The new material irradiation infrastructure at the BR2 reactor

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ABSTRACT

Together with the third refurbishment of the BR2 reactor, which took place from March 2015 until July 2016, the experimental capabilities of the reactor are modernised. In the first phase, structure material irradiation rigs are designed constructed in order to meet the modern requirements for material irradiation programmes in support of ageing management for existing reactors and qualification of materials for new installations. The basic characteristics of these installations are fundamentally different and represent an evolution with respect to the capabilities of the BR2 reactor before its refurbishment. For irradiation of materials in support of the ageing management programmes of existing reactors, the RECALL device offers the possibility to irradiate standard size samples for fracture toughness testing of pressure vessel material. The specification of the device requires strict temperature control of the specimens before, during and after the irradiation (+/- 5°C in a range between 250 and 320°C), irrespective of the reactor power, so all neutron damage is accumulated at constant temperature. The in pile section can accept 4 sets of 5 standard Charpy specimens, alternative sample designs can be loaded in the same volume. The irradiation conditions are selected to achieve between 0.05 and 0.15 dpa (in steel) in a single reactor cycle of 3 weeks. The evolution with respect to current or past devices is the flexibility in loading position of the rig (with respect to the past CALLISTO loop) and the volume available for the specimens (with respect to the LIBERTY device).

For qualification of materials at high fast neutron flux and high service temperature, the HTHF device (High Temperature, High Flux) targets the irradiation of materials for fusion and Generation 4 reactors for use at high temperature (300°C to 1000°C) and high fast flux (up to 6×10^{14}n/cm^{2}s, E>0.1MeV). This device has a dedicated in-pile section for each irradiation demand, but has a generic design and out of pile control equipment. The HTHF rig is designed to be loaded inside a standard 6 plate fuel element, maximising the fast flux and loading flexibility, with the potential to accumulate damage dose up to 10 dpa in steel (total irradiation time of 45 weeks), under nuclear heating conditions from 8 up to 14 W/g inside a dry medium. The first irradiation project is focussed on tungsten irradiation at 800°C to achieve 1dpa (in Tungsten metal). The control system is designed to offer a stable irradiation temperature within 20°C for samples loaded over a range of axial flux positions (100% down to 70% of maximum flux). The irradiation campaign is complemented with irradiation of specimens in non-instrumented capsules, with target irradiation temperatures between 400 and 1200°C.

CHARACTERISTICS OF THE BR2 REACTOR

The neutronic performance of the light water cooled, beryllium moderated core offers a wide range of neutron fluxes for experiments:

- At regular operating power (55 to 65 MW thermal), the total flux in the central core region reaches 1015 n/cm^{2}s. This flux can be highly thermalized in the central flux trap, yielding thermal flux levels of 1015 n/cm^{2}s, while at the peripheral reflector channels, flux levels go down to 7×1013 n/cm^{2}s.
- Fast neutron flux irradiation positions are available in the central cavity of fuel elements or irradiation channels surrounded by fuel elements. The fast flux ($E>1$ MeV) with standard fuel elements ranges from 3×1014 down to 5×1012 n/cm^{2}s.

The reactor is cooled by pressurized (1.2 MPa) water, therefor the allowable heat flux on the fuel surface, exposed to the nominal primary flow, is 470 W/cm^2 for the driver fuel, up to 600 W/cm^2 in experimental-set ups cooled by the primary water. The fuel elements are tubular, with 6 concentric tubes, each made of 3 circular formed fuel plates. In the centre of the fuel elements, there is sufficient space for an irradiation device. The fuelled zone is 762mm long, the reactivity control of the load occurs through the addition of burnable poisons in the fuel meat and the vertical motion of the shim/control rods. The driver fuel elements are reloaded typically for 5 or 6 cycles, accumulating up to 60% of average burn-up.

