EXPERIMENTAL IRRADIATIONS OF MATERIALS AND FUELS IN THE BR2 REACTOR: AN OVERVIEW OF CURRENT PROGRAMMES

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1. INTRODUCTION

The BR2 reactor is the main research tool of the Belgian Nuclear Research Centre (SCK•CEN). Its first criticality was reached in 1961, and it has been operated since 1963, with two major shut downs for refurbishment in 1979 and 1996. The BR2 reactor is a vessel in pool type of reactor, cooled with light water and moderated by light water and solid beryllium. The reactor pool is installed in a containment building, serving as a tight barrier against any release of radioactivity into the environment. The geometry of the BR2 reactor vessel has been designed in order to maximise the core density and provide good accessibility to the reactor channels. The resulting shape is a hyperboloid of revolution, where the mid-plane diameter is about half of the diameter at the top (see figure 1). The core of the reactor is composed of 79 channels, with diameter ranging from 50 to 200 mm, most channels being 84mm in diameter. All channels are accessible from the top cover, while the possibility of installing through loops from the bottom cover of the reactor is also available. Through loops are fed by equipment, installed in the shielded sub-pile room of the reactor.

The reactor's primary circuit is pressurised to 1.2 MPa and the average coolant temperature is about 40 °C. Under standard thermo hydraulic conditions, the maximum heat flux on the driver fuel elements is 470 W/cm². The driver fuel elements are made of six concentric rings of aluminium alloy clad U-Al_x dispersion type fuel. The control rods of the reactor are also used as shim rods; with an absorbing element in the control rods of metallic Hf; six control-shim rods are loaded, complemented by two safety rods and one regulating rod.

The reactor can be operated with thermal power levels up to 100 MW. The maximum flux levels that can be attained depend on the core configuration and reactor power; typical maximum values are 10^{15} cm^{-2}s^{-1} for thermal neutrons and 6×10^{14} cm^{-2}s^{-1} for fast neutrons (E>0.1MeV). The reactor channels' load is not predetermined but each channel can be loaded with a fuel element, control rod or reflector plug. Experiments can be loaded either in reflector plugs or in the centre of a fuel element. The current reactor configuration is shown in Figure 2.

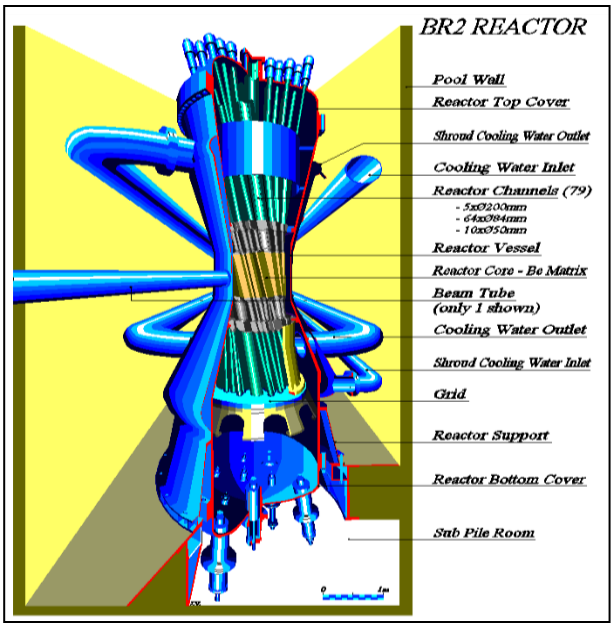

Fig. 1. general lay out of the BR2 reactor.

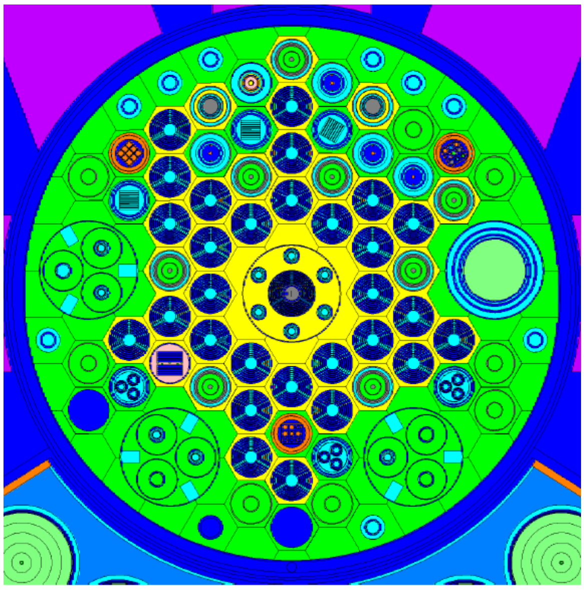

Fig. 2. current reactor core configuration.

