

# **The Jules Horowitz Reactor (JHR), a European Material Testing Reactor (MTR), with extended experimental capabilities**

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## Abstract

- The Jules Horowitz Reactor (JHR) is the European MTR (Material Testing Reactor) designed to provide, after 2010, the necessary knowledge for keeping the existing power plants in operation and to design innovative reactors types with new objectives such as : minimizing the radioactive waste production, taking into account additional safety requirements, preventing risks of nuclear proliferation ...
- To achieve such an ambitious objective. The JHR is designed with a high flexibility in order to satisfy the current demand from European industry, research and to be able to accommodate future requirements. The JHR will offer a wide range of performances and services in gathering, in a single site at Cadarache, all the necessary functionalities and facilities for an effective production of results : e.g. fuel fabrication laboratories, preparation of the instrumented devices, interpretation of the experiments, modelling. The JHR must rely on a top level scientific environment based on experts teams from CEA and EC and local universities.
- With a thermal flux of  $7,4.10^{14} \text{ ncm}^{-2} \text{ s}^{-1}$  and a fast flux of  $6,4.10^{14} \text{ ncm}^{-2}\text{s}^{-1}$ , it is possible to carry out irradiation experiments on materials and fuels whatever the reactor type considered. It will also be possible to carry out locally, fast neutron irradiation to achieve damage effect up to 25 dpa/year. (dpa = displacement per atom.)
- The study of the fuels behavior under accidental conditions, from analytical experiments, on a limited amount of irradiated fuel, is a major objective of the project. These oriented safety tests are possible by taking into account specific requirements in the design of the facility such as the tightness level of the containment building, the addition of an alpha hot cell and a laboratory for on line fission products measurement.

## **1. – CONTEXT**

The research reactors are nuclear facilities organized around a neutron source and dedicated to fundamental and applied research.

Since the divergence of the first nuclear reactor built in the world, the atomic pile CP1, at the University of Chicago, in December 1941, more than 500 research reactors were built in the world. Among those, the reactors known as technological irradiation reactors (the Material Testing Reactors) are more particularly intended for :

- the study of fuel and material behaviour under irradiation for various nuclear reactor types
- the irradiations for industry and medical applications.

In France, in order to meet these needs, CEA built the SILOÉ reactor (35 MW), in Grenoble (criticality in 1963), then the OSIRIS reactor (70 MW), in Saclay, (criticality in 1966). The SILOÉ reactor was shut down in 1997. Similar European reactors are now more than 40 years old and will be 50 years old by 2010.

In this context, the CEA has decided to build at Cadarache a new reactor, named the “Jules Horowitz Reactor” (JHR), which will be a structuring infrastructure of the European research area. The main purposes are :

- Supporting existing power plant operation (material reliability, fuel performance and safety, ...) by carrying out relevant separate effect and integral experiments on fuels and materials, in response to both industry and regulatory requirements.
- Supporting the development and the qualification of advanced materials and new fuels at conditions anticipated for new fission reactors and fusion by carrying out limited scale experiments prior to any larger scale technological demonstration.
- Developing expertise and supporting the training of the staff to be employed in the nuclear industry which is a necessary condition for the restart of nuclear energy in the coming years.
- Supporting countries and the European Community future decisions related to new nuclear power plants construction or new concepts assessment.

The criticality of the reactor is planned for 2013. The lifetime considered is at least 50 years. Detailed studies started in January 2003.

The main objective of the JHR is to meet “The Scientific Need”. The reactor and the connected fission platform will provide all the “downstream” and “upstream” functions of the experimental process.

