USER'S GUIDE

BR2
Belgian Reactor 2 US National Scientific User Affiliate facility User's Guide

Mol, January 2018

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http://www.sckcen.be

1. Introduction

The United States Department of Energy (DOE) and Belgium's Studiecentrum voor Kernenergie/Centre d'Etude de l'Energie Nucléaire (SCK•CEN) (also known as the Belgian Nuclear Research Centre) signed a Memorandum of Understanding (MOU) concerning cooperation in nuclear energy research and development on January 13, 2017.

This MOU will enable collaboration on future irradiations and post-irradiation examinations (PIE), including planned SCK•CEN activities to take place in the Belgium Reactor–2 (BR-2) and associated Laboratory for High and Medium Activity (LHMA) hot cells.

Through this agreement, the SCK●CEN facilities become accessible as affiliate infrastructure in the frame of the DOE's Office of Nuclear Energy Nuclear Science User Facilities (NSUF). The outcomes of this collaboration will support and enhance future NSUF opportunities and capabilities for nuclear energy researchers.

The nuclear industry may access some of these capabilities through the Gateway for Accelerated Innovation in Nuclear (GAIN) initiative to help achieve faster and cost-effective development of innovative nuclear energy technologies toward commercial readiness.

The BR2 material test reactor is located at SCK●CEN operational site in Mol, Belgium. With its nominal power of 125MW and unique adaptable core configuration, the BR2 is one of the most powerful and flexible material test reactors in the world. Since its start-up in 1962 the reactor has operated on highly enriched metallic uranium fuel with pressurised water as coolant. The core moderation is done by a combination of light water and metallic Beryllium. This combination of materials and the unique geometrical design provides a compact core with high neutronic performance.

The mission of the BR2 reactor is to provide a versatile platform to expose materials to radiation and perform scientific and engineering tests under various irradiation conditions. In order to do this, the BR2 has a total of 79 irradiation channels within the reactor vessel, a number of pool side neutron irradiation facilities and gamma irradiation facilities. These facilities can be accessed using standard or dedicated irradiation devices to expose materials and/or instruments to radiation during a predefined period. As the reactor operates in cycles of typically 3 to 4 weeks, experiments can be performed during a full reactor cycle, but also possibilities exist to perform experiments over multiple or parts of reactor cycles.

Due to its flexibility in core configuration, the BR2 reactor can generally accommodate additional experiments besides its domestic and international programs. Also, the inscription in a multi-user framework like NSUF provides users with the opportunity to pool resources in order to achieve experiments, otherwise beyond their individual capacity. This model is successfully applied with other user groups from the BR2 reactor.

This document provides a guide for potential experimenters interested in performing experiments in the BR2 reactor and its associated facilities for experiment preparation and post irradiation examinations. Also logistic as well as back end issues are dealt with in the document.

2. BR2 as affiliate facility to NSUF

The designation of the BR2 as an affiliate in the US Nuclear Scientific User Facilities network provides an additional neutron source, positioned in power and performance in between the ATR and the MITR, to ensure the US NSUF users are able to meet their goals.

The BR2 NSUF affiliation is not restricted to the reactor, but also allows access to the SCK-CEN materials expertise, as well as its hot lab facilities and irradiation rig engineering, providing a complete solution for irradiation and PIE programs. The affiliation provides opportunities for users to either outsource to SCK-CEN or contribute themselves to

- experiment design and engineering, in which the irradiation vehicle can go from a simple uninstrumented irradiation capsule, over the use of the existing suite of irradiation vehicles available at the BR2 (see later in this document) up to the full engineering (mechanical design, thermohydraulics and neutronics) of an instrumented irradiation rig dedicated to simulating the specific irradiation conditions required by the user
- construction and commissioning of irradiation devices, in which the safety review of the experiment needs to be performed in collaboration with the SCK-CEN staff.
- performing the irradiation with online follow-up, in which the data from the instruments together with the important reactor parameters can be regularly forwarded to the users if they cannot be physically present at the site
- unloading and dismantling the experiment using the BR2 hotcell without requiring transportation (hot cell directly on the BR2 site)
- performing the required PIE on the specimens at the hot lab, featuring the required equipment for non-destructive metrology, mechanical testing and microscopic analysis.
- modeling of material behaviour and performance, using the SCK-CEN expertise in modeling of structural materials and fuel performance codes.