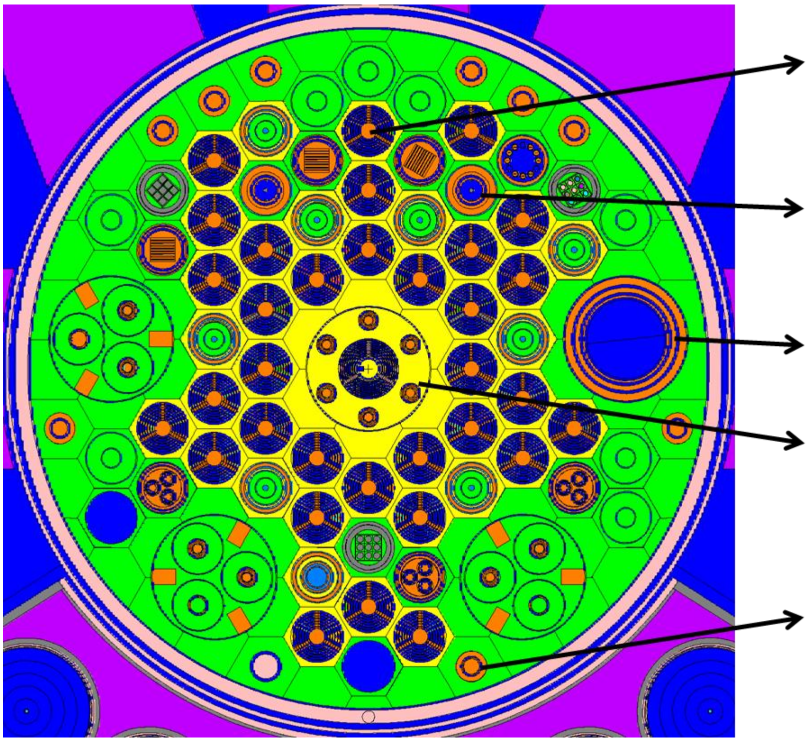
The position and number of control rods and fuel elements are not fixed by design and therefor adaptable to the requirements of all experiments in a reactor cycle. For a typical configuration, as shown in figure 1, between 30 and 35 driver fuel elements are loaded, together with 6 control/shim rods. A regulating rod and eventually a safety rod are added. Such configuration can typically be operated 21 to 28 days at a reactor power between 55 and 70MW. The standard type of fuel element used in the six plate element (with F1 type of irradiation position in its centre, see table 1). Upon request of experimenters, 5 plate elements can be regularly made available (F2). Historically, also other types of elements have been used and can be refabricated for dedicated experiments.

The typical spectrum for the BR2 reactor is given in figure 2. Application of absorbing screens, such as Cd, are feasible in order to tailor the neutron spectrum in experiments.

Experiments in the BR2 reactor can be loaded in 4 types of irradiation positions (see figure 1):

- Irradiation positions inside fuel elements: these can be in standard 6 plate elements (F1) (diameter 25.4 mm) or dedicated 5 plate elements (F2) (diameter 32 mm) for more space. Typically, these positions yield the highest fast flux levels but limited space. The fluxes quoted in the table scale with the power level of the reactor and can vary depending on the position of the element and the burn-up level of the surrounding elements.
- Irradiation in standard channels (S): flux levels will depend on the position of the channel in the reactor (total flux) and the thermal to fast flux ratio will be optimized by the number and burn-up of the surrounding fuel elements. All standard channels have a diameter of 84 mm; the flux level generally varies with the distance to the reactor's central flux trap.

- Irradiation in large channels: there are 5 large channels (H), offering space up to 200 mm in diameter. These channels can contain a single irradiation rig (200 mm), 1 to 3 standard channels (84 mm) or a combination of a standard channel with 6 small channels (33 mm).
- Irradiation in peripheral channels (P; 50 mm diameter), located at the edge of the reactor.


Irradiation position inside fuel element (25 or 32mm)

Irradiation position in standard channel (84mm)

Irradiation position in large channel (200mm)

Irradiation position in small cavity (33mm) in central large channel

Irradiation position in small peripheral channel (50mm)

Figure 1: cross section of BR2 reactor at mid plane with indication of irradiation channel types.

Table 1 gives the nuclear characteristics for the different irradiation channels. The quoted values are typical ranges, taken at mid plane of the reactor for a reference power level of 60MW. The gamma heating is quoted for aluminum, but is also representative for steel.