As the reactor can have various configurations, modelling of the irradiation conditions inside the core and their evolution in time is of great importance for the management of the reactor core and experiments. The reactor core is therefore modelled by a three dimensional MCNP model, a general-purpose Monte Carlo N–Particle code that can be used for neutron, photon, electron or coupled neutron/photon/electron transport [1]. The code is capable of treating an arbitrary three-dimensional configuration of materials in geometric cells with point-wise cross-section data. A detailed model of the reactor core with all its load elements the fuel elements, reflector plugs and experiments, is treated in this model. For neutrons, all reactions given in a particular cross-section evaluation such as ENDF/B-VI are accounted for. For photons, the code takes account of incoherent and coherent scattering, the possibility of fluorescent emission after photoelectric absorption, absorption in pair production with local emission of annihilation radiation and bremsstrahlung. Also, photoneutron production is taken into account. Important standard features that make MCNP very versatile and easy to use include a powerful general source, a criticality source and a surface source; both geometry and output tally plotters; a rich collection of variance reduction techniques; a flexible tally structure; and an extensive collection of cross-section data. In order to capture the time evolution of the composition of the reactor core, mainly the burn-up of fuel and buildup of fission products, the MCB Monte Carlo Continuous Energy Burn-up Code [2], version 1C, is coupled to the MCNP model.

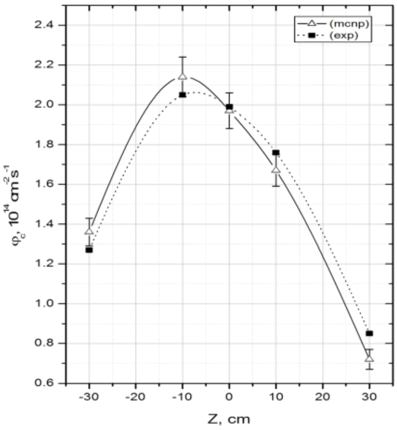

Fig. 3. MCNP code prediction compared to post irradiation dosimetry.

The model predictions have been qualified by measurement of the thermal balance of the loaded in-pile sections (IPS) during irradiation and the comparison between the measured burn-up distributions with the predicted one. The modelling is validated by online measurements of, for example, the thermal balance of an experiment, or by post irradiation dosimetry experiments using either activation dosimeters or fission product determination in irradiated fuel. The former gives a validation of the average predicted value in space, while the latter gives a validation on the integrated value in a single point or small sampling volume. The discrepancy between thermal balance measurement and predictions is generally in the order of 5%, while the punctual discrepancy for post-irradiation dosimetry may be up to 10%, while the average correspondence for this method is generally also better than 95% (see Figure 3).

2. APPROVAL OF EXPERIMENTS

Experiments in the BR2 reactor are approved after a four stage process:

- After a first contact with the client, the compatibility of the requested experiment with the reactor schedule is evaluated internally;
- Then a 3 phase safety review is done by an expert committee, independent of the reactor operator:
    - In the first phase, the experiment's conceptual design's compliance with the reactor safety assessment report criteria is verified. Upon positive advice, a detailed design of the experiment is made;
    - In the second phase, the detailed design is evaluated — mechanics, thermal-hydraulics, reactivity, corrosion, instrumentation and dismantling aspects are considered. A positive advice leads to permission for experiment assembly; and
    - In the third phase, the experiment's reception test results are reviewed, as well as the normal and accidental operational procedures.
- Based on the three phase evaluation, the nuclear safety department issues a report on the experiment. The final permission for irradiation is issued by the safety authority upon approval of the reactor load before the start of the reactor operation cycle; and
- A return of experience review is recommended and obligatory when a repetition of the experiment is foreseen. A repetition experiment can be approved in a short procedure, if the return of experience (fourth phase review) is positive.

3. PRESSURISED WATER REACTOR (PWR) EXPERIMENTS

3.1. PWR irradiation devices

Two major PWR irradiation devices exist in the BR2 reactor:

— The Capability for Light Water Irradiation in Steady State and Tranient Operations (CALLISTO) PWR experimental loop for steady state irradiation; and
— The Pressurized Water Cycle/Cycling and Calibration Device (PWC-CCD) capsules for power transient testing.

The CALLISTO loop consists of three main parts [3]:

(i) The double walled pressure tubes inside the reactor vessel, also called IPS: there are three identical IPSs connected to the loop; they provide a constant irradiation environment with PWR representative cooling conditions. The coolant enters and leaves the IPS from the bottom of the reactor, while the experimental load is inserted from the top cover (see Figure 4). The inlet streams through the central part, with flow inversion above the core of the reactor, after passing through the experiment. The outlet flows on the outside of the experimental basket of the inner pressure tube of the IPS. The outer pressure tube is separated by a controlled pressurised helium filled volume, providing thermal insulation and a leak detection capability.

(ii) The experimental basket: in a "standard" configuration, the experiment is loaded into a shroud tube with square 43.5 mm x 43.5 mm cross section. This basket is suspended to the upper lid of the IPS and fixed to a lower support tube by a labyrinth seal in order to guide the coolant flow. The inlet and outlet temperature of the experimental basket is monitored by three sets of three thermocouples. Also, a pressure drop measurement is installed in order to detect eventual pressure drop variations across the experiment, which is indicative of a mechanical failure of a component. In the standard configuration, the shroud tube can hold 9 PWR fuel pins in a 3 by 3 grid, with 3 zircalloy grids supporting them. Typically, 9.5 mm diameter rods are irradiated with a total length of 1136 mm, but variations on these dimensions are possible.

