JULES HOROWITZ REACTOR, BASIC DESIGN

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ABSTRACT

Since the shutdown of the SILOË reactor in 1997, the OSIRIS reactor has ensured the needs regarding technological irradiation at CEA including those of its industrial partners and customers. The Jules Horowitz Reactor will replace it. It has the ambition to provide the necessary nuclear data and maintain a fission research capacity in Europe after 2010. This capacity should be service-oriented. It will be established in Cadarache.

The Jules Horowitz reactor will also:
- represent a significant step in term of performances and experimental capabilities,
- be designed with a high flexibility, in order to satisfy the current demand from European industry, research and be able to accommodate future requirements,
- reach a high level of safety, according to the best current practice.

This paper will present the main functionalities and the design options resulting from the "preliminary design" studies.

I. The experimental potential of the Jules Horowitz Reactor in the Cadarache fission platform

1 Context

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

Since the divergence of the first nuclear reactor built in the world, 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 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
- the analysis and characterization of the materials

In France, in order to meet these needs, CEA built the SILOË reactor (35 MW), in Grenoble (criticality in 1963), then the OSIRIS reactor (70 MW), in Saclay, (criticality in 1967). The SILOË 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 2011. The lifetime considered is at least 50 years. The phase of detailed studies is about to start.

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 [5]

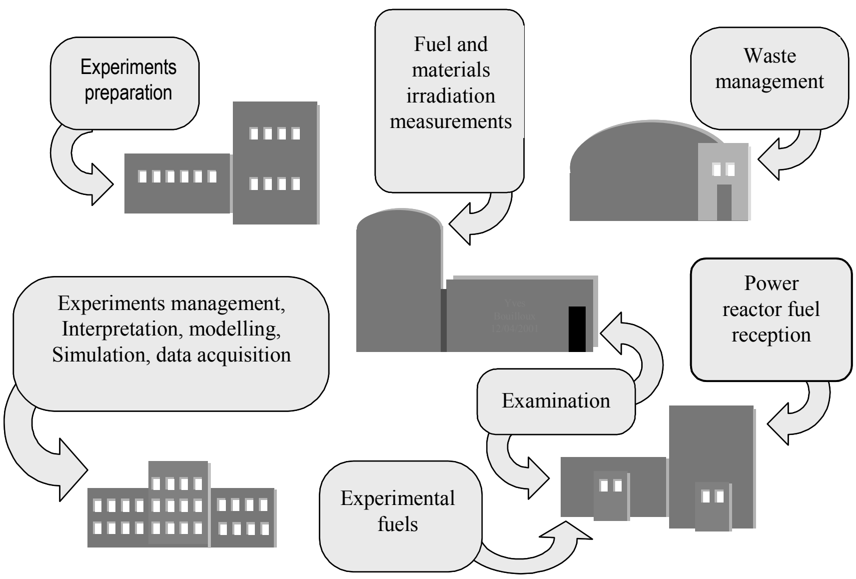
The scientific facility JHR will profit from the proximity of universities (Nice, Aix-Marseille and Montpellier). Furthermore, it will profit from a favourable environment on the Cadarache site.

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.

2.1 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.