During the last years, the BR2 reactor has been operated with 5 to 6 cycles per calendar year. Each cycle lasts for 3 to 4 weeks. During such cycle, the reactor power is generally kept at constant level between 55 and 70MW, according to the experimental needs. Specific tests, such as fuel transient tests, are done in dedicated (short) cycles with variable power.
Irradiation devices loaded inside the reactor's primary circuit can in general not be unloaded during the reactor cycle (Mo-99 production devices being an exception). Hence, all rigs or baskets loaded inside fuel elements and most other rigs are irradiated for the entire reactor cycle. However, some thimble tube type devices are available, allowing the selection of flexible irradiation times (see paragraph on irradiation devices).

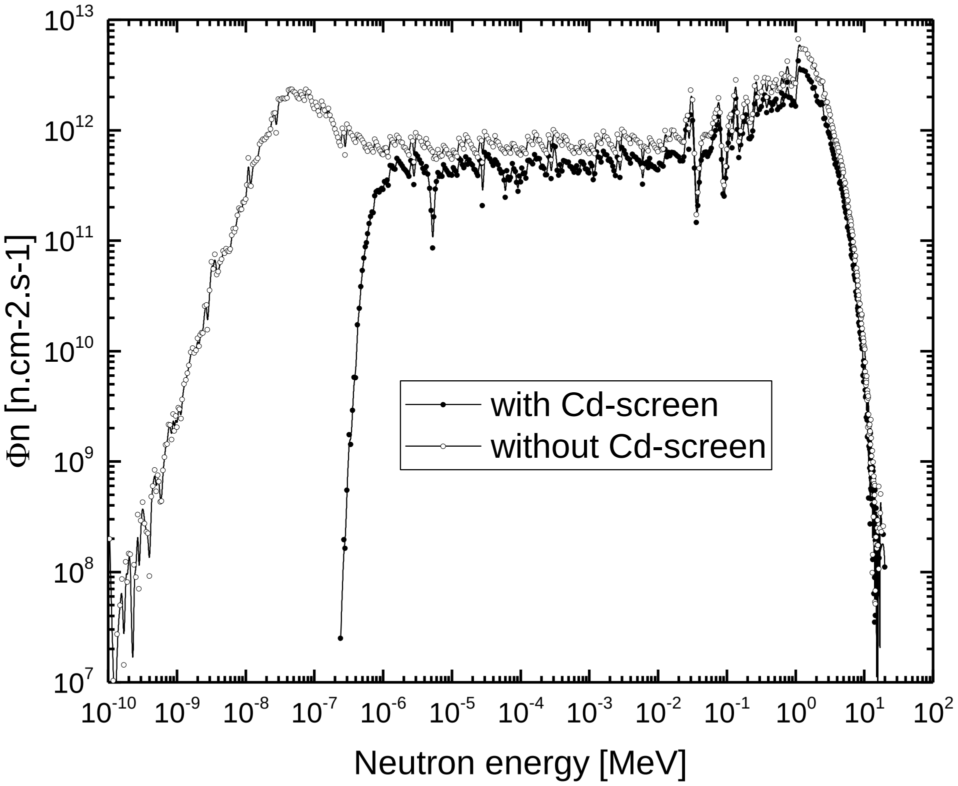


Figure 2: neutron spectrum typical for the BR2 reactor.

Table 1: Nuclear characteristics of the irradiation channels

Channel type	thermal flux range (10^{14}n/cm^{2}s)	fast flux range (10^{14}n/cm^{2}s) (E>1MeV)	Gamma heating (W/g Al)	diameter (mm)	typical number available
F1	1 to 3.5	0.5 to 2.8	1.7 to 8.8	25.4	30
F2	up to 2.5	up to 2.5	up to 6.8	32	2*
S	1 to 3.5	0.1 to 0.7	0.9 to 2.3	84	24**
Central large channel H1	up to 10	up to 1.8	3	200	1***
Peripheral large channel Hi	3	1.3	0.1	200	4****
Peripheral small channel P	0.7 to 1.5	0.05 to 0.1	0.4 to 1	50	9

* The five plate elements are loaded upon experimental request; the amount in the core depends on the number of used/available rigs requiring a 5 plate element.

** The number of available standard channels depends on the configuration (number of fuel elements, control rods and isotope irradiation facilities loaded).