With suitable transport capabilities also in place (Flying Pig container for type A air shipments of irradiated materials and fuels between Europe and the USA), opportunities exist to also transfer samples to other hotlabs, for example within the NSUF partner facilities.

The BR2 welcomes users for internships or PhD programs for which the NSUF can provide a funding source for the experiment, whereas funding for the travel and scholarship can come from other sources, including the SCK-CEN Academy for Nuclear Science and Technology. The SCK-CEN Academy also offers opportunities for advanced education, such as a Master-after-Master course on advanced nuclear engineering.

3. Description of the BR2 reactor and associated facilities

This reactor is effectively the most powerful materials test reactor currently operating in Europe and offers a number of unique features to its users.

Firstly, 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 10^{15} n/cm²s. This flux can be highly thermalized in the central flux trap, yielding thermal flux levels of 10^{15} n/cm²s, while at the peripheral reflector channels, flux levels go down to 7×10^{13} n/cm²s.
- 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 3×10^{14} down to 5×10^{12} n/cm²s.

As the reactor is cooled by pressurized (1.2 MPa) water, the allowable heat flux on the fuel surface, exposed to the nominal primary flow, is 470 W/cm² for the driver fuel, up to 600 W/cm² 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 center of the fuel elements, there is sufficient space for an irradiation device. The fueled 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 center, 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 taylor 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.

- Irradiations 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.

