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Materials subjected to fast neutron irradiation/Matériaux soumis à irradiation par neutrons rapides

Jules Horowitz Reactor: a high performance material testing reactor

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Abstract

The physical modelling of materials' behaviour under severe conditions is an indispensable element for developing future fission and fusion systems: screening, design, optimisation, processing, licensing, and lifetime assessment of a new generation of structure materials and fuels, which will withstand high fast neutron flux at high in-service temperatures with the production of elements like helium and hydrogen.

JANNUS and other analytical experimental tools are developed for this objective. However, a purely analytical approach is not sufficient: there is a need for flexible experiments integrating higher scales and coupled phenomena and offering high quality measurements; these experiments are performed in material testing reactors (MTR). Moreover, complementary representative experiments are usually performed in prototypes or dedicated facilities such as IFMIF for fusion. Only such a consistent set of tools operating on a wide range of scales, can provide an actual prediction capability. A program such as the development of silicon carbide composites (600–1200 °C) illustrates this multiscale strategy.

Facing the long term needs of experimental irradiations and the ageing of present MTRs, it was thought necessary to implement a new generation high performance MTR in Europe for supporting existing and future nuclear reactors. The Jules Horowitz Reactor (JHR) project copes with this context. It is funded by an international consortium and will start operation in 2014. JHR will provide improved performances such as high neutron flux (10^{15} n/cm^2/s above 0.1 MeV) in representative environments (coolant, pressure, temperature) with online monitoring of experimental parameters (including stress and strain control). Experimental devices designing, such as high dpa and small thermal gradients experiments, is now a key objective requiring a broad collaboration to put together present scientific state of art, end-users requirements and advanced instrumentation. ***To cite this article: D. Iracane et al., C. R. Physique 9 (2008).***

Résumé

Réacteur Jules-Horowitz : un réacteur d'haute performance pour des essais des matériaux. La modélisation physique du comportement des matériaux en environnement sévère est une contribution indispensable au développement des systèmes innovants, qu'ils soient basés sur la fission ou la fusion : identification, conception, optimisation, fabrication, approbation, évaluation de la durée de vie d'une nouvelle génération de matériaux de structure et de combustibles qui seront capables de fonctionner sous haut flux de neutrons rapides et à haute températures avec la production d'éléments tels que l'hélium et l'hydrogène.

Des outils analytiques tels que JANNUS sont développés dans ce but. Toutefois une approche purement analytique ne suffit pas : il faut également pouvoir réaliser des expérimentations dans un environnement représentatif, où les phénomènes sont effectivement couplés, avec une instrumentation permettant des mesures de haute qualité. Ces expériences sont conduites dans des réacteurs de recherche (Material Testing Reactors, MTR). De plus, des expériences complémentaires sont généralement conduites sur des prototypes ou des installations spécifiques comme IFMIF pour la fusion. Un réel pouvoir prédictif de la modélisation ne peut être

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atteint qu'en s'appuyant sur un tel ensemble cohérent d'outils, couvrant une large gamme d'échelles d'observation. Cette stratégie est exposée sur le cas du développement des matériaux composites à base de carbure de silicium.

En raison du vieillissement des MTR actuellement en fonctionnement, il était nécessaire de mettre en place une nouvelle génération de réacteurs expérimentaux en Europe pour faire face aux besoins en irradiations expérimentales. C'est dans ce contexte qu'est développé le réacteur Jules Horowitz (JHR). Celui-ci est financé par un consortium international et entrera en opération en 2014. JHR offrira à la communauté des performances accrues telles qu'un flux de neutrons élevé (10^{15} $\mathrm{n/cm^2/s}$ au dessus de 0.1 MeV) dans divers environnements (fluide de refroidissement, pression, température), avec un contrôle en ligne des paramètres expérimentaux (y compris les contraintes mécaniques). La conception des systèmes expérimentaux est maintenant un objectif clé nécessitant une large collaboration rassemblant la communauté scientifique, les utilisateurs finaux, et les experts en instrumentation. ***Pour citer cet article : D. Iracane et al., C. R. Physique 9 (2008).***

Keywords: Jules Horowitz Reactor; Material testing

Mots-clés : Réacteur Jules-Horowitz ; Essai des matériaux

1. Introduction

Current nuclear power plants (Generation II) contribute both to the continuity of electricity supply and to the limitation of emissions of greenhouse gases; this makes nuclear power an attractive component of the energy mix in many areas of the world.

Furthermore, the fast growing energy demand driven by the increasing world population and the fast development of large emerging countries, together with recognised assets of nuclear energy in terms of energy security and limitation of greenhouse gas emission, have led to acknowledge the role that nuclear energy ought to play amongst other energy sources to satisfy the future energy needs of mankind. Generation III light water reactors (LWRs), which materialise optimised versions of current nuclear generating facilities, are anticipated to develop in large populated countries, as well as to replace or augment existing nuclear power plants.