## **2. - A FISSION PLATFORM IN CADARACHE [1]**

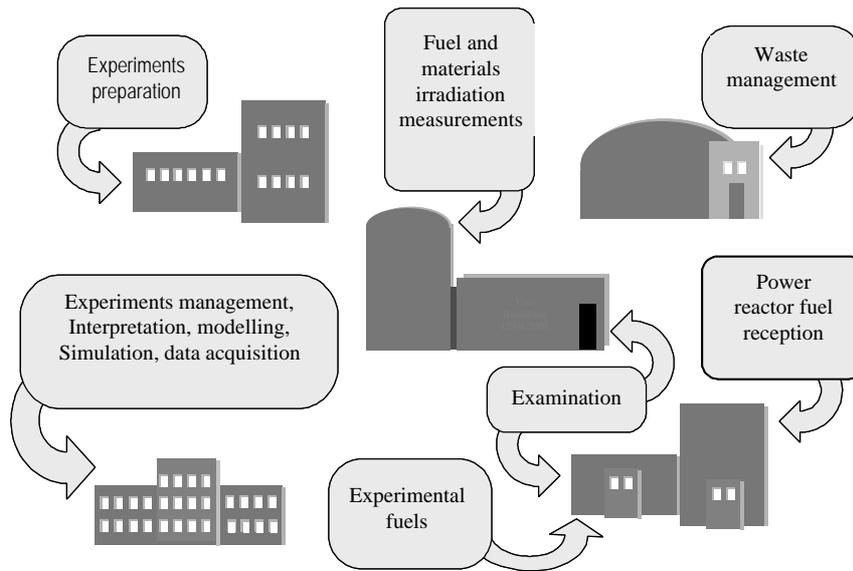
The scientific facility JHR will take advantage from the proximity of universities (Nice, Aix-Marseille and Montpellier). Furthermore, it will profit from a favourable environment on the Cadarache site.

Around the JHR, will be gathered on a single site (fission platform concept) all the functionalities necessary to an effective production of knowledge: fuel and targets manufacturing, instrumentation of experiments to be tested, irradiation, inter-irradiation and post-irradiation analyses, samples and waste management ...

The platform is structured around a permanent scientific team, which is the interface between the platform and the customers. The main roles are related to experiments design (knowledge of industrial needs and their translation in term of experiments), data processing and support for interpretation.

The integration of these functions on the same site allows the rationalization of management in terms of effectiveness (results production time, consistence and complementarity of the examination means between reactor and laboratories), cost and optimisation of material fluxes (limitation of transport). Significant savings are expected from this integration.

These features will improve the level of efficiency and service quality for customers.



The JHR platform includes an accommodation area for scientists, the reactor, the preparation and the examinations laboratories, and the service buildings.

#### Advantages of this structure

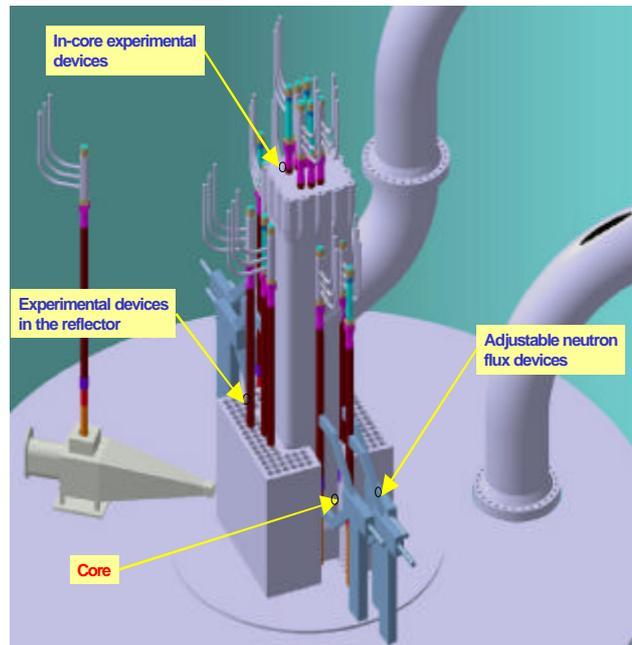
- Expertise from the experimental fuel fabrication to the interpretation of irradiation/examination results will form the surrounding complex of this material test reactor. It includes the preparation of fuel and material samples (fuel fabrication and re-fabrication), the preparation of the irradiation devices (loop, boiler...) and their instrumentation (on-line measurements), their irradiation, the intermediate examinations (non-destructive tests), the destructive and non-destructive post irradiation examinations.
- On one hand, this platform is organised, around a permanent group of material and fuel experts covering devices, sensors development, data acquisition and a group able to provide expertise on modelling and simulation. On the other hand, the platform will be able to work as an element of a network formed by laboratories and industry in Europe or even worldwide.