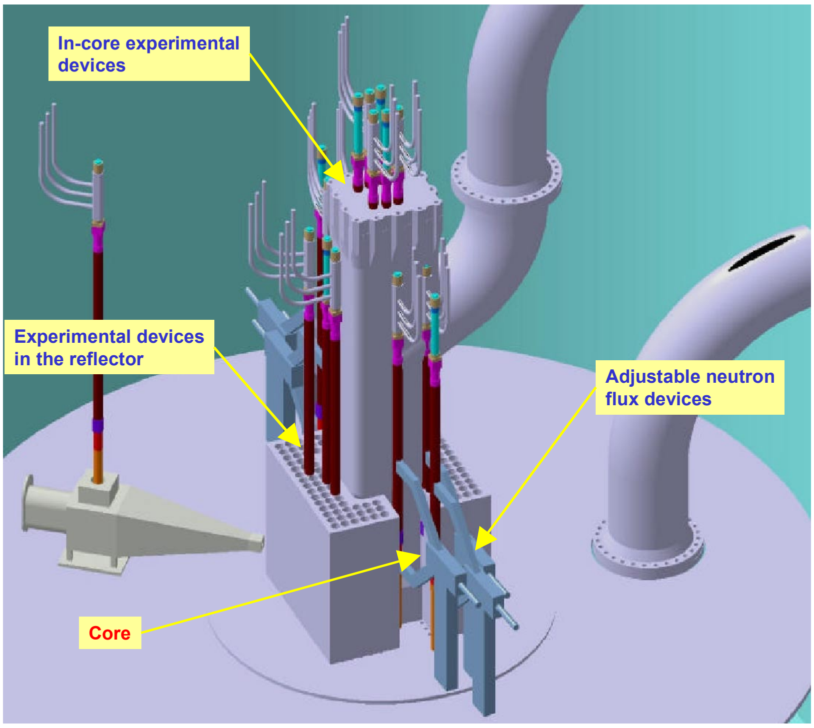
- On one hand, this platform is organised, of course, around a permanent group of material and fuel experts covering loop and devices, sensors development, data acquisition and a group able to provide expertise on modelling and simulation. On the other hand, the platform will be able to work as an element 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, nuclear steam system suppliers, 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

2.2 Needs taken into consideration for the Jules Horowitz Reactor design [3]

2.2.1 Improved Economics / Safety of working reactors

The main challenge for nuclear electricity is that reactors can be run safely and economically. As a consequence, it is essential to develop the understanding of fuel and materials performance and to embody this knowledge in codes to provide best estimate predictions of behaviour. This in turn leads to a better understanding of fuel performance, 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 performance assessment. 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 to the environment, 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, working 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.

Ramp conditions

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) [6]. The second approach takes into account a criterion based on the correlation between the strain level and the occurrence of a failure [7]. Sometimes and especially for MOX fuel, the influence of fission gas release could be important. [8].

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) [6]
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. [9] [10] [11].
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…) [12] [13] 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.

2.2.2 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 increased 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…):
EPR and the advanced P 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.

2.2.3 Medical and industrial applications

The technological irradiation reactors constitute a key tool in Europe for the radioisotopes production (in particular ^{99}Mo for the hospitals) or the manufacture of radioactive sources.

Very few installations are able to meet this need: 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 is:

- production of artificial radioisotopes, essential today:
  - 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)

2.2.4 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.

2.2.5 Transmutation, fusion, water chemistry…

Studies on transmutation are technically close to fuel and are mainly focused on matrix and actinide evolution under irradiation. 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.

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.

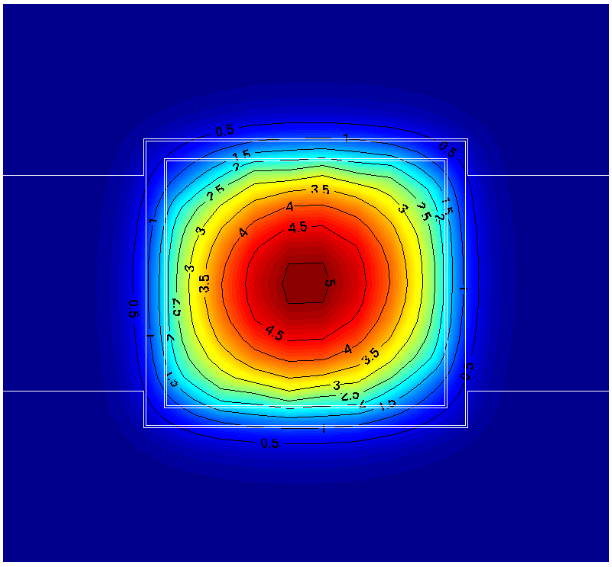
Water chemistry in reactors is a very prominent area of research that impacts the reactor safety, the radiation exposure and therefore the reactor economics. At high temperature, water is an aggressive medium when in contact with structural materials. This means that the reliability of many nuclear power 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.