Finally, in parallel with the implementation of these best available LWR technologies, it is essential to start developing breakthrough technologies that will be needed to prepare the longer term future:

- fast neutron reactors with a closed fuel cycle, which will allow a more efficient use of uranium resources and minimising long-lived radioactive waste;
- high temperature reactors (HTR) able to drive more efficient processes to generate energy products other than electricity, such as hydrogen, synthetic hydrocarbon fuels from coal or biomass, or heat for industrial processes, thus contributing to enlarge the range of applications of nuclear energy;
- accelerator driven systems (ADS), which may contribute to transmute minor actinides, in addition to transmutation through advanced recycling modes in fast reactor systems; and
- fusion reactors, which use as fuels lithium and deuterium abundant in nature and do not produce long lived radioactive waste.

Several initiatives today, such as the Generation IV International Forum (GENIV) and the IAEA International Project on Innovative Nuclear Reactor (INPRO), aim at revisiting the technologies that led to early prototypes of fast neutron and high temperature reactors, and to search for innovations that could make them progress significantly in competitiveness, safety and operability so as to prepare the development of new attractive commercial nuclear systems.

2. Key material issues

Key technologies for such systems encompass high temperature structural materials, fast neutron resistant fuels and structural core materials, advanced fuel recycling processes with co-management of actinides, and specific reactor and power conversion technologies.

The main requirements for the materials to be used in these reactor systems are their dimensional stability under irradiation for the in-core materials (swelling, growth, irradiation creep or relaxation), the stability of their mechanical properties (high temperature strength, ductility, fracture toughness), and their resistance to corrosive environments

Table 1
Main characteristics of innovative nuclear systems and major candidate materials

Tableau 1
Principales caractéristiques des systèmes nucléaires avancés et matériaux de structures envisagés

	Sodium Fast Reactor	Gas Fast Reactor	Lead Fast Reactor & ADS	High Temperature Reactor	Supercritical Water Reactor	Molten Salt Reactor	Fusion
Coolant	Liquid Na few bars	He, 70 bars 480–850 °C	Lead alloys 550–800 °C	He, 70 bars 600–1000 °C	Water	Molten salt	He, 80 bars 300–480 °C Pb–17Li, ∼ 1 bar 480–700 °C
Core structures	Wrapper: Martensitic steels Clad. tubes: ODS	SiCf–SiC composite or ODS (back up)	Target structure: Martensitic steels Window & Clad: Martensitic, ODS	Graphite (structures) Composites C/C, SiC/SiC for control rods	Ni based Alloys F/M steels	Graphite	Martensitic steels ODS Ferritic steels SiC_f–SiC therm. & elect. insulator
Temperature	390–750 °C	500–1200 °C	350–480 °C	600–1600 °C	350–620 °C	700–800 °C	FW: T_{max}: 625 °C → ODS Channel: T_{max}: 500 °C Insert T_{max}: 1000 °C
Dose	Cladding: 200 dpa	60/90 dpa	Clad: ∼ 100 dpa	7/25 dpa	Several 10 dpa	N.A.	∼ 100 dpa + He(10 appm/dpa) and H(45 appm/dpa)
Other components		IHX or turbine: Ni based alloys	ADS/Target: ∼ 100 dpa + He	IHX or turbine: Ni based alloys			

(reactor coolant or process fluid). In this respect, it is important to look for commonalities in service conditions for different systems. For instance, lead-cooled fast reactor (LFR) materials have benefited from research done in the frame of ADS programs, and fusion materials (ferritic/martensitic (F/M) steels, oxide dispersion strengthened (ODS) steels, SiC_f/SiC composites) are also widely considered for Generation IV systems.

The main parameters envisaged for innovative systems are summarised in Table 1, along with some of the candidate materials. It appears that the major challenges result from the temperatures, significantly higher than the typical operating temperature of current LWR, the high irradiation doses, and the compatibility with some of the coolant or other fluids considered.

The common innovative structural materials could be grouped into three main categories to cover increasing operating temperature required [1]: (a) 9Cr martensitic steels, including low activation versions, for applications up to 550 °C; (b) ODS ferritic alloys with improved thermal creep resistance to use at temperatures beyond 550 °C, (c) SiC_f/SiC composites, constituted by stoechiometric fibres in a ceramic matrix for applications up to 1200 °C. Large R&D and qualification programmes are needed, in particular, for the two last groups of materials.

The GEN IV objectives of sustainability will also require fuels allowing actinide management in a closed fuel cycle. In France, priority will be given to oxide fuels although nitride, carbide and metal fuels may also be considered. Major issues for these new fuels are their ability to sustain high burn-up, and retain radio-elements and fission gases.