The presence of all the necessary services on the same site and the efforts in non destructive testing will allow a better management of the experiments. It will reduce transportation, personal doses, the volume of destructive testing and wastes and therefore the cost of experiments.

- The technical challenge is to set up a research complex which would be :
  - A versatile tool to cover several reactor types, including existing reactors, their evolution and the studies on new types of reactors. These studies would lead to the determination of the main fuel or systems technical options of future reactors and are a necessary step to build a possible demonstration reactor. This platform could be used by utilities, fuel fabricators, research organisations and safety authorities and therefore its cost will have to be shared between countries, institutions or with the E.U.
  - A tool able to produce for 50 years the relevant data for the various foreseeable or not yet know needs. This is depending on the scientific know how (interpretation, modelling, simulation...) surrounding the platform, the flexibility of the reactor to accommodate future evolution of research needs, the level of instrumentation and

examination available on the platform to deliver in (or nearly) real time a large amount of quality data. The pertinence of the technical choices retained for the platform depends on the determination of a technical envelope (flux, volume, specific power, payload, instrumentation, types of irradiation rig...).

- An evolutionary device: flexibility is maximal under the constraint of a reasonable investment cost. Therefore the choice of the technical characteristics will be based on a cost/quality optimisation.



Reactor core and irradiation devices

### **3. – IRRADIATION NEEDS TAKEN INTO CONSIDERATION FOR THE JULES HOROWITZ REACTOR DESIGN [2]**

#### **3.1 - Improved Economics and Safety of power plants in operation**

The main challenge for nuclear electricity is that power stations can be run safely and economically. As a consequence, it is essential to develop the understanding of fuel and materials performances and to embody this knowledge in codes to provide best estimate predictions of the behaviour. This in turn leads to a better understanding of fuel performances, a reduction in operating margins, flexibility in fuel management and improved operating economics. In the necessary licensing process, reliable predictions of fuel behaviour constitute a basic demand for safety-based calculations, for design purposes and for fuel performances assessments. The ultimate goal of modelling is a description of fuel behaviour in both normal and abnormal conditions. From this knowledge, operating rules can be derived to prevent fuel failures and the release of fission products also, in an extreme case, to prevent escalation of fuel and core damage and the consequential hazards.

To compete economically on a deregulated market the first directions given to the research are to improve the load factor, increase the fuel burn-up and extend the plant life (PLIM (plant life

management) / PLEX (plant life extension)). To back up these programmes, studies will be conducted on fuel from power reactors, decommissioned reactors and mainly on experiments in MTR which can explore a wider domain of application, especially areas where safety is involved.

Each time the design or the burn-up is modified, the fuel has to be licensed in steady state, ramp and accident conditions.

### **Steady state**

In steady state it is first qualified in MTR experiments (pellets and short rods). In a further step, the fuel can be tested in lead test assemblies (LTA) in power reactors. In this phase the number of assemblies and their burn-up is progressively increased. At each step fuel examinations are carried out to check the behaviour of the fuel according to licensing requirements.

### **Power ramping**

In ramp conditions safety criteria used are the Pellet-Clad Mechanical interaction (PCI), which is related to the stress on the cladding, produced by the pellet expansion in a short period of time. This situation can result in an interaction and if the stress is high enough and the cladding ductility low enough the "ramp" situation can lead to a clad failure.