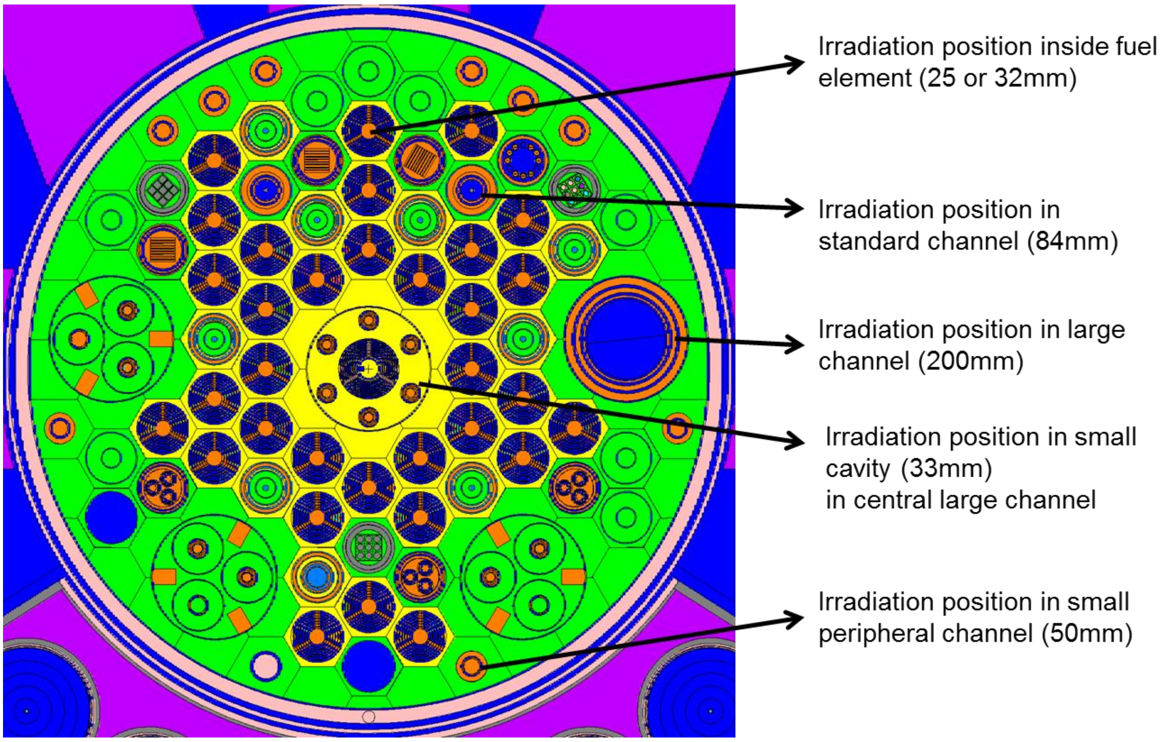

Figure 1: cross section of BR2 reactor at mid plane with indication of irradiation channel types.

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.

The number of reactor cycles can be increased to 8 annually from 2019 on, if economically viable.

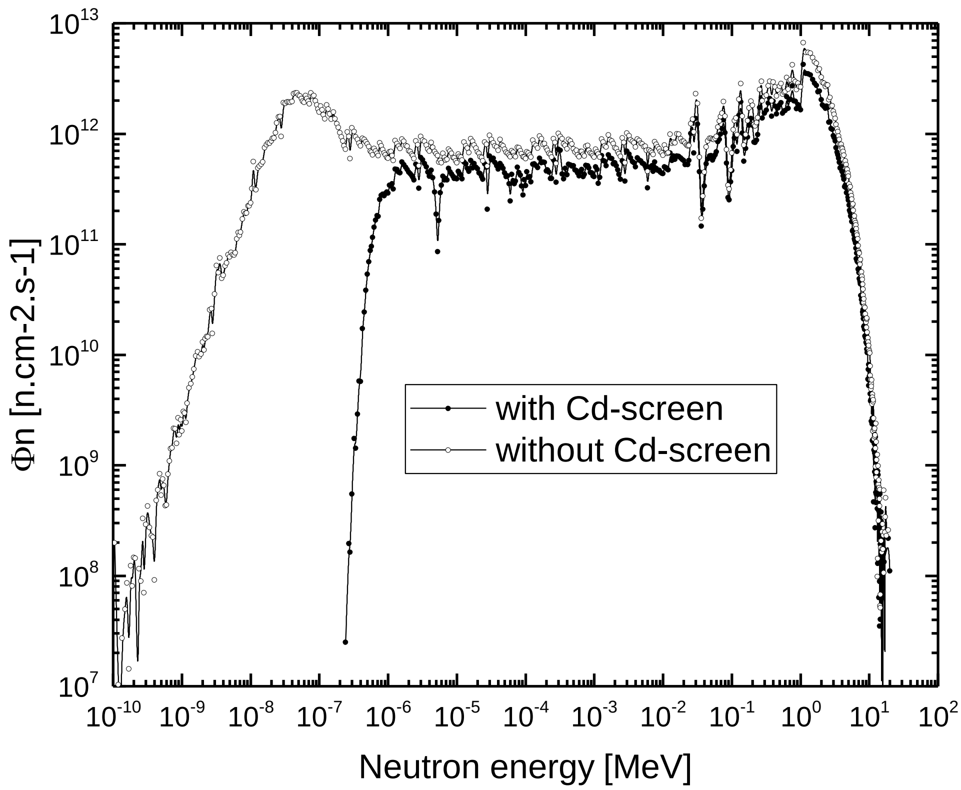

Figure 2: neutron spectrum typical for the BR2 reactor.

Table 1: Nuclear characteristics of the irradiation channels

Channel type	Thermal flux range ($10^{14}n/cm^2s$)	fast flux range ($10^{14}n/cm^2s$) (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.

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).