3. Modelling and basic material science

A good understanding of the basic mechanisms controlling material performance will really aid the selection and optimisation of materials and the assessment of their durability as well. It is therefore very important to develop a predictive material science where physical modelling will play a central role. Indeed, since the experimental databases do not generally cover the whole range of conditions needed in terms of temperature, time, neutron spectrum, and so on, it is essential to develop robust physical models to extrapolate with some confidence outside the experimentally known domain. Furthermore, modelling and simulation give access to basic information that can hardly be obtained by global irradiation tests, e.g. on the dynamics of impurities and defects under irradiation. The understanding of the mechanisms governing the material's behaviour is critical to identify and finally control the most relevant parameters. For example, the actual microstructure of oxide nano-clusters in ODS steels and the mechanisms responsible for the

Fig. 1. Different manufactured products in SiC_f/SiC ceramic composite.

Fig. 1. Différents types de produits fabriqués à partir des céramiques composites fibreux SiC_f/SiC.

enhancement of high temperature strength are unknown as well as their behaviour under in-service conditions. This approach will also provide a powerful tool to optimise existing materials or develop new materials.

Physical modelling based on the theoretical computation of atomic cohesive forces that control thermodynamics, kinetics and mechanics has already been undertaken for LWR structural materials, for instance in the frame of the integrated project PERFECT within the 6th Framework Program of the EU (https://www.fp6perfect.net). Modelling in the field of thermodynamics and kinetics in metals and alloys has reached a relatively mature level that allows predicting with some confidence the evolution of microstructure under irradiation. This level of physical robustness has now to be extended to model the mechanical behaviour by coupling microstructure and mechanics (plasticity–fracture) and to describe a wider class of materials like nano-structured alloys, ceramics and composite materials.

Modelling must indeed make the best use of the continuously increasing computing capabilities, but it must also be supported by a dedicated experimental strategy. The actual understanding of radiation damage at the atomic scale allows computing radiation induced microstructures and dislocation dynamics in volumes that are of the same order of magnitude as those that can be irradiated with ion beams and experimentally characterised by Transmission Electron Microscopy (TEM), X-Rays, atom probes, ion beam analysis, nano-indentation, in-situ TEM testing, ... For example, the JANNUS facility, currently under development by CEA and CNRS, will provide a unique way to validate the atomic scale modelling and build predictive tools for radiation effects up to high dose and high contents of transmutation products.

However, this approach must be completed and assessed by data obtained in a real nuclear reactor environment like in material testing reactors (MTRs), which are the indispensable tools for the qualification of new materials and licensing processes.

More generally, these experimental and theoretical methodologies will give the basis for developing materials more resistant to radiation effects. The case of SiC ceramics could illustrate this approach. Ceramic materials are needed for core components undergoing very high temperature ($>1000\,^{\circ}C$) such as control rod sheath and fuel structures of very high temperature reactors (VHTR) and gas-cooled fast reactor (GFR) as shown in Fig. 1.

A major effort of research is being invested in developing ceramics forms with improved ductility and fracture toughness such as fibre-reinforced ceramic composites, or nano-structured ceramics. SiC_f/SiC composites, investigated for fusion applications, are the best candidates today.

They are manufactured from a bi- or three-directional architecture of fibre preforms, which undergo several chemical and sintering processes. The resulting microstructure is quite complex and constituted by fibres, matrix and inter-phases between fibres and matrix. Indeed, very scattered physical and mechanical properties of composite mate-

Table 2
List of the main European Material Testing Reactors

Tableau 2
Liste de réacteurs européens expérimentaux en fonctionnement à l'heure actuelle

Countries	Reactor	First criticality	Power (MWth)
Czech Rep.	LVR15	1957	10
Norway	Halden	1960	19
Netherland	HFR	1961	45
Belgium	BR2	1961	60
France	OSIRIS	1966	70

rials are found depending on the manufacturing methods, the fibre quality, specific geometries of products (plates or tubes). Thus, the reproducibility of material properties is a very important concern.

Understanding and modelling of the composite behaviour will be essential for assessing component performance and lifetime. This requires a multi-scale modelling approach. Fibres are chosen according to the specific required properties (tensile strength, impurity contents) and the architecture of the composites is such it supports the thermal-mechanical load applied to the components.

The relative evolution of the fibres and the matrix must be assessed since they will impact the global performance of the material. Moreover, the inter-phases between the fibres and the matrix seem to make an important contribution to the properties of the composite material.

However, the evolution with the temperature and irradiation conditions of the physical and mechanical properties of different constituents of the microstructure remains poorly understood. A comprehensive approach to this problem should address each contribution to the behaviour under irradiation. For this purpose, a step-wise approach is needed:

(i) the behaviour of one elementary SiC fibre under controlled irradiation conditions, temperature, dose, applied mechanical stress/strain;
(ii) the behaviour of a plain composite object where the fibres in a simple geometry and the matrix are jointly exposed to controlled irradiation, temperature and mechanical loading;
(iii) finally, the behaviour of a realistic composite element.