PCI can also happen in "ramp" conditions. In this case the stress corrosion cracking in the clad is associated with ramp (start up, return to nominal power...). In PCI both stress and corroding agents are necessary to lead to a fuel failure. This type of failure is initiated at the spot of a small defect of the cladding and propagates until the stress exceeds the UTS (Ultimate Tensile Strength) resulting in a failure.

To achieve this type of experiment, the fuel is placed in a testing device located on a displacement system to perform the transient. The power dissipated by fuel can be two to three times (or more) higher than its standard nominal power.

Other types of tests will be necessary to determine the fission product release in case of fuel failure.

Fuel behaviour in accident conditions has to be studied in representative experiments. For the present industrial reactors, the most common accidents studied are the LOCA (Loss Of Coolant Accident) and the RIA (Reactivity Insertion Accident). The role of the JHR is complementary but essential to the accident dedicated facilities (CABRI, PHEBUS, ACPR, NSSR, NSRR...).

### **Reactivity Insertion Accident**

In RIA two approaches are used in safety analysis. The first one is based on the energy deposited during the test (at the time of the failure) [3]. The second approach takes into account a criterion based on the correlation between the strain level and the occurrence of a failure [4]. Sometimes and especially for MOX fuel, the influence of fission gas release could be important. [5].

In any case the objective is to determine a safety domain in which there is no fuel failure or no fuel dispersion and the fuel cooling function is preserved (critical heat flux not reached) [3] RIA experiments are mostly carried out in dedicated reactors, however separate effect experiments can be done in MTRs.

### **Loss of coolant accidents**

The US regulation on which the acceptance criteria for emergency core cooling systems for LWR is based, requires that the calculated total oxidation of the cladding shall nowhere exceed 0.17 times the total cladding thickness before oxidation. In such an accident it is assumed that a certain number of fuel failures happen but that the cooling function of the core is preserved and therefore the rods keep their geometry and are not fragmented.

To address these questions separate effect programmes have been undertaken on the kinetics of the cladding oxidation at a temperature around 1200°C and the assessment of the ductile-fragile limit.[6] [7] [8].

Integral experiments in MTRs are also foreseen in several countries. In this case the fuel is installed in a specific experimental device and irradiated at its nominal power. Then, the coolant is evacuated according to a given scenario. The fuel overheats up to its limit conditions. The fuel re-flooding is then carried out.

### **Fission gas Release (FGR) in steady state, ramp and accident conditions**

The objective of this type of experiment is the parametric study of fission gas release according to various parameters like the temperature, the ramp speed, the atmosphere (oxidizing, reducing, steam...) in order to simulate the conditions encountered during various events.

This type of experiment permits the identification of the mechanisms involved in FGR (inter or intra granular...) [9] [10] and assess the influence of design and irradiation (primary irradiation or re-irradiation in MTR) parameters on FGR. It helps greatly to identify and quantify models used in codes and thus improve their prediction ability. A complementary application is to quantify the source term in accident studies.

These experiments can be carried out in the JHR (in the core or the connected hot cells). For this kind of experiment (where fuel can be damaged), the JHR will be equipped with an alpha cell ready for degraded samples containing high alpha transmitter content (plutonium, americium, neptunium, curium).

This will extend the experimental possibilities of the JHR beyond what is currently available.

## **3.2 – Research on future reactor types**

Recently several countries in America and Europe agreed to a multinational effort aimed at developing advanced reactor technology that would be partly able to respond to the world's increase electricity demand and would be safer, more competitive as well as more proliferation resistant. It means that any new development of commercial nuclear energy will have to take into account important improvements (intrinsic safety features, waste disposal, proliferation resistance...).

In this context it can be considered that the transmutation of actinides and LLFP (long life fission products) will remain an objective for many years as it can reduce the waste toxicity that is one of the major focuses of public attention now and for the years to come. Most studies can be carried out in MTR reactors because they are technically close to fuel experiments and are mainly focused on matrix and actinide evolution under irradiation.