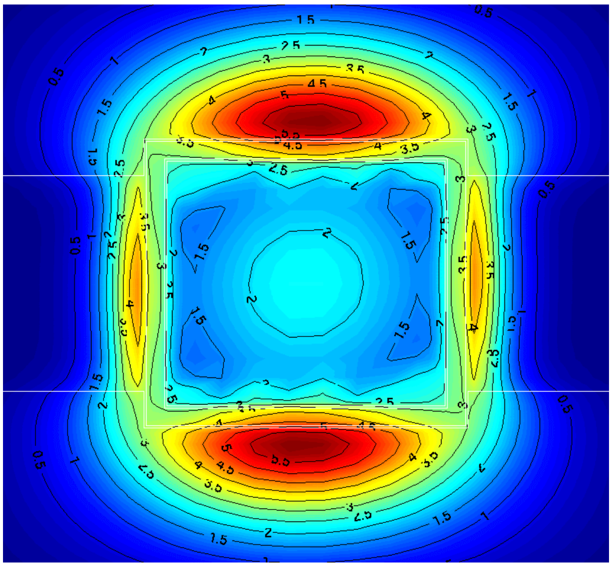
II. Jules Horowitz Reactor: a real step in design [4]

1 Higher performances, wider experimental field

The two charts of "non-disturbed neutron flux" below illustrate the irradiation performances.



Fast flux (E>0.907 MeV, axial mean ×10^{14} n/cm^2/s)



Thermal flux (E<0.625 eV, axial mean ×10^{14} n/cm^2/s)

The JHR is mainly characterized by:

- performances covering a broader range of usable neutron flux, a large experimental capacity and very rigorous quality standards.

  This requires a new generation of experimental devices allowing tests under severe experimental conditions including fuel failure or fast evolutions of the physical parameters,

- more financial constraints, for both the investment and the costs of the experiments,

- safety requirements as demanding as those used for currently designed reactors (EPR, RES) and which marks a real step forward compared to the former MTR generation.

To satisfy these requirements a structured design approach is necessary.

2 A general-purpose experimental reactor

Because of economic considerations, the JHR must meet at the same time the European Utilities short and medium term needs, and those of new reactor types. In addition, the long lifetime under consideration for this reactor implies a high level of flexibility able to accommodate most of the future needs. These requirements lead to:

- detailed attention in the dimensioning of the "not-so-easy-to-replace" components to make sure that they can face a sufficient range of performances,

- constructive provisions ensuring a high flexibility of the installation. The whole "reactor block" (everything between the primary inlet and the outlet) located in the reactor pool is dismountable and changeable.

In the same way, the experimental shielded compartments, which present high requirements in terms of containment and protection against radiation, are designed in a modular and evolutionary way.

- evolutions of hot cells is foreseen. Reservation is already made to construct additional cells or to enlarge one of the existing ones.

3 Main design principles

General architecture makes it possible to meet all the requirements by developing the functional segregation of the activities according to their type and the risks they generate and limiting the interactions between these various activities.

This first main principle resulted in separating the activities in two buildings, isolating:
- systems and activities specific to the reactor and the experiments within a reactor building. These two types of systems are also separated within this building in a reactor operation zone and an experiments operation zone,
- other systems relating to the nuclear activity and in particular means of pre-irradiation and post-irradiation treatment of the experiments in a Nuclear Auxiliaries Building (NAB).

The second principle is the concept of “water block”, i.e. a monolithic structure of civil engineering, inspectable from the outside, including the pools and the bunkers containing the primary circuit. This structure is continuous from the reactor building to the NAB. It includes an underwater lock ensuring the containment continuity of the two buildings. This water block guarantees that core is kept underwater in the event of primary circuit leakage.

4 Load factor improvement

The high performances in term of fast and thermal neutron flux requires an innovating core concept. The need for many and various experiments implies an easy access to the core.

After study of several alternatives, a pool-type reactor was chosen. This concept allows easy evolution and accessibility to the experiments. Therefore it is a favourable factor to improve the reactor experimental load factor.

The main characteristics are given in the following table.