3.1. Available standard irradiation devices

3.1.1. Fuel irradiation

3.1.1.1. Pressurized water capsule (PWC-CD) for fuel pin irradiation

The pressurized water capsule for fuel irradiation is an instrumented capsule that can be used for base irradiation of fuel pins up to 1m long, with on line power monitoring and control of the cladding temperature by setting the water pressure in the capsule (figure 4). The device can also be used for transient testing, either by loading a mobile absorber in the vicinity (multiple transients with small amplitude) or by varying the overall reactor power (large single transients). The setup of the device is such that fuel pin failure can be tolerated. Eventually, a fuel pin with instrumentation can also be loaded in the device.

The characteristics of the PWC device are as follows

Number of pins	1	**Fuel pin size**	∅ : 8 to 12.5 mm L : 20 to 100cm
Environment	demin water	**Maximum linear power**	750 W/cm
Pressure	1 to 160 bar	**Power transient rate**	<100 W/cm.min
Temperature (hot wall)	130°C-375°C	**Accuracy of power measurement**	5%
Irradiation position	S	**Reuseable**	yes

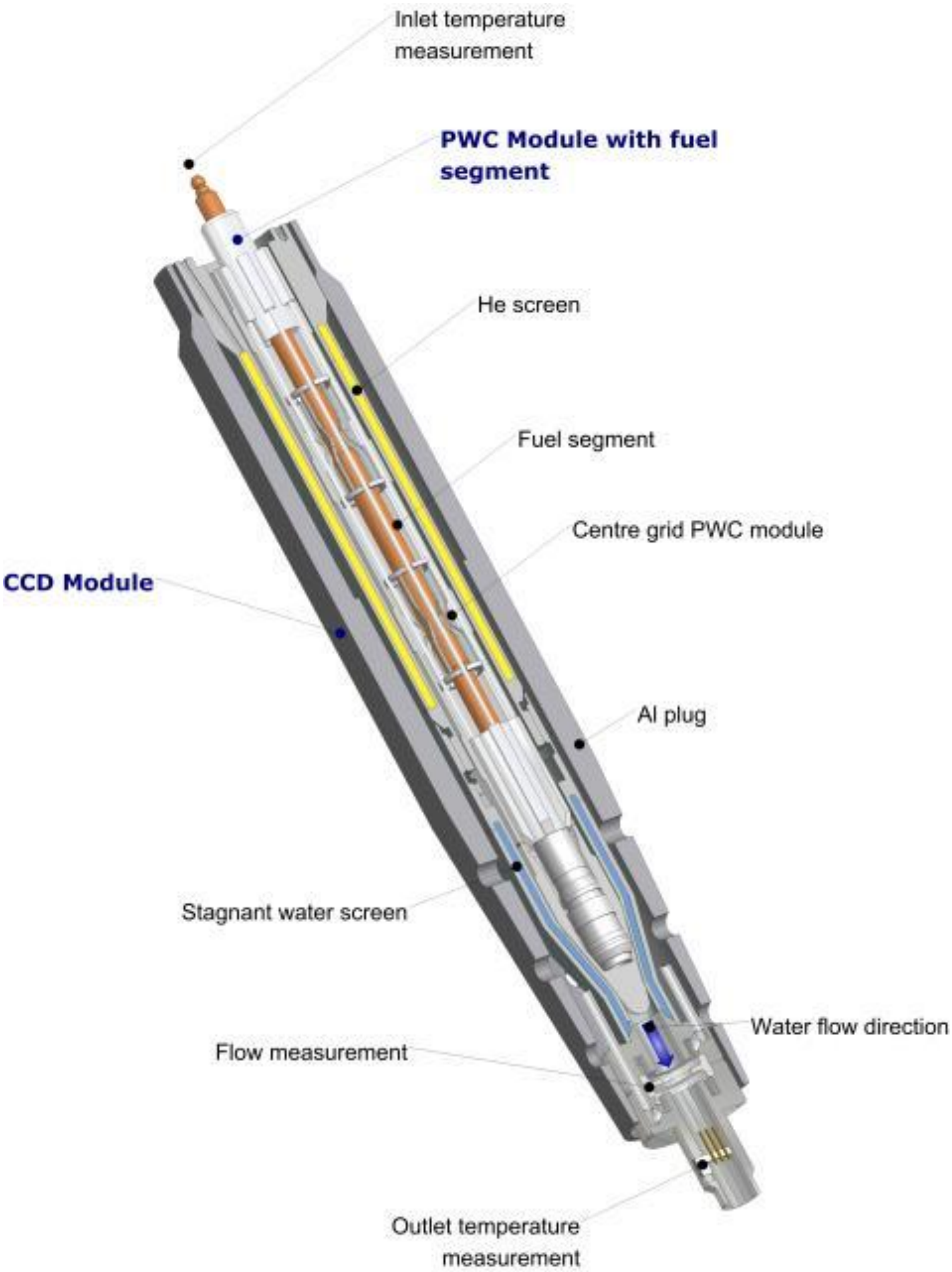

Figure 4: PWC-CD device

3.1.1.2. MTR plate irradiation

Material test reactor fuel plates can be irradiated in the primary water of the BR2 reactor in different ways. The most straightforward for flat plate irradiations is the use of the so-called FUTURE basket (figure 5). Up to 4 flat fuel plates can be loaded in this basket (in its current design), replacing a standard fuel element of the reactor (standard channel S). Fuel plate failure can be tolerated up to the contamination limit of the primary water. The environment of the basket is adapted in order to achieve the desired power level in the basket. The basket allows the loading of activation dosimeters. 