EPR and the advanced PWR and BWR are improving the situation regarding reactors safety. This step forward could be performed together with reactors lifetime and fuel burn-up improvements. In this case, new types of fuel and materials would probably have to be used and extensively tested in MTRs.

## **3.3 – Medical and industrial applications**

The technological irradiation reactors constitute a key tool in Europe for the radioisotopes production (in particular <sup>99</sup>Mo) or the manufacture of radioactive sources.

Very few installations are able to meet this need in Europe : the High Flux reactor in Petten in the Netherlands, the OSIRIS reactor in France, and the BR2 reactor in Mol in Belgium. The JHR will contribute to secure this market by providing back-up capability.

The main production to day is:

- production of artificial radioisotopes :
  - for examinations and medical diagnostics: gamma radiography (technetium 99m, xenon 133, gadolinium 153),
  - for therapies (cancer with iridium 192, caesium 137, cobalt 60) and the treatment of thyroid with iodine 131,
  - for medical materials sterilization (cobalt 60).
- production of artificial radioisotopes for industry :
  - instrumentation with iridium 192, krypton 85, promethium 147,
  - tracing with krypton 79, bromine 82, technetium 99m,
  - ionisation (cobalt 60).

### **3.4 - Scientific applications of analysis and characterization**

The activation analysis allows the determination of the chemical and / or isotopic composition of samples. The physical method used allows a good level of precision on very small quantities of impurities. It relies on the use of pneumatic or hydraulic channels and on a laboratory integrated to the facility.

The applications concern :

- industry: to determine impurity traces in highly pure materials (electronic component, photovoltaic cells),
- environment: quantification of heavy metal pollution and pollutant (arsenic, cadmium, mercury, lead) in the air,
- earth sciences: to seek elements in geological materials (relative accuracy :  $10^{-8}$ ) and which determination is significant to establish geothermic models,
- geology: dating of break before the establishment of a tunnel, oil exploration
- archaeology : dating.

### **3.5 – Other needs considered : fusion, water chemistry ...**

Although MTR reactors are not the perfect tool to work on fusion materials because of the need for high doses (120 dpa or more) and high-energy neutrons (14 MeV), the selection of materials can be performed successfully in MTRs.

Water chemistry in reactors is a very prominent area of research that impacts the reactor safety, the radiation exposure and therefore the reactor economics. At high temperature, water is an aggressive medium when in contact with structural materials. This means that the reliability of many nuclear power plant systems (e.g. fuel assemblies and steam generators) is dependent on the water chemistry. Experience with water cooled power reactors shows that even under normal operating conditions some undesirable effects can occur, including corrosion, erosion, hydriding or deposition of corrosion products on heat transfer surfaces.

In addition to the adverse effects of corrosion on the mechanical properties of components and corrosion products deposition on heat transfer surfaces able to produce reactivity abnormalities (axial offset), the migration of activated corrosion products may lead to the formation of highly radioactive deposits on some of the out of core surfaces of the primary circuit. This is the main cause of radiation exposure during repair and maintenance and may require decontamination of some equipment or of the primary circuit as a whole.

## **4 – RJH EXPERIMENTAL FIELD AND CAPACITY**

**4.1. - Flux level** : flux requirements for existing and future power reactor compared to typical performances of the MTR (OSIRIS) and JHR are provided in this table :

Power Reactors	Typical $P_{th}/V_{core}$ (kW/l)	Fast Flux $E > 0.907$ MeV ( $n/cm^2/s$ )	Thermal Flux $E < 0.625$ eV ( $n/cm^2/s$ )	dpa/year (on core internals)
PWR/BWR	80	$1.30 \cdot 10^{14}$	$9.00 \cdot 10^{13}$	2 - 3
HT Gas-Cooled RS	6.6	$1.00 \cdot 10^{13}$	$1.20 \cdot 10^{13}$	< 1
Gas-Cooled Fast RS	20 - 150	$0.18 - 1.40 \cdot 10^{14}$		3 - 21