Power	100 MW
Volume power	600 kW/l
Moderator	H_2O
Reflector	H_2O, Beryllium
Coolant	H2O
Max non-disturbed fast neutrons flux (> 0.907 MeV)	6.4 10^{14} n/cm^2/s
Max non disturbed thermal neutrons flux (< 0.625 eV)	7.3 10^{14} n/cm^2/s
Inlet core temperature	25°C
Outlet core temperature	41°C
Coolant velocity in core	15 m/s
Direction of the flow in the core	Ascending
Maximum enrichment	20%
Average surface heat flux (on the fuel plates)	190 W/cm²
Maximum surface heat flux (on the fuel plates)	500 W/cm²
^{235}U core mass	21 kg

JHR characteristics, given for UMo fuelled core (8 gU/cm^3)

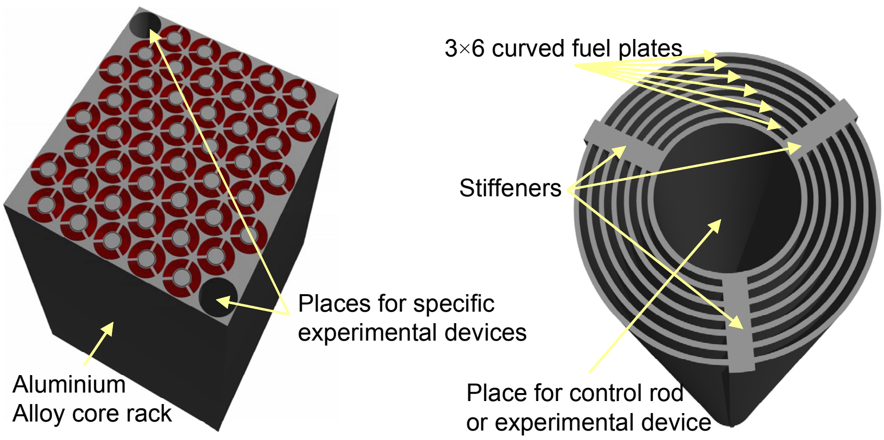
5 A high performance core

5.1 A cylindrical fuel element

The core consists of fuel plates curved and assembled in cylindrical elements. The curved shape of the fuel plates allows a high water flowrate and therefore a high specific power. The fuel plates are obtained by the "picture-frame" technique consisting of a hot-rolled fissile core (a compacted mixture of uranium alloy powder (U-7Mo) [2] and of aluminium powder) between two plates of aluminium alloy.

5.2 A small size core

The core consists of fuel elements loaded in an aluminium rack.



JHR core and fuel element

5.3 A dismountable core rack

The primary circuit is closed and constitutes the second containment under power operation. It operates under low pressure (up to 1.5 MPa), which improves the operating margins. The rack, which is a part of the primary circuit, containing the core is dismountable. It is partially surrounded by a beryllium reflector.

Experimental devices are the major design priority. The core design optimisation takes into account the following objectives:

- ten experimental devices can be simultaneously inserted in the core. They can be inserted into the centre of a fuel element or replace a complete fuel element,
- in the core periphery, six irradiation devices on displacement systems, allowing neutron and heat flux adjustment.
- possibility of many complementary experiments in the reflector, in particular to produce radioisotopes for industrial or medical use, or for the activation analyses at various levels of neutron flux.

5.4 Core control mechanisms

Some of the fuel element central hole are occupied by control rods which are operated by mechanisms located under the core pool. They do not affect the number of usable "experiment locations". The rods assigned to the control of the reactor and those ensuring the emergency shutdown are separated functionally and technologically. A complementary shutdown system, based on soluble absorbent, is designed to mitigate the hypothetical failure of several mechanisms.

In the experimental cycle few equipments will play a special role:

5.5 Hot cells

The majority of the human interventions on radioactive or contaminating materials are carried out in shielded cells.

The operations in hot cell includes the handling of radioactive experimental samples, their installation in the experimental device, the intermediate examination, their after irradiation recovery, the non-destructive post-irradiation measurements and their conditioning for transport to other specialized installations, the controls of irradiated fuel from the reactor itself and the maintenance or interventions on radioactive structures (measurement bench, tools, components of the reactor or experimental devices).

The JHR will be equipped with five hot cells, conferring to the installation reception capacities avoiding bottleneck situations frequently met on former installations. Each hot cell is designed for a main function but its use is flexible. This approach makes effectiveness and flexibility compatible.

One of the hot cells is conceived to allow the handling of alpha emitter substances: the JHR can deal with failed fuel.