(iii) The out-of-pile equipment (OPE): this equipment feeds the in-pile sections with pre-heated and conditioned feed water. Its main loop consists of the primary circulation pumps, the pressuriser, the main cooler and main heater and the auxiliary feed-bleed system for purification and conditioning of the loops primary coolant.

The irradiation conditions in the CALLISTO loop are given in Table 1:

TABLE 1. IRRADIATION CONDITIONS IN THE CALLISTO IN-PILE SECTIONS; IPS1 HAS 1 ADJACENT DRIVER FUEL ELEMENT, IPS3 HAS 2 AND IPS2 IS SURROUNDED BY 6 DRIVER FUEL ELEMENTS

IPS no. — position	Thermal flux (10^{13} $cm^{-2}s^{-1}$)	Fast flux (>1 MeV) ($10^{13}cm^{-2}s^{-1}$)	γ heating (W/g)
1 – K49	12	1	1
2 – D180	41	9	6
3 – K311	15	2	1.3

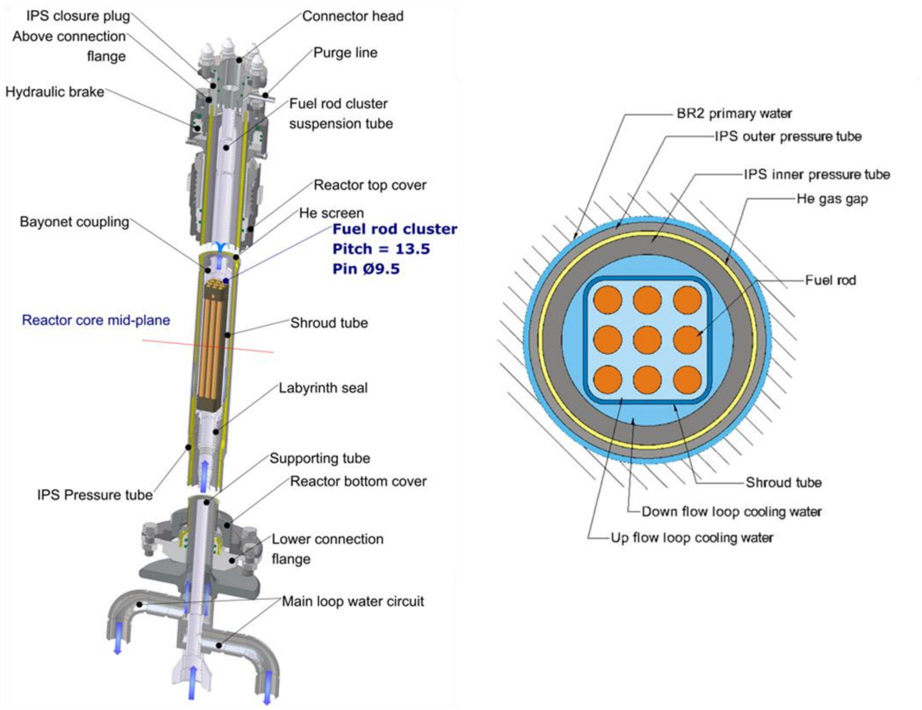

Fig. 4. Layout of the in-pile section of the CALLISTO loop.

The typical functioning conditions of the CALLISTO loop are:

— Coolant inlet temperature: 290°C;
— Coolant outlet temperature: 315°C (depending on the experimental load);
— Coolant pressure 15.5 MPa;
— Coolant mass flow rate 2.1 kg/s, leading to a flow speed of about 3 m/s on the surface of the fuel rods. The cooling capacity of the entire loop is 1300 kW; a 9 rod cluster in one IPS with linear power density of 350 W/cm generates 200 kW; and
— Water chemistry: pH at 25 °C is 7.5 by addition of 400 ppm boron, as boric acid, and 2 ppm of lithium, as lithium hydroxide; addition of 50 cc/kg.

The design pressure of the inner pressure tube is 19 MPa, while the design temperature is 375°C for the material in the BR2 core zone.

The CALLISTO loop and its auxiliary systems provide a number of safety functions, such as:

— Fast cooling of the loop in case of excessive outlet temperature of the loop, low flow conditions, low level (leak) or high level in the pressuriser; this action results in a temperature drop from 300°C to 180°C in five minutes;
— Emergency cooling at low pressure by the feed-bleed system in case of LOCA of the CALLISTO loop;
— Insulation and containment of radio-nuclides in case of fuel pin failure inside the CALLISTO loop; and
— The CALLISTO loop control interacts automatically with the BR2 reactor control system in order to provide safe conditions for both the reactor as CALLISTO in case of incident occurring in either of both.