Osiris MTR (CEA Saclay, France)	Typical $P_{th}/V_{core}$ (kW/l)	Fast Flux $E > 0.907$ MeV ( $n/cm^2/s$ ) (1)	Thermal Flux $E < 0.625$ eV ( $n/cm^2/s$ ) (1)	dpa/year (max on irradiated samples)
Core	320	$2.70 \cdot 10^{14}$	$3.40 \cdot 10^{14}$	6
Reflector			$2.70 \cdot 10^{14}$	

JHR MTR (high flux core configuration)	Typical $P_{th}/V_{core}$ (kW/l)	Fast Flux $E > 0.907$ MeV ( $n/cm^2/s$ ) (1)	Thermal Flux $E < 0.625$ eV ( $n/cm^2/s$ ) (1)	dpa/year (max on irradiated samples)
Core	600	$6.40 \cdot 10^{14}$	$3.50 \cdot 10^{14}$	18
Reflector			$7.30 \cdot 10^{14}$	

(1) undisturbed maximum flux

With the options taken for the design of the JHR it's possible to cover a wide range of flux conditions and to secure it's ability to meet future needs whatever the reactor type considered.

**This experimental field will be extended** by using specific devices in order to increase locally :

**4.1.1 -The fast flux** in order to achieve a damage effect at least of 25 dpa/year (displacement per atom).

This can be achieved by increasing locally the fission density.

The JHR neutron converter is based on a specific fuel element which can replace a standard fuel element in the core with, in the middle, a location for an experimental rig containing samples to be irradiated.

The fuel design is based on the russian cruciform shape design used in SM and PIK reactors. This design allows to remove easily the power generated.

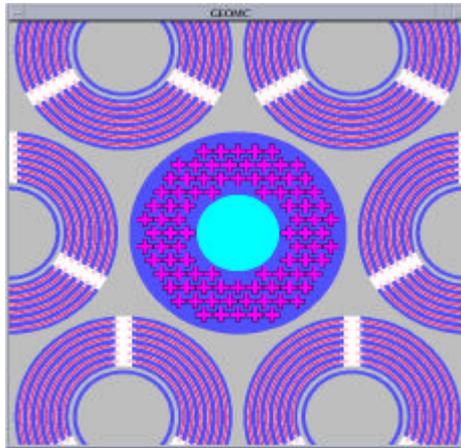
According to the thermohydraulics calculations the JHR primary circuit is compatible with such a design and the flow rate is large enough to prevent overheating of the fuel pins and water boiling.

Various types of fuel pins are considered both by changing the pin geometry (on keeping the cruciform shape) and by changing the components of the fuel meat.

In the example below the neutron converter is made of : 90 pins of 6,00 diameter.

- number of fuel pins : 90
- pin diameter : 6,00 mm

- fuel meat :  $\text{UMo}_7$
- dpa on samples in the experimental cavity : 29,6 dpa/year