4 devices (1 for 2 plates and 3 for 4 plates) are currently available, but others can be constructed quickly to accommodate plate geometries or experimental requirements.

The characteristics of FUTURE are:

Number of plates	4 (current device)	**Fuel plate size**	5.7×80 cm (current device)
Environment	demin water	**Flow rate**	10 m/s
Pressure	12 bar	**Maximum Power density**	600 W/cm^2
Temperature	depends on power	**Reuseable**	yes
Irradiation position	S		

For screening experiments, downsized plates can be irradiated in the INSPIRE device, which in its current design can host up to 18 platelets. This device can be constructed and adapted to fit experimental needs in terms of platelet size and allowable flux peaking at the edges of the platelets.

Alternatively, a MTR fuel experiment can be performed as a 'mixed element' or a dedicated Lead Test Assembly (LTA). For a mixed element, the outer ring of plates (3) of a standard BR2 element is replaced by a ring of the plates to be tested. As the outer ring is the most solicited during irradiation, the irradiation history of these plates can be adjusted up to the maximum achievable in BR2 (470W/cm^2 in normal conditions and 600W/cm^2 for dedicated experiments).

For LTA testing, dedicated rigs can be constructed to simulate reactor environments, such as cooling flow rate. These rigs are typically dedicated for customer requirements, but the existing design for an enhanced flow rate rig (EVITA) can be directly used as a basis.