*** the 200 mm central flux trap can be configured to hold one 200 mm rig, or one 84 mm rig and six 33 mm rigs. In the 84 mm rig also a fuel element in the central flux trap can be loaded with an irradiation rig inside.

**** the available peripheral 200 mm channels are configured with three inner 84 mm channels in the standard configuration. 1 channel is reserved for silicon doping.

MATERIAL IRRADIATION AT HIGH TEMPERATURE AND HIGH FAST FLUX

For irradiating materials at maximum fast flux (2.8×1014 n/cm²s, E>1 MeV) in a standard fuel element (F1) and controlled temperature up to 1000°C, a gas filled capsule (diameter 21 mm) with active temperature control is designed (figure 2). This capsule contains a matrix of graphite, allowing high temperature stability and heat evacuation under the highest fluxes available in the BR2 reactor. The design is adjusted according to the experimental needs (specimen material and geometry, temperature range) and the capsules are single use. However, capsule cost and experiment lead time are controlled by the generic design and the reuse of the out of pile control equipment. The availability of several driver fuel elements with comparable neutronic conditions allows for the simultaneous irradiation of multiple HTHF devices, for example to compare different materials or generate data at different irradiation temperatures.

The device temperature control is based on design and the regulation of gas pressure and electrical heating in the in pile section. The design takes into account the experimental load and the expected nuclear heating for the irradiation position and flux selected. The electrical heating allows to preheat the specimens before start up and the pressure regulation in the capsule allows to adjust the irradiation temperature of the specimens. The gradient of the irradiation flux over the length of the core has to be compensated by the variation in the gas gap between the samples and the external wall, cooled by the BR2 primary water.

The heat transfer coefficient is determined by tests at zero power with electrical heating only. During the irradiation start up, the nuclear heating prediction can be validated by comparing the result of the measured temperature with the model.

The start-up measurements indicate an average heating power of 0.45W/g, inducing a temperature difference of 33.3°C between the samples and the cooling water. At 40% reactor power, the nuclear heating was 2.82W/g and the electrical heating was shut down I order to avoid overheating. The start-up profile is given in figure 4; at higher reactor power, adjustment of the helium pressure in the capsule was used to control the irradiation temperature.

The response of the sample temperature to helium pressure and slight variations in the reactor load was somewhat unstable, due to initial degassing of the material as well as to non-optimal setting of the electronic control loop. After optimising the electronic control loop parameters, no manual intervention was needed in the second irradiation cycle of the HTHF device (figure 45). The first irradiation cycle was performed under a fast flux of 1.7 10^{14}n/cm²s, the second cycle under 1.5 10^{14}n/cm²s. The differences arise from the optimisation of the reactor load between cycles (the second cycle being a 4 week cycle, while the first cycle was a 3 week cycle and different experiments being loaded resulted in a somewhat lower flux for the second cycle). The operational experience demonstrates the capability of the system to accommodate a significant variation in irradiation conditions from the thermal point of view. This is also reflected by the temperature stability over the reactor cycle, as the hot spot factor varies over the reactor cycle by a similar amount as the cycle to cycle difference.