**4.1.2 - The thermal flux** to get the appropriate power rating in specific oriented safety experiments.

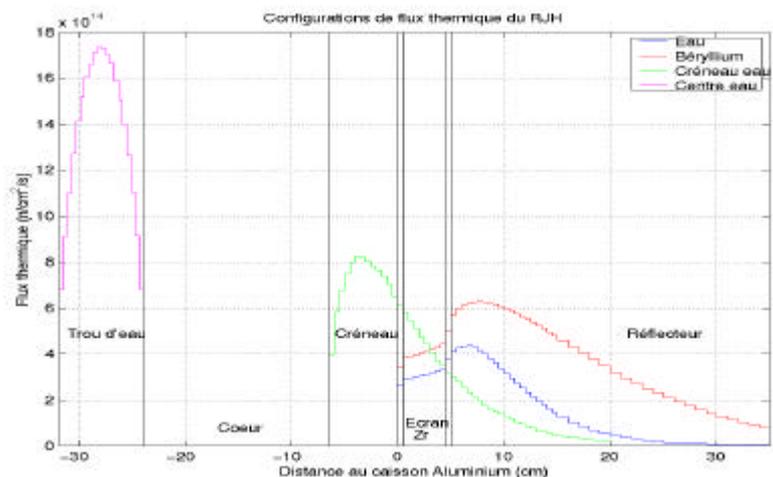
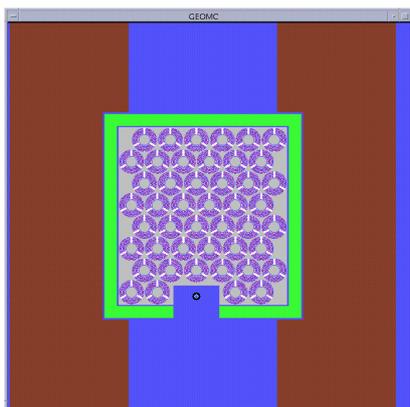
The main objective is to carry out experiments to study the fuel behavior during accidental conditions typically a reactivity insertion accident (RIA).

The target figure is a power rating of about 20 times higher than the mean power rating in the PWR (180 W/cm) during a transient of about 20 ms.

According to the preliminary studies it's possible to get the expected performances in having a water wall around the fuel pin to be tested thick enough to locally enhance significantly the thermal flux.

Depending on the exact location of this device the effect of the water wall is more or less efficient :

Location of the device	Distance of the device from the core limit	Thermal flux
Water reflector	6,5 cm	$4,37 \cdot 10^{14}$
Beryllium reflector	9 cm	$6,27 \cdot 10^{14}$
Crenel	3,7 cm	$8,2 \cdot 10^{14}$
Core	28 cm	$1,74 \cdot 10^{15}$



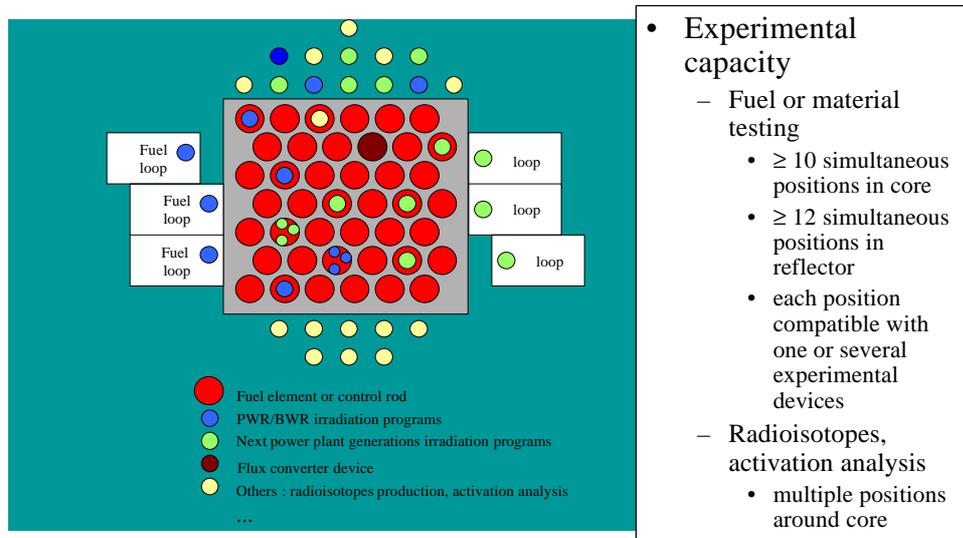
In this example, the power rating on a standard PWR fuel pin unirradiated, irradiated (65 000 Mwj/t), unirradiated MOX is respectively 8300 W/cm, 4300 W/cm, 9200 W/cm.