While the first type of experiment (with elementary fibres) is planned on JANNUS, the second and third need to be performed in a material testing reactor and require the development of a specific instrumentation allowing a fine control and monitoring of the experimental parameters (temperature, dose, dose rate, applied stress or strain rate, dimensional changes, gas release, environment).

4. Material Test Reactors in Europe

European MTRs have provided essential support for nuclear power programs over the last 40 years. Associated with hot-cell laboratories for the post irradiation examinations, they are structuring facilities for the European Research Area in the fission domain. They address the development and the qualification of structural materials and fuels under irradiation conditions relevant for nuclear power plants in order to optimise and demonstrate safe operations of existing and coming power reactors as well as to support future reactors design.

However, existing MTRs in Europe will be more than 50 years old in the next decade and will face the increasing probability of shut-down. Such a situation cannot be sustained on the long term since nuclear energy is a competitive energy source meeting the dual requirements for energy security and the reduction of greenhouse gas emissions, and is also an essential component of the energy mix.

The list of main MTR's operating in the EU is given in Table 2. OSIRIS will be shut down at the beginning of the next decade.

Renewing the experimental irradiation capability will meet not only technical needs but also important stakes such as maintaining a high scientific expertise level by training of new generations of researchers, engineers and operators. This answers the European concern about the availability of competences and tools in the coming decades.

Thus, a consensus has been drawn in Europe on the following statements [2,3]: "*There is clearly a need for irradiation capability as long as nuclear power provides a significant part of the mix of energy production sources*", "*Given the age of current MTRs, there is a strategic need to renew MTRs in Europe. At least one new MTR shall be in operation in about a decade from now*".

5. The Jules Horowitz Material Test Reactor

To cope with this context, the Jules Horowitz Reactor Project (JHR) has been launched as a new MTR in Europe to be implemented in Cadarache (in the south of France); the start of operation is foreseen in 2014 [4].

JHR will offer modern irradiation experimental capabilities for studying material and fuel behaviour under irradiation. JHR will be a flexible experimental infrastructure to meet industrial and public needs related to power reactors of generation 2, 3 and 4, and to different reactor technologies.

JHR is designed to provide a high neutron flux (producing typically twice the material damage per year than available today in European MTRs), to run highly instrumented experiments in order to support advanced modelling giving predictions beyond experimental data, and to operate experimental devices giving environment conditions (pressure, temperature, flux, coolant chemistry, ...) relevant for water reactors, for gas cooled thermal or fast reactors, for sodium fast reactors, etc.

This irradiation experimental capability will address:

- power plant operation of existing and coming reactors (Gen II & III) for material ageing and plant life management;
- design evolutions for Gen III power reactors (in operation for all the century) such as performance improvement and evolution in the fuel cycle;
- fuel performance and safety margin improvements with a strong continuous positive impact on Gen II & III reactor operating costs and on fuel cycle costs (burn-up and duty-cycle increase for uranium and mixed oxide (UOX and MOX) fuels);
- fuel qualification in incidental or accidental situations;
- fuel optimisation for HTRs;
- innovative material and fuel development for Gen IV systems in different environments (very high temperature, fast neutron gas cooled systems, various coolant such as supercritical water, lead, sodium, ...) [5].

These objectives require representative tests of structural materials and fuel components, as well as in-depth investigations with separated effects experiments coupled with advanced modelling.

The JHR design accommodates improved on-line monitoring capabilities such as the fission product laboratory directly coupled to the experimental fuel sample under irradiation. This monitoring can be used to get key information on the fission gas source term during transients related to incidents. It can also provide time-dependent data on the fuel microstructure evolution during the irradiation, which is, of course, a valuable input for modelling developments.

The JHR design is optimised for the above technical objectives. As an important secondary objective, in connection with other producers, the JHR will contribute to secure the production of radioisotopes for medical applications in Europe, as a key public health stake.

6. JHR planning and funding

The JHR construction schedule is the following:

- completion of definition studies: 2003–2005 (typically 100 persons per year);
- development studies: 2006–2007;
- public consultation and public enquiry completed in spring 2005 and 2007 without difficulty;
- preliminary safety analysis report submitted to the Safety Body in February 2006;
- construction permit delivery: 2007;
- construction phase: 2008–2013;
- start of operations: 2014.