Single fuel pins can be irradiated in a pressurised water capsule (PWC), cooled externally by the primary flow of the BR2 primary circuit (Figure 5). The water in the capsule is stagnant, so long term irradiations are not recommended in this device. Water sampling is continuously possible in order to verify defects in the fuel pin, leading to fission product release.

The PWC is inserted into a calorimetric device, called the calibration and cycling device (CCD). This device consists of a diaphragm flow meter and is equipped with thermocouples at inlet and outlet so a thermal balance can be made in order to determine the power in the fuel pin. The heat losses towards the reactor environment are minimised using a helium gas screen around the in-pile part of the PWC, where the fuel pin is located. A calibration irradiation with a stainless steel dummy needle is performed in order to determine the gamma heating contribution to the thermal balance.

Power transients can be performed in the PWC-CCD device by increasing BR2 reactor power. Therefore, a dedicated short reactor cycle is performed with pre-conditioning irradiation and power transient according to the experimental prescriptions.

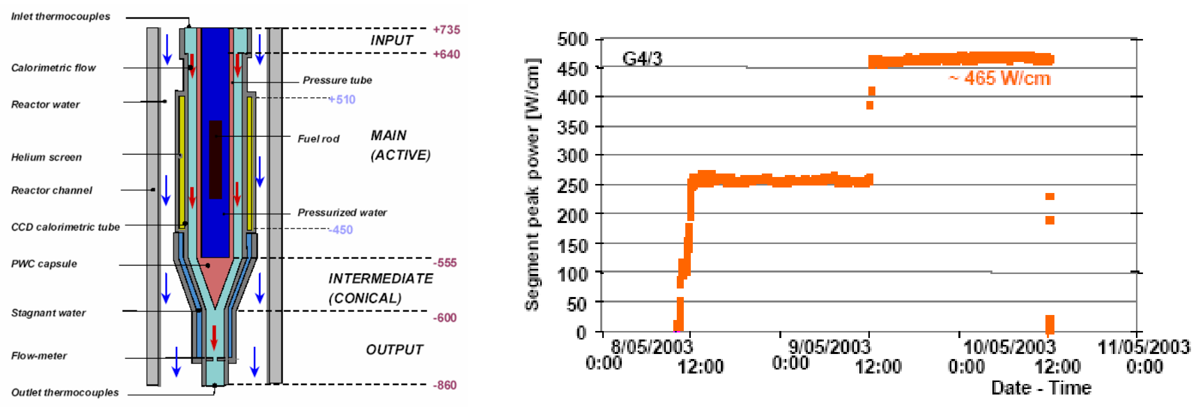

Fig. 5a (left): lay out of the PWC-CCD device for fuel pin testing; figure 5b (right): power profile during a transient test of a fuel pin in the PWC –CCD device.

3.2. LWR fuel irradiation programmes

The study of the behaviour of light water reactor fuels focuses on two types of studies:

(i) Behaviour of commercial fuels beyond their licensed limits, especially the behaviour of mixed oxide fuels with a high Pu concentration at elevated burn-up levels. The materials under study are taken from industrial production and eventually refabricated into fuel pins of suitable length.

(ii) Studies of innovative fuels: Screening irradiations of experimental fuel pins at low to intermediate burn-up. Also model validation studies are incorporated in these irradiations.

Post irradiation analysis of the fuel pins, irradiated in the CALLISTO loop, has demonstrated that the results obtained are in line with the behaviour in commercial reactors when the peak power behaviour is considered. Due to the high form factor of the BR2 reactor (maximum-to-average power ratio is about 1.6), some deviation in average behaviour is observed between commercial reactors and BR2 irradiations.

The irradiation programmes of LWR fuels are supported by both the MCNP modelling of the reactor core and the modelling of LWR fuel behaviour using the in-house developed

MACROS code. The latter code provides a prediction of the thermo mechanical behaviour of a fuel rod, taking into account the behaviour of fission gasses and the evolution of the microstructure of the fuel during irradiation. The code is verified by online measurements on instrumented fuel rods as well as by post-irradiation non destructive, for example, gamma scanning, and destructive examinations such as microprobe and wet radiochemical analysis of fuel samples. Both type of methods can be performed at the SCK•CEN hot laboratories, so no transportation of the irradiated fuel beyond the site is needed. Figure 6 shows the comparison between measured and predicted fission gas and thermal behaviour of the fuel, irradiated in the CALLISTO loop **Error! Reference source not found.**. The measured central temperature in experimental fuel pins inside the CALLISTO loop is compared to code predictions in Figure 7 [4].