The hot cells are built just above the water channels. The direct transfer of components decreases the transfer times and risks related to the handling of active components.

5.6 Pools

In the reactor building is located the main pool where the reactor and the experiment locations are. There is also an "intermediate" pool intended to underwater storage of the radioactive structures during the maintenance phases and of irradiated fuel before the transfer to the NAB.

The NAB contains four pools and channels for underwater transfer to the hot cells and the reactor building. Two pools respectively ensure the underwater storage of irradiated fuel elements and the most radioactive components resulting from the experiments. The two other pools are dedicated to the underwater interventions, required by the operation of the experimental devices (recovery of the samples, connection and disconnection of electric, fluid or gas circuits).

6 A safety approach based on the defence in depth principle [1]

The design of the JHR relies on the defence in depth concept, based on the five following levels:

- 1st level: prevention (quality of design and realization, prevention of the anomalies),
- 2nd level: monitoring, detection, control and protection (quality of the operation, maintenance of the installation in the authorized operation range),
- 3rd level: safety actions,
- 4th level: accidents management and protection of the containment, limitation of the radiological consequences (prevention of the degradation of the accidental conditions and limitation of the consequences in case of serious accidents),
- 5th level: organization to answer any emergency (being able to lead to radioactive release).

The defence in depth principle leads to the implementation of several barriers between the radioactive products and the environment. For JHR, special attention is given to containment robustness and to the achievement of a homogenous safety base as regards internal events and / or hazards.

The reactor design takes into account:

- the experimental character of the installation that implies the segregation as much as possible between the operating systems of the reactor and the experimental devices,
- the risks related to internal hazards such as fire and internal flood and to external hazards such as earthquake, aircraft crash or extreme climatic conditions,

The safety of the experimental devices is designed taking into consideration the experimental constraints and the risks induced by the reactor.

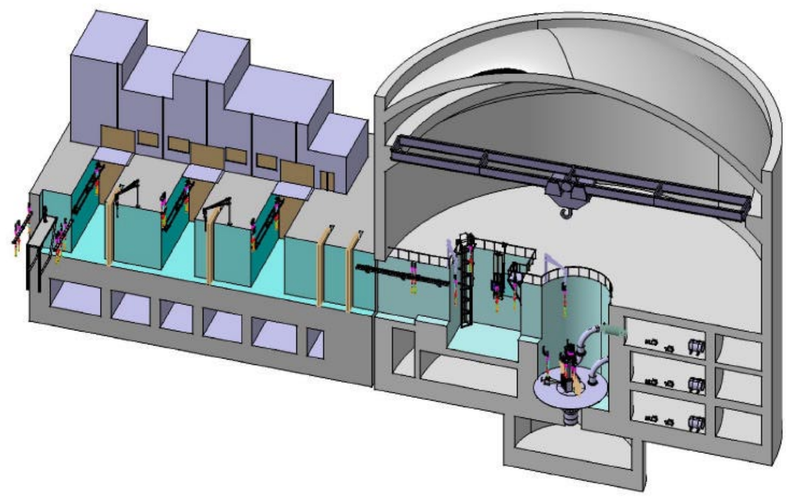
The design takes into account the experience feedback obtained in the field of experimental irradiation:

- to limit the normal operation releases, waste and worker doses with an ALARA approach,
- to integrate the human factor for the man / machine interface and for the working groups organization in charge of the reactor and of the experimental devices,
- to take into account the reactor maintenance constraints and the reactor dismantling.

7 A global containment solution

The penetrations in the reactor building are directed towards a zone known as “leakoff recovery zone” located between the two buildings (the reactor building and the NAB), which provides leak collection, and filtration. This global containment solution is supplemented in the lower part of the building (below the top level of the pools) by gathering on a single foundation slab the reactor building, the NAB and the leakoff recovery zone, within a single platform known as “nuclear unit”.

The reactor building will be made of concrete and will be circular in order to ensure its good behaviour in case of an accident leading to pressure increase.



View of the JHR

8 The management of the accidental situation by the safety approach

The severe accident considered for the JHR is a beyond design reactivity insertion accident, involving instantaneous core melt and core destruction phenomena, the core remaining underwater. The third barrier is designed to manage and to mitigate this severe accident.

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 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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