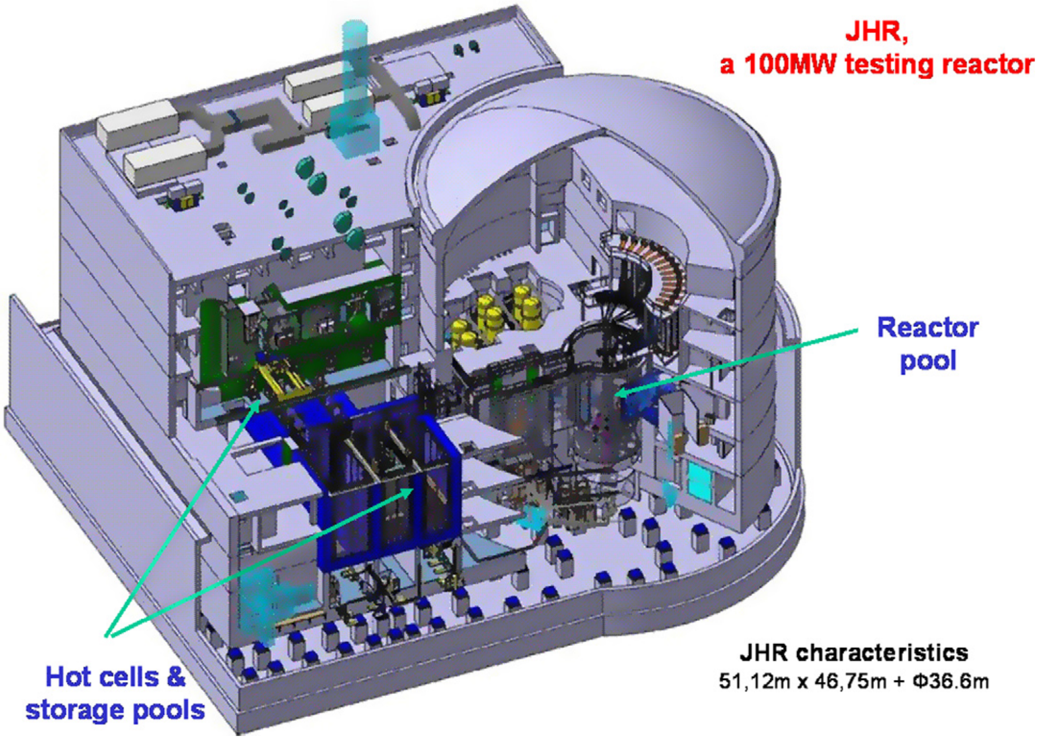

Fig. 2. Scheme of JHR project.

Fig. 2. Vue d'ensemble du projet de réacteur Jules Horowitz.

The flexible research infrastructure of the JHR project, meets at the same time (i) middle term needs for the industry (utilities, vendors) and (ii) long term public issues related to sustainability and energy policy. For that reason, JHR is funded by of consortium of industry and public entities.

7. Experimental capability characteristics

JHR is a 100 MW tank pool reactor [6–8]. The main features are shown in Fig. 2.

The core area is inserted in a small pressured tank (section in the order of 740 mm diameter) with forced coolant convection (low pressure primary circuit at 1.5 MPa, low temperature cooling, core inlet temperature in the order of 25 °C). The reactor primary circuit is completely located inside the reactor building.

The reactor building is divided into two zones. The first zone contains the reactor hall and the reactor primary cooling system.

The second zone hosts the experimental areas in connection with in-pile irradiation (eg., typically 10 loops support systems, gamma scanning, fission product analysis laboratory, etc.). The Fission Product Laboratory will be located in this area to be connected to several fuel loops either for low activity gas measurements (HTR, ...) or high activity gas measurements (LWR rod plenum, ...) or water measurements (LWR coolant, ...) with gaseous chromatography and mass spectrometry.

Bunkers and laboratories in the experimental area will use 300 m^2 per level on 3 levels.

Pools in the reactor building are limited to the reactor pool (including neutronography for experiments) and an intermediary decay pool (for temporary storage of fuel elements, reflector elements or replaced core mechanical structures). During reactor shutdown, experimental devices can be temporarily stored in a dedicated rack in the reactor pool.

Hot cells, laboratories and storage pools are located in the nuclear auxiliaries building.

The experimental process will make use of two hot cells to manage experimental devices before and after the irradiation. Safety experiments are an important objective for JHR and require an 'alpha cell' to manage devices with