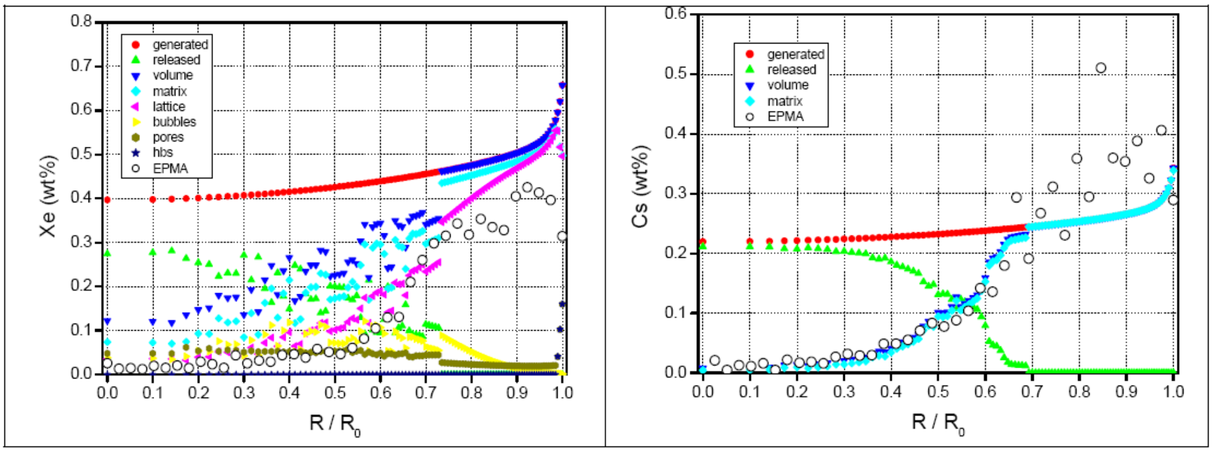

Fig. 6. Prediction of fission product behaviour in irradiated MOX fuel and comparison with microprobe analysis; note that released Xe is not detectable by EPMA due to the sample preparation method.

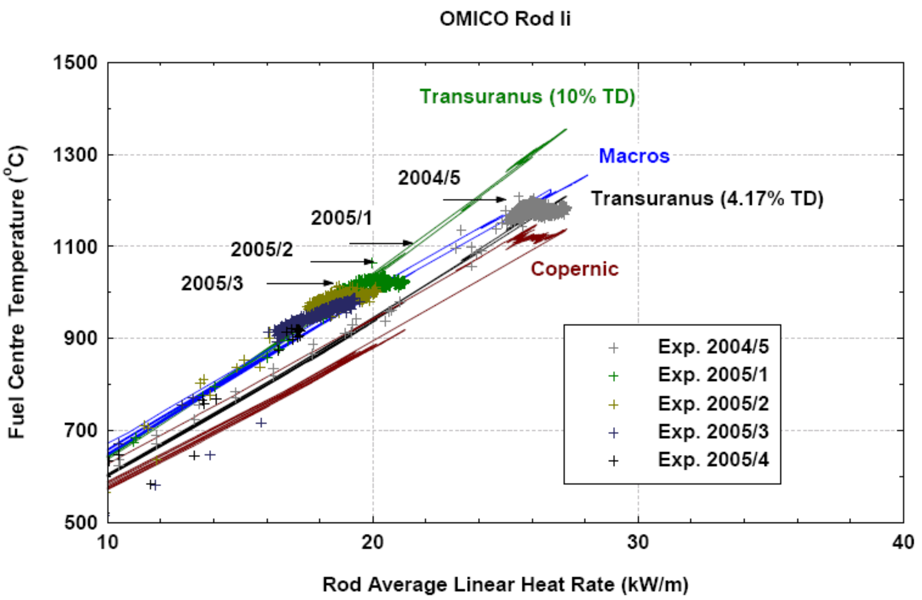

Fig. 7. Code predictions versus measured internal temperatures in the OMICO experiment in the CALLISTO loop.

3.3. LWR structure material irradiation programmes

Reactor internals are subject to high neutron fluxes and damage doses during their service life. The accumulation of irradiation damage, which is mainly proportional to the fast neutron fluence, results in significant hardening, ductility reduction and micro chemical effects. Also, irradiation creep and swelling may occur.

The former effects are already very noticeable at relatively low doses (a few dpa) and the effect of these radiation induced modifications may result in irradiation assisted stress corrosion cracking (IASCC) of irradiated stainless steel in a primary environment. Due to its higher fast flux and large volume with stable irradiation conditions, the IPS-2 of the CALLISTO loop has been used for screening irradiations in order to identify the governing metallurgical effects that determine the IASCC susceptibility of stainless steels in PWR water. Short irradiations, 4 reactor cycles to reach 1 dpa, allow, for example, for distinguishing the effect of stacking fault energy on the deformation mode development and the IASCC susceptibility of stainless steels.

The presence of the LWR relevant coolant in the CALLISTO loop also allows performance of in-pile tests. For example, the irradiation of stainless steel swelling mandrels, filled with a ceramic composite of boron carbide and aluminium oxide, allows the study of the nucleation of stress corrosion cracks by the simultaneous accumulation of radiation damage, the plastic strain imposed by the expanding ceramic and the corrosive action of the PWR coolant. A threshold combination of 2.45 dpa and an accumulated strain of 3.25% were found to nucleate shallow cracks in a specimen, irradiated for 220 days.

