision no 2011-DC-0224 de l’Autorité de sûreté nucléaire du 5 mai 2011 prescrivant au Commissariat à l’Energie Atomique et aux énergies alternatives (CEA) de procéder à une évaluation complémentaire de la sûreté de certaines de ses installations nucléaires de base au regard de l’accident survenu à la centrale nucléaire de Fukushima Daiichi.

[7] Décision no 2015-DC-0477 de l’Autorité de sûreté nucléaire du 8 janvier 2015 fixant au Commissariat à l’énergie atomique et aux énergies alternatives (CEA) des prescriptions complémentaires relatives au noyau dur et à la gestion des situations d’urgence, applicables à l’installation nucléaire de base no 172 (dénommée réacteur Jules Horowitz), située sur le site de Cadarache (Bouches-du-Rhône)