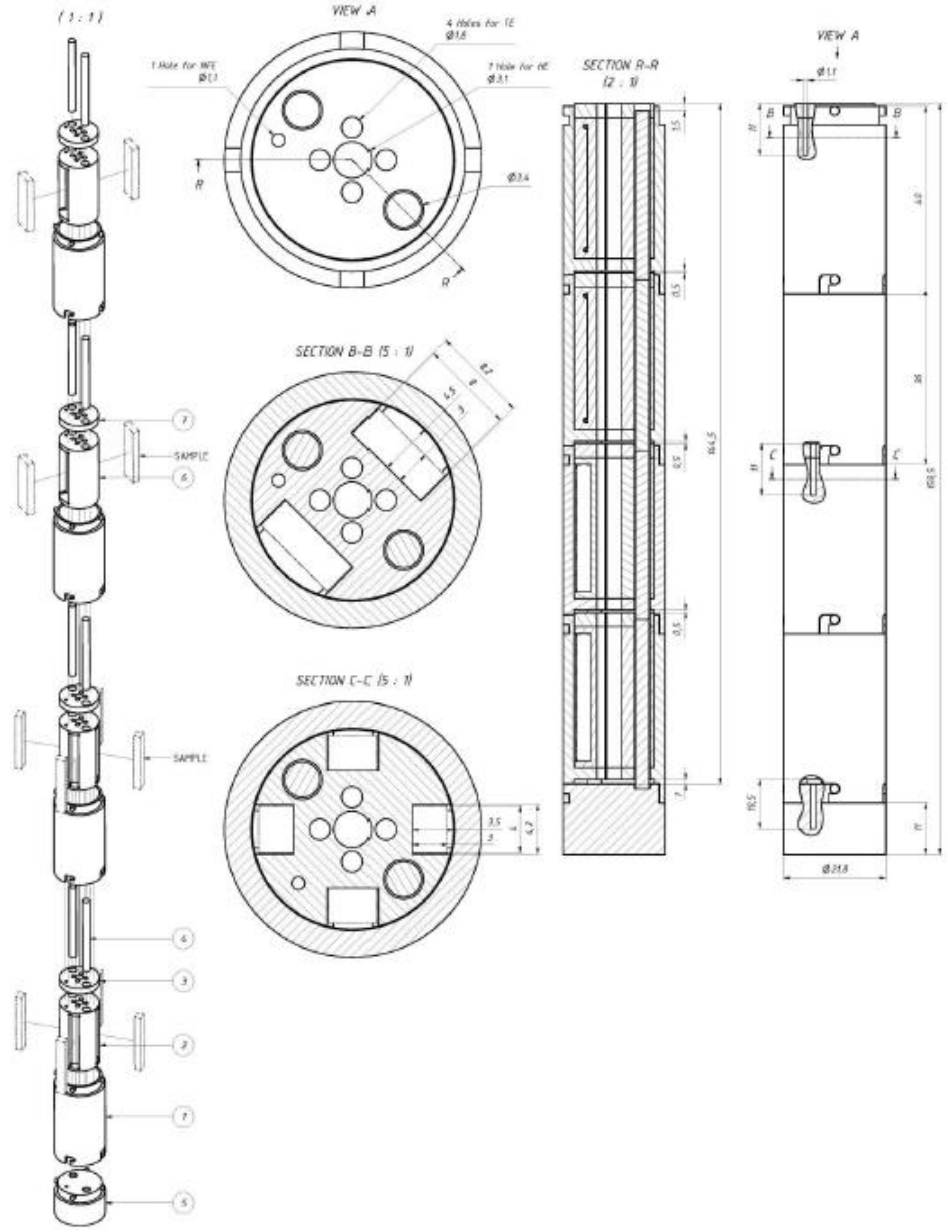


Figure 3: schematic of the HTHF device load.