Reactor vessel materials are subject to less intense irradiation than the internals, so irradiation positions with lower flux are of interest for these materials. The BR2 reactor can be used for accumulation of dose levels that are representative of 40 years of operation or more. The benefits of these irradiations are various:

- Evaluation of the flux effect on hardening and embrittlement: As the vessel of a reactor is usually irradiated under a significantly lower flux than the material for the surveillance programme, the effects of flux on irradiation hardening may be of relevance. The CALLISTO loop offers a possibility to establish a database, complementary to surveillance programmes at the higher dose rates.
- For those reactors where no or insufficient surveillance data are available, the gaps can be filled in relatively quickly, provided archive material is available. The advantage of the CALLISTO loop is the large available space in the loop with stable irradiation conditions. This allows for a full set of standard Charpy specimens to be irradiated with a dispersion in neutron flux of less than 10%. The flux level is tailored by variation of the BR2 load in the environment of the IPS3, where these experiments are usually carried out.
- For better understanding of the effects of irradiation on microstructure and mechanical behaviour, model alloys are studied under PWR representative conditions. Due to its space and flexibility, the CALLISTO loop allows the irradiation of a multitude of specimen types. Also, deviations in irradiation temperature can be obtained, increasing the irradiation temperature by encapsulation of the specimens. Detailed modelling of the irradiation conditions (including gamma fluxes) and well controlled fabrication of the specimens and capsule leads to a predictable irradiation temperature.

4. IRRADIATIONS OF MATERIALS FOR ACCELERATOR DRIVEN SYSTEMS

SCK•CEN is developing the Multi-purpose Hybrid Research Reactor for High-Tech Applications (MYRRHA) project for the construction of an accelerator driven research system (ADS) by 2023. The target of this research infrastructure is to demonstrate ADS and heavy liquid metal cooled fast reactor concepts on a pilot scale (100 MW), to study the transmutation of high level nuclear waste with long lifetime and to serve as a material test facility for Generation IV reactors. The concept of the ADS system is based on a spallation source using a liquid metal target and feeding neutrons into a subcritical fast reactor core cooled by the same liquid metal. The optimal liquid metal for this application is a eutectic lead bismuth alloy (LBE), which combines a high atomic number with low melting point and favourable nuclear properties. However, a number of material issues are to be addressed in order to validate the material selection in the design of the ADS that are also relevant to other fast reactor concepts. The main issue is the combined effect of irradiation and exposure to the liquid metal coolant.

The issue of combined irradiation and liquid metal corrosion and embrittlement requires the application of an irradiation device that provides the requested irradiation environment and temperature (450 °C) while maximising the fast neutron dose rate. In order to achieve these objectives, a double walled irradiation capsule filled with LBE has been designed containing temperature control by electric heating and adjustment of the helium pressure in the gap between the inner and outer capsule (Figure 8). The double wall concept also guards against release of ^{210}Po from the potentially contaminated atmosphere in the inner capsule. The capsule is to be irradiated in the central position of a BR2 driver fuel element, where the fast neutron flux is maximum. The out of pile equipment serves to control the inner temperature in the capsule, including controlled melting and solidification of the LBE during start up and shut down of the reactor, as well as to provide different barriers against release of ^{210}Po. In order to maximise the uniformity of the irradiation conditions, the gap size between the capsules is varied along the axis of the capsule. The thermal design of the experiment is supported by MCNP modelling in order to take into account significant nuclear heating in the LBE filled capsule. Despite the limited volume (the capsule has to fit in the 24 mm diameter in the central fuel element space), 100 test specimens can be loaded inside the irradiation capsule over a total length of 1100 mm in order to also assess the effect of dose on the phenomena. The experimental load consists of tensile specimens, compact tension specimens, mini Charpy-V type specimens and small disc specimens for transmission electron microscope specimen preparation and small punch tests.