The study of the fuels behavior under accidental conditions (such as reactivity insertion, or loss of coolant accidents), in carrying out analytical experiments, on a limited amount of irradiated fuel, is a major objective of the project. These oriented safety tests are possible :

- by designing specific irradiation devices to get locally the appropriate conditions
- by providing all the necessary laboratories to study the damaged fuel ( $\alpha$  hot cells, fission products laboratory ...)
- by taking specific provisions for the safety of the facility such as the tightness of the barriers.

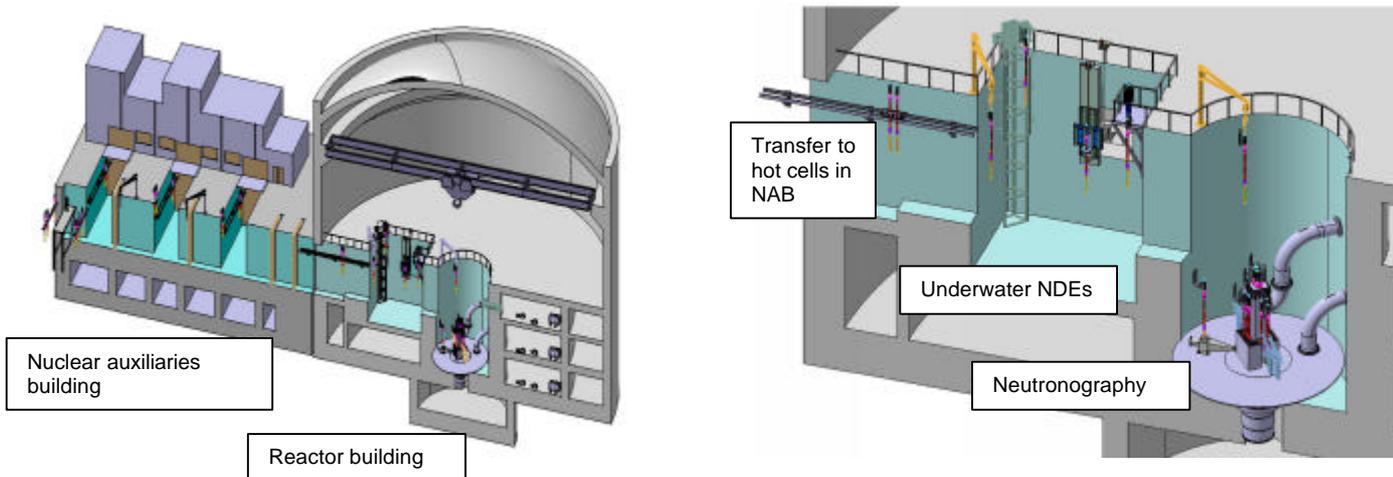
Experiments can be carried out either inside the core or in the reflector (beryllium or water).

Typically the experiments which require fast flux have to be carried out inside the core (material testing). While most of the fuel tests, the radioisotopes production ... can be carried out in the reflector.



Schematic view of a typical core loading

Five hot cells are directly connected to the reactor pool to improve the efficiency of the experimental process. A hot cell is mainly devoted to manage  $\alpha$  contaminated experiments resulting from oriented safety experiments in which fuel could be failed and partly melted.



### **III – CONCLUSION**

The JHR design results from the need to offer experimental possibilities as broad as possible for at least 50 years. It takes into account the foreseeable evolution of the programs related to the study of the new reactor types, in particular the gas cooled reactors. It also takes into account the analytical experiment needs for materials and fuels behaviour modelling under irradiation, including accidental situations.

The choice to build the JHR in Cadarache shows the will of CEA to guarantee to this research infrastructure a high level of excellence, offering a complete service.

It will be in the heart of a scientific platform. It will be broadly opened to the European and international co-operation. It will gather all the functionalities. It will offer the possibility of an effective knowledge production, with optimised costs.

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