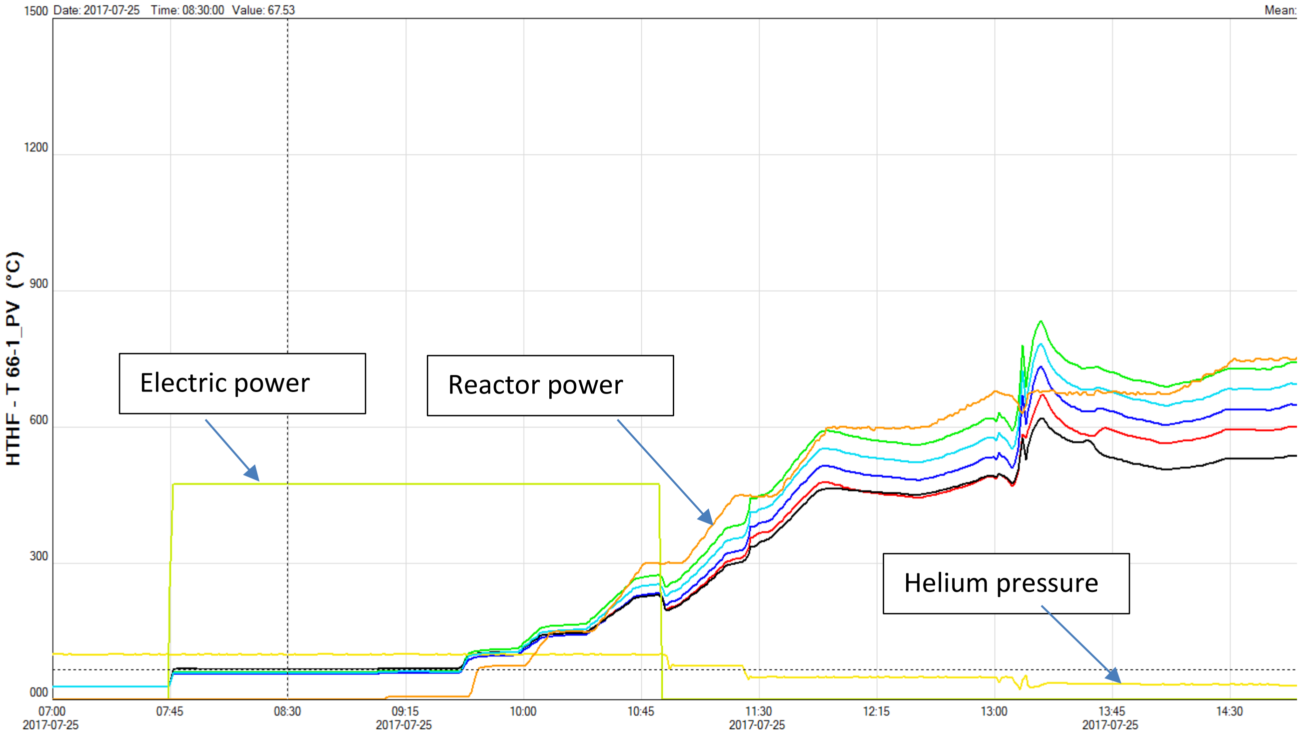


Figure 4: temperature curve as a function of reactor power with switching from electric heating to helium pressure control. Start of the first irradiation cycle

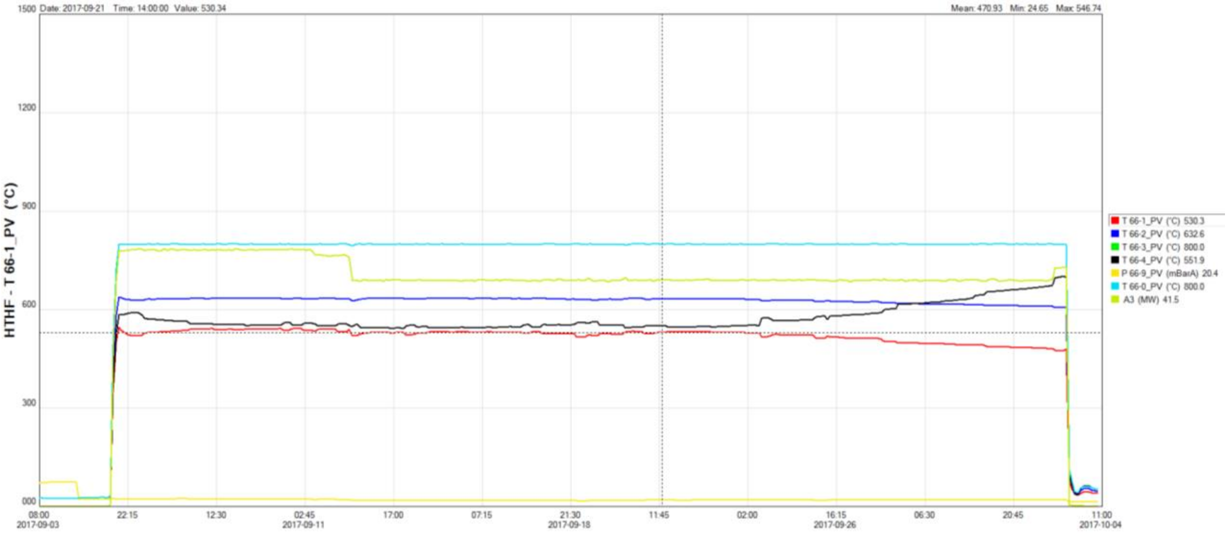


Figure 5: temperature history of the HTHF device during the second reactor cycle.