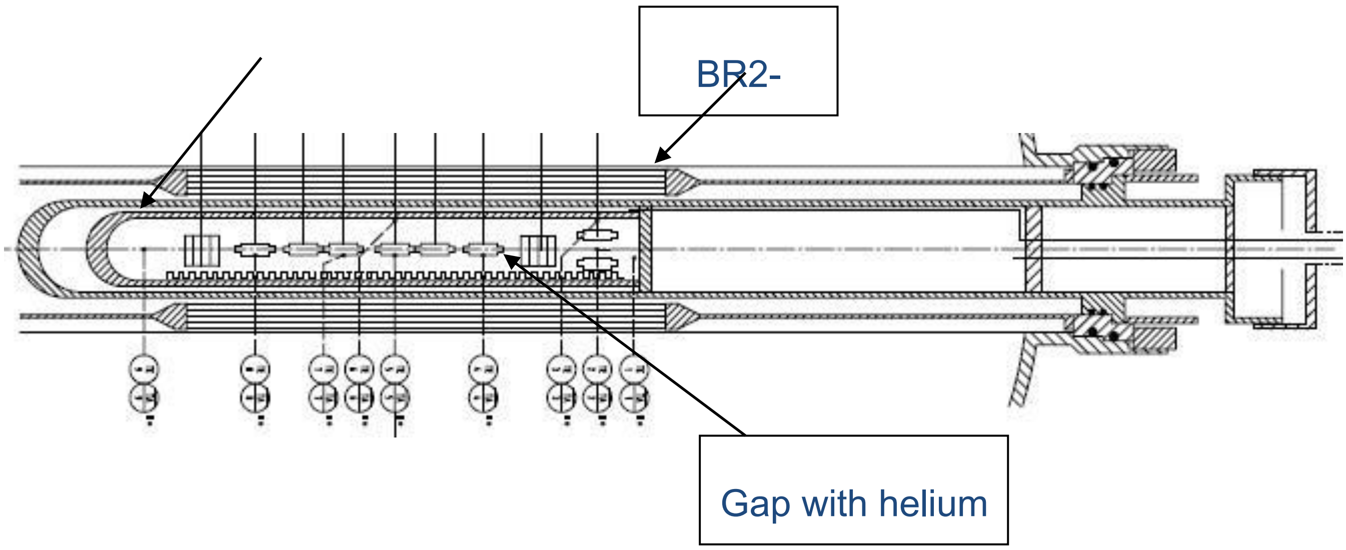

Fig. 8. Schematic of the LBE capsule for irradiation of materials in ADS relevant conditions inside a BR2 fuel element.

5. IRRADIATIONS OF FUEL FOR MATERIAL TEST REACTORS

The development of new fuels for material test reactors is driven by both the development of new high performance reactors as well as the drive to convert existing high performance reactors to low enriched uranium (LEU) based fuels. In the fuel development process, different steps have to be undertaken before a new fuel type can be deployed:

- Selection of fuel and cladding type based on screening tests of small specimens;
- Validation at full scale with representative scale specimens irradiated to target burn-up at representative power levels;
- Demonstrations in representative geometry for mixed element irradiation; and
- Full element qualification of "lead test" assemblies.

For the development of LEU fuel for high performance reactors, a collaborative project between test reactor operators and a fuel producer is being performed. In this project, a selected U-Mo dispersion type fuel is tested in full scale plate irradiation and mixed element irradiations in the BR2 reactor. Afterwards, lead test assemblies will be irradiated as an internal project for licensing the conversion of the core.

The irradiation of full scale plates is done in a basket containing four plates with different processing parameters. The challenge of the experiment design consists of obtaining the desired power level while respecting the thermo hydraulic limits of the reactor. Optimisation of the loading of the basket in the reactor results in the achievement of the maximum desired power density (470 W/cm², same as the limits on the current BR2 driver fuel), with a plate–to-plate variation between 460 and 470 W/cm². The test conditions will be verified by dosimeters positioned in the central plate of the basket.

For the qualification of a full size element for the future Jules Horowitz Reactor (RJH) in France, a dedicated experimental loop was constructed in the central channel of the BR2 reactor [6]. The challenges for this irradiation project were:

- Accommodation of the full size RJH element in the BR2 core: the outer diameter of the RJH element is 96 mm, so only the 200 mm channels can be used;
- High power density is required (516 W/cm²): only the central channel can be used;
- Plates in the element are closely spaced (1.95 mm instead of 3 mm in BR2 element): higher pressure drop and coolant velocity required; and
- 60% burn up to be reached while no burnable poisons are included in the element: absorption of the environment to be modified in the course of the irradiation.

In order to meet these challenges, an open loop was constructed in the BR2 to provide enhanced coolant flow to the H1 channel containing the RJH fuel element. This option takes advantage of the BR2 safety systems; the main additional safety feature of the loop is the battery backup for the feed pump, providing required coolant flow for at least one hour in case of a loss of external power and reactor scram.

In order to cope with the effect of burn-up accumulation on the reactivity of the RJH element, a change of the environment of the in-pile section of the loop is foreseen. Two interchangeable in-pile sections are used, the first one with an adaptive plug between the

200 mm diameter of the channel and the 100 mm tube containing the RJH element made of a aluminium honeycomb with 30% volume water channels and the second made of solid beryllium. The reactivity effect of the replacement of the Al-water plug by the (fresh) Be plug has a positive effect of about 6 δk for a burn-up of 27% of the fuel element loaded in the central channel

.

The irradiation of the RJH elements is supported by detailed neutronic and thermo hydraulic analysis in order to establish the expected hot spot and to correlate this to the measured power generated in the central channel. After the first irradiation cycle, some deviation between the expected and measured power level was observed, the measured values being lower. This was analysed in detail and corrections were made to take into account the following factors:

- The effect of nuclear heating on the thermocouples used for establishing the thermal balance, which accounts for a deviation of about 5%; and
- The effect of non-uniform heating of the water, also introducing an uncertainty of about 5%.