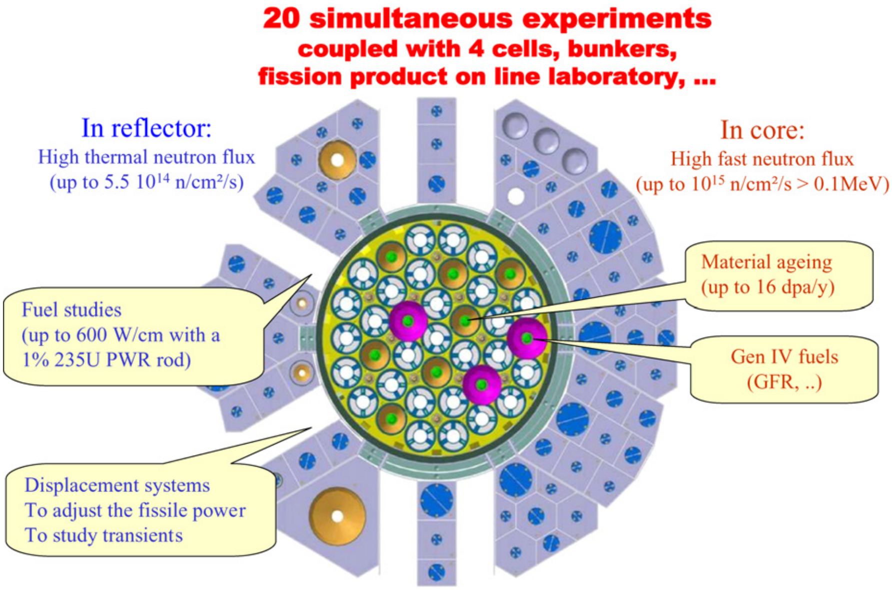

Fig. 3. Location of experimental devices in JHR core.

Fig. 3. Emplacement des différents dispositifs de mesure et d'irradiation de matériaux dans le cœur du réacteur Jules Horowitz.

failed experimental fuel. A fourth hot cell will be dedicated to the transit of radioisotopes for medical applications and to the dry evacuation of used fuel. Three storage pools are dedicated respectively to spent fuel, experimental devices and mechanical component management.

8. Core features

The core (600 mm fuel active height) is cooled and moderated with water. It is operated with a high density low enriched fuel (U enrichment lower than 20%, density 8 g/cm^3), requiring the development of UMo fuel. The fuel element is circular shaped (set of curved plates assembled with stiffeners) and comprises a central hole. The UMo fuel is under development within an international collaboration (UMo/Al dispersion solutions and monolithic UMo solution) [9]. As a back-up solution, for a limited period, the JHR may be started if necessary with an U_3Si_2 fuel with a higher enrichment (typically 27%).

As shown in Fig. 3, the core area is surrounded by a reflector, which optimises the core cycle duration and provides intense thermal fluxes in this area. The reflector area is constituted of beryllium elements and water. Irradiation devices can be placed either in the core area (in a fuel element central hole or in place of a fuel element) or in the reflector area.

In-core experiments will address typically material experiments with high fast neutron flux capability up to 5×10^{14} $n/cm^2/s$ with neutron energies larger than 1 MeV, and up to 10^{15} $n/cm^2/s$ for energies larger than 0.1 MeV, taking into account the fast neutron flux perturbed by neighbouring experiments.

In-reflector experiments will typically deal with fuel experiments with thermal flux up to 5×10^{14} $n/cm^2/s$ considering the neutron flux perturbed by nearby experiments. Experiments can be implemented in fixed locations, but also on displacement systems as an effective way to investigate transient regimes occurring in incidental or accidental situations.

These conditions provide a flexible experimental capability able to create up to 16 dpa-Fe/year[1] for in-core material experiments (with 260 full power operation days per year) and for in-reflector fuel experiments, to reach up to 850 W/cm of fuel linear power.

The JHR facility will allow performing a significant number of simultaneous experiments in core (~ 10) and in reflector (~ 10) positions.

[1] The foreseen damage rate, expressed in displacement per atom 'dpa'/year, is evaluated for pure Iron samples.

9. Experimental devices

JHR will be operated from 2014 for fifty years, with a continuous evolution of the experimental programs. It will allow the simultaneous implementation of several experiments, such as, for example:

- Testing materials behaviour[2] under high fast flux with in-pile capsules dedicated:
  - for temperature range relevant for water cooled reactors; bi-axial on-line controlled load is considered;
  - for high temperature (steels reinforced by nanoprecipitates such as ODS, refractory alloys); uni-, bi-axial and cyclic on-line controlled mechanical load, with well controlled environment (gas, vacuum, liquid metals) is considered;
  - for very high temperature (SiC_f/SiC), as presented above.
- Testing large samples in limited flux for assessing the pressure vessels ageing.
- Corrosion loop with in-pile irradiation assisted cracking growth rate measurements including local electric potential drop measurement.
- Safety oriented fuel experiments for water cooled reactors, and notably the fuel thermal-mechanical behaviour and the fission gas release, thanks to a cluster of instrumented rodlets (central thermocouples, pressure gauges and fission gas sweeping lines) placed in a loop. Several loops and capsules will be implemented to support the experimental programs contributing to the demonstration of the fuel safe behaviour in different situations.
- Experiments to simulate accidental situations, such as the LOCA test for water cooled reactors or other reactor technologies, with online fission product measurement capability and a cell dedicated to failed experimental fuel management.
- Loop to test fast neutron reactor fuels in transient regime.
- Development of key instrumentation technologies (high temperature, miniaturised fission chamber, force and strain gauges, extensometers, ...) as a key cross-cutting topic.