MATERIAL IRRADIATION IN SUPPORT OF THE AGEING OF PRESSURE VESSELS

The RECALL device is a pressurized water capsule device, loaded in a standard reflector channel (S), with small flow rate (see figure 6). The device allows accurate active temperature control in the range from 250 to 320°C, independent of the reactor power level. The device is loaded for the entire reactor cycle and allows to irradiate 20 standard Charpy V specimens within a homogeneous flux zone (+/-15% axial deviation). Alternative sample geometries, such as tensile or miniature compact tension samples, are also feasible within the same geometrical constraints as 4 x 5 standard Charpy specimens. The positioning of the device is flexible in order to achieve between 0.05 and 0.15 dpa in steel in one reactor cycle. The device is reusable, offering very short lead times for experiments.

The irradiation temperature is controlled by electric heating of the feed water in the top section of the capsule in the central down comer of the experiment. The temperature of the feed water is stabilized by setting the pressure in the capsule slightly above the saturation pressure at the desired temperature at the basket inlet. The temperature in the basket is then stabilized by boiling heat transfer from the nuclear heating of the specimens. When nuclear heating of the specimens becomes larger than the heat loss through the baffle and pressure tube, cold water is injected at the top end of the basket in order to cool down the water in between the baffle and basket, so the radial heat loss is increased and the steam fraction in the device is controlled.

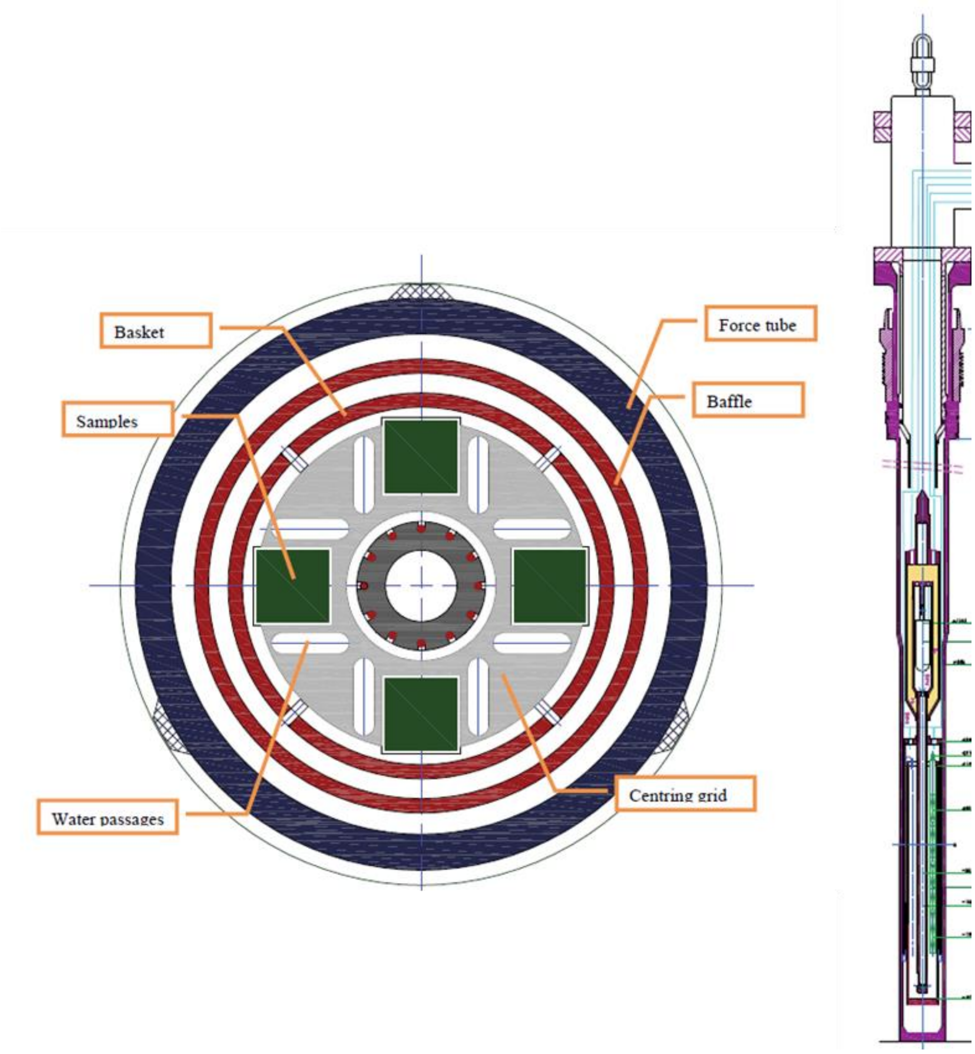


Figure 6: Layout of the RECALL device; the sample trains are shown in green.