The resulting corrections bring the measured and predicted power levels in correspondence within the uncertainty range on both methods.

The first RJH prototype element was irradiated during 2 reactor cycles of 4 weeks up to a burn-up of 38% (Figure 9). No release of fission products was observed, indicating the integrity of the fuel cladding after the irradiation. After 100 days of cooling, the fuel element was transferred to the hot cell for dimensional measurements and extraction of plate segments for destructive analysis.

The irradiation of the second element is ongoing; the target burn-up of the second element is 55-60%, so the in-pile section was modified to the beryllium plug after 2 cycles of irradiation (27% of burn-up).

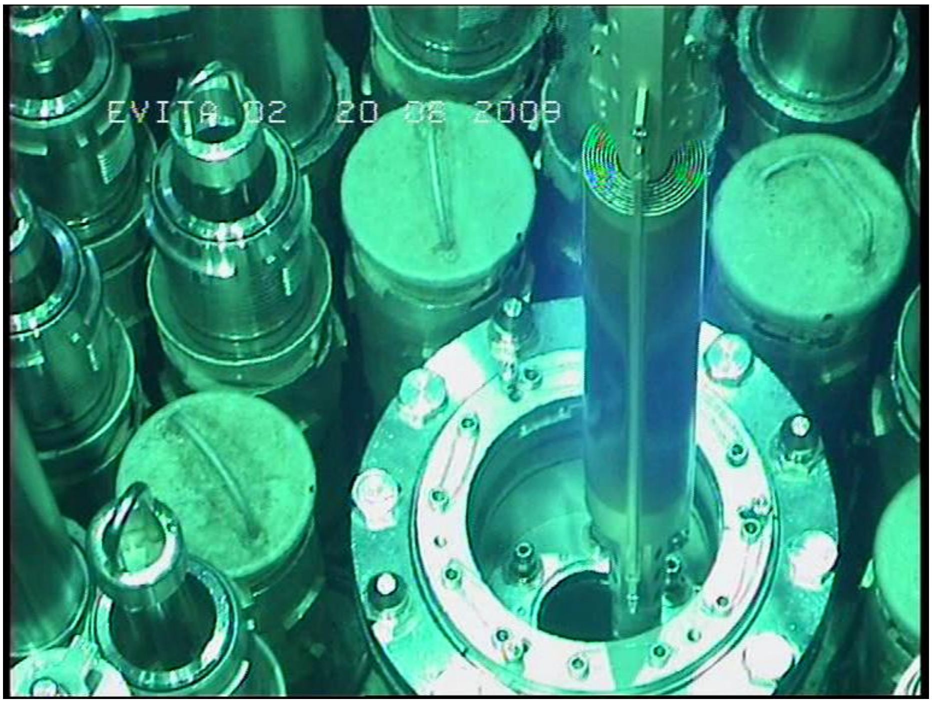

Fig. 9. Unloading of the prototype RJH fuel element from the test loop after irradiation in the BR2 reactor.

6. SUMMARY AND CONCLUSIONS

The ongoing irradiation programmes demonstrate the capability of the BR2 reactor to accommodate a wide range of experiments with various demands in terms of nuclear and irradiation environment requirements. This potential is realised thanks to a strong support of the reactor operation and experiment development and utilisation by modelling, post irradiation analysis and irradiation rig engineering experience.

The irradiation tests of fuels and materials make use of one or more of the unique features of the BR2 reactor:

- High fluxes, up to 10^{15} $cm^{-2}s^{-1}$ thermal flux and 6×10^{14} $cm^{-2}s^{-1}$ fast flux (E>0.1MeV);
- High power levels, even in fuels with high burn-up levels;
- Availability of significant irradiation volumes in core;
- Availability and potential of experimental devices providing a high variety of irradiation temperature (40-1000°C) and environment (water, gas, liquid metal); and
- Flexibility of the reactor core layout.

As the flexibility of the BR2 reactor is however finite, irradiation projects are selected based on the following criteria:

- Strategic importance: the scope of the irradiation programmes should fit in the strategic core business of the institute;
- Compatibility of the total experimental load and prioritisation according to strategic and economic criteria;
- Valorisation and validation of acquired expertise and knowledge, this applies for example to the studies on PWR materials and fuels. These studies often qualify as repetition experiments in combination with a strong post irradiation testing and modelling activity in order to provide scientific added value to the end user of the results;
- Opportunity for development of expertise for future objectives. The studies on ADS materials and MTR fuels partly are targeted at this objective. They involve often a significant effort on the preparation side of the experiment and reflect a shared interest between both SCK•CEN and the external partners; and
- Construction of a balanced user community from research centres and academics, vendors, safety authorities and utilities.

Within the totality of irradiation projects, a balance is required between service oriented projects and joint developments. This balance targets the continuous improvement of the quality of experiments and the scientific support in interpretation of the results of the irradiation programmes. In this way, added value is created for all partners in the irradiation programme.

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