International collaboration offers important added value from the early development of these experimental devices, and subsequently in the implementation of research programs. This added value has to be understood as:

- First, by cross-fertilising the large technical experience available in Members' lab, meeting up-to-date scientific and technological state of art as well as anticipated users' needs.
- Second, as a most effective way for preparing the utilisation of JHR from its start-up.
- Third, to train new generations of scientists and engineers taking benefit of the important cross-disciplinary expertise involved in device development.

The development of JHR experimental devices offers a unique opportunity to develop a new generation of devices meeting up-to-date scientific and technological state of art as well as the anticipated users' needs.

Development of experimental devices and related programmes requires international collaborations to benefit from the available large experience and to increase the critical mass of cross-disciplinary competences. Several scientific topics have already been assessed within the European 6th framework program JHR coordination action (2004–2005) [10–13].

In parallel, a new impetus has been put on instrumentation technologies by the creation of a joint lab between CEA and SCK·CEN [14].

As an important subsequent step, a new FP6 project ('MTR plus' integrated infrastructure initiative, MTR+I3 has been launched for the period 2006–2009 in order to reinforce the European MTR Community through personnel exchanges, manufacturing practices, measurement best practices, opening access for testing experimental devices innovations, support state of the art design, fabrication and test of innovative irradiation devices or components with associated instrumentation. Fig. 4 gives the list of partners participating in the MTR+I3 (FP6th).

[2] The foreseen innovative structural materials are common to fission and fusion application. Structural materials for fast reactors as well as fusion blanket materials require structural materials which have to sustain a high fast neutron flux and a high temperature.

EURATOM 6th FP MTR+I3 (2006-2009) Partnership					
Institute	Country		MTR	Power (MW)	Pulse (MW)
CEA	France		OSIRIS	70	
NRG	Netherlands		HFR; LFR	45; 0.03	-
SCK	Belgium		BR2	60	-
UJV (NRI)	Czech Rep.		LVR15	10	-
VTT	Finland		-	-	-
Univ. Karlsruhe	Germany		-	-	-
IRSN	France		-	-	
INR Pitesti	Romania		2 Triga	14; 0.5	-; 22000
PSI	Switzerland		-	-	-
KFKI- AEKI	Hungary		BRR	10	-
Studsvik	Sweden		R2 (shutdown mid05)	50	
CIEMAT	Spain		-	-	-
ITU	Europe		-	-	-
IPTA Demokritos	Greece		GRR-1	5	-
ATI	Austria		Triga	0.25	250
ITN	Portugal		RPI	1	-
AVN	Belgium		-	-	-
GRS	Germany		-	-	-

Fig. 4. Partners of MTR+I3 (FP6).

Fig. 4. Liste des organismes participants au programme européen « MTR+I3 » du 6ème PCRD.

10. The JHR consortium

The JHR design phase was achieved in the period 2003–2005. During this period, the project has been promoted and discussed at the international level. For example, a JHR International Advisory Group has been established within the OECD/NEA framework to assess the project and to promote it as an international users-facility.

As a result, a JHR Consortium has been set up to finance the JHR construction and to provide funding Members a secured and guaranteed access to the JHR experimental capability. This Consortium gathers major industrial companies such as Electricité de France (EDF) and AREVA and research institutes from several European Member States such as France (CEA), Belgium (SCK), Czech Republic (NRI), Finland (VTT), Spain (CIEMAT) as a representative of a pool of industries and public bodies.

JHR is a mature project and is identified as a research infrastructure of pan-European interest by the European Strategic Forum for Research Infrastructure (ESFRI). Following the ESFRI process and through successive steps in the 7th FP and 8th FP, the European Commission, represented by the Joint Research Centre, will become a full Member of the JHR Consortium in order to have access to JHR experimental capacity for implementing the European Community policy.

Discussions are ongoing with other European and non-European countries to enlarge the JHR Consortium.

Members contributing to the financing of JHR construction will have guaranteed and secured access rights to experimental locations in the reactor in order to perform their Proprietary Experimental Programs. In parallel, a Joint Program will be opened to international collaboration in order to address issues of common interest.

The establishment of the JHR Consortium and the networking of relevant research laboratories is the most important step to build the future generation of R&D competences and infrastructure. This is required to cope with R&D needs to support present and future power reactors.

11. On the roadmap for fast neutron reactor deployment

Fast neutron reactors with closed fuel cycles are required to optimise the use of natural resources and to minimise the production of long lived radioactive waste.