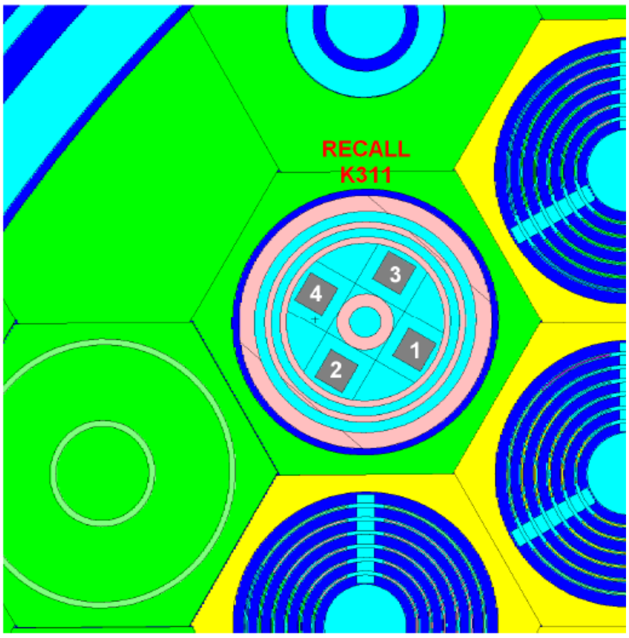


Figure 7: illustration of the positioning of the sample stacks in a typical irradiation configuration in the RECALL device.

The neutronic analysis of the experiment in a given configuration as shown in figure 7, yields fast neutron fluxes in the range of 3 to 5 10^{13}n/cm²s (E>1MeV) for positions 4 and 1 in figure 7, respectively. For the positions 2 and 3, the mid plane flux values are 4.2 to 4.4 10^{13}n/cm²s. In practical irradiation programmes, two irradiation cycles are applied, with 180° rotation of the irradiation rig between the two cycles. Total irradiation dose is obtained through optimisation of the length of both irradiation cycles, the overall reactor power and the local configuration (number and burn up of the neighbouring fuel elements).

The RECALL device is currently under commissioning in a full scale hydraulic test loop for validation of the operation at temperature and to test the actions of the in- and out of pile equipment. The device will be transferred to the reactor after the current operational cycle and will be installed for first irradiation in February 2018.

CONCLUSIONS

This paper presented the general features of the BR2 reactor as it is now operated after its third refurbishment in 2015-2016. Two new irradiation devices are introduced that make use of the accessibility and flexibility of the core configuration in order to perform 2 types of very different irradiation experiments. The high temperature – high flux rig is of a generic design, demonstrating the accessibility to high fast flux irradiation positions in the BR2. Due to its compatibility with the standard fuel elements, it can be positioned in a flexible way in the reactor core to achieve the targeted irradiation conditions. As it is typically deployed for multi-cycle experiments to accumulate significant fast neutron fluence, it needs to provide a flexible operation mode in order to compensate for intra and intercycle variation of flux in order to provide stable irradiation temperature. The RECALL device offers large space irradiation capacity at well controlled thermal conditions for low dose irradiation. It is a fully reusable device, offering experiments with very low lead times, including the option of re-irradiating materials from other irradiation programmes. The thermal stability of the device, irrespective of reactor power, fully simulates the irradiation conditions for vessel surveillance materials, so the data generated with samples, irradiated in such device are fully compliant with the existing databases.

Both irradiation devices are a demonstration of the potential to provide high quality and cost efficient irradiation services and will be available for irradiation programmes for at least the coming licensing period of the BR2 reactor, which extends to 2026.