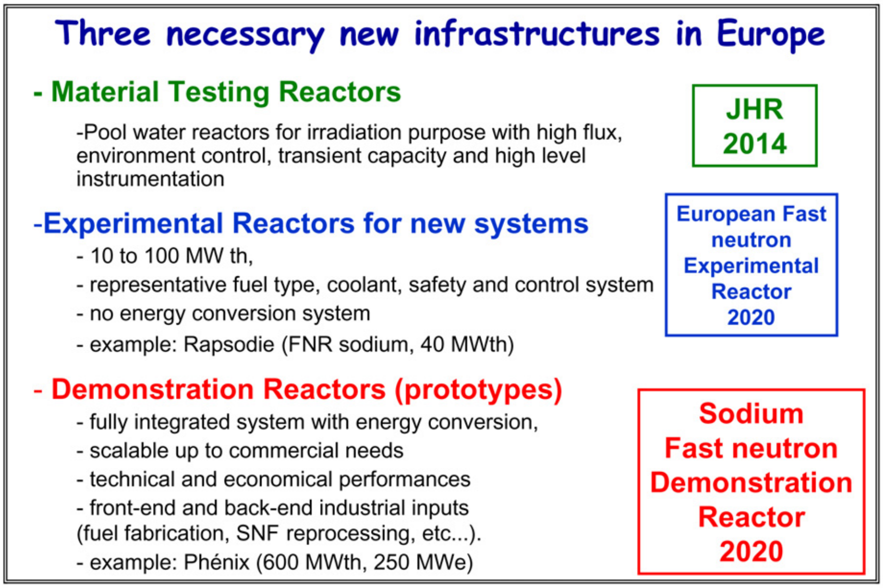

Fig. 5. Development of infrastructures to implement Generation IV systems.

Fig. 5. Nouvelles infrastructures européennes nécessaires au développement des systèmes nucléaires de GEN IV.

High performance MTRs such as JHR will be necessary on the roadmap toward fast neutron power reactors. Such an infrastructure is a cross-cutting tool producing important both thermal and fast neutron flux together with suited environment control and high capacity of instrumentation.

The roadmap toward fast neutron power reactors requires complementary new infrastructures as indicated in Fig. 5.

First, deployment of fast neutron technology at a horizon of 2040–2050 will require the realisation of a Demonstration Reactor around 2020 for the most mature technology: Sodium Fast Reactor (SFR).

Second, an alternative technology to sodium cooled technology is necessary to secure the availability of fast neutron reactors, to answer market needs and for public acceptance. This needed alternative track can be either the GFR or the LFR. Therefore, a European Fast neutron Experimental Reactor (EFER) is needed to develop and demonstrate this alternative track.

Material testing reactors, experimental reactors and demonstration reactors are all together necessary, with quite different and complementary new infrastructures needed to implement generation IV systems.

SCK·CEN and the CEA agreed to assess EFER technology, fuel cycle, and, partitioning and transmutation (P&T) based on results from both institutes or available from FP6 European projects, among others: sub-critical versus critical, coolant technology, fuel technology, power level, power density and associated flux irradiation levels for material research, needed R&D support, facility cost assessment, industrialisation scenarios.

An important decision milestone is foreseen around 2010.

SCK·CEN volunteers to host this experimental facility on the site of Mol and build up European partnerships for design, construction and operation. CEA, as a candidate partner, is joining this effort to prepare with SCK·CEN a feasibility study and to work out the financing plan for the realisation of this facility at Mol.

12. Conclusion

Nuclear electricity plays an important role and will stay for the long term a part of the energetic mix since it contributes to assure energy supply and limit greenhouse gas production.

Nuclear plants will follow a long-term trend driven by the plant life extension and management, reinforcement of the safety, waste and resources management, flexibility and economics improvement.

In depth technical assessments will be required both for optimising existing and coming plants and for the validation of new reactor concepts. Industry and safety bodies will need to have access to experimental capabilities and technical expertise since qualified knowledge will be needed for predicting structural component lifetime, for improving fuel management and reactor operation, for the development of new fuels and materials.

Failure to meet such needs would lead to an economic and technical burden due to growing technical challenges for the future of nuclear energy: end of life of existing plants, construction of new reactors and development of new reactor concepts to meet sustainability issues.

Answering this need, the JHR will secure for a large part of the century the experimental irradiation capability in Europe for the benefit of international industries and public stakeholders.

If JHR appears to be a key tool for the development of materials and fuels for future reactors, an experimental fast neutron facility will be necessary in Europe to optimise and qualify these materials and fuels and to demonstrate the technico-economical effectiveness of the chosen concept. SCK·CEN and CEA are favouring this strategic vision at European scale and are looking forward to the realisation of such as experimental fast spectrum facility.

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