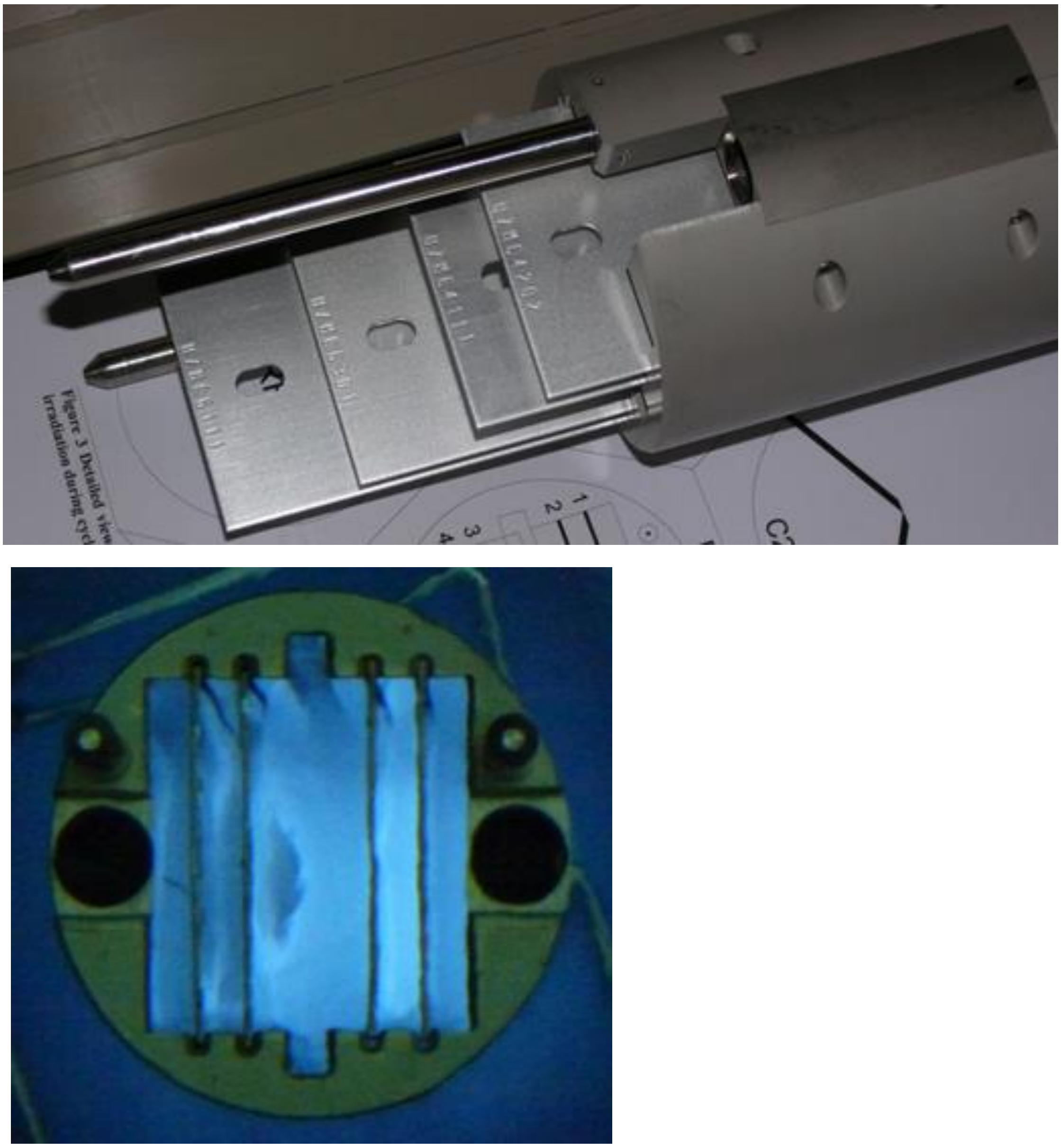

Figure 5: Picture of the FUTURE type basket for irradiation of 4 MTR fuel plates. The central aluminum plate, containing activation dosimeters, is removed in these pictures.

3.2. Material irradiation

3.2.1. BAMI capsules

The BAMI capsules are un-instrumented capsules that can be loaded in irradiation positions inside fuel elements (F1) or in standard channels (S) (see figure 6). Up to 8 capsules of diameter 15mm (F1) or 25mm (S) are loaded in one irradiation position. The capsules can be loaded in the primary water flow (entire cycle irradiation) or in a thimble tube device (flexible irradiation time). The capsules can be open to the water (irradiation temperature <100°C) or can be gas filled, in which case the irradiation temperature is determined by the irradiation position, the mass of the samples, the composition of the gas (typically He) and the spacing between the samples and the cold wall of the capsule. The BAMI capsules offer the lowest cost and lead time for irradiating structural material samples.

The characteristics of BAMI are:

Number of capsules	8 (∅ : 15-25 mm)	**Sample size**	design dependent
Environment	demin water gas	**Flow rate**	10 m/s
Pressure	variable	**Reuseable**	no
Temperature	passive control 80-500°C		
Irradiation position	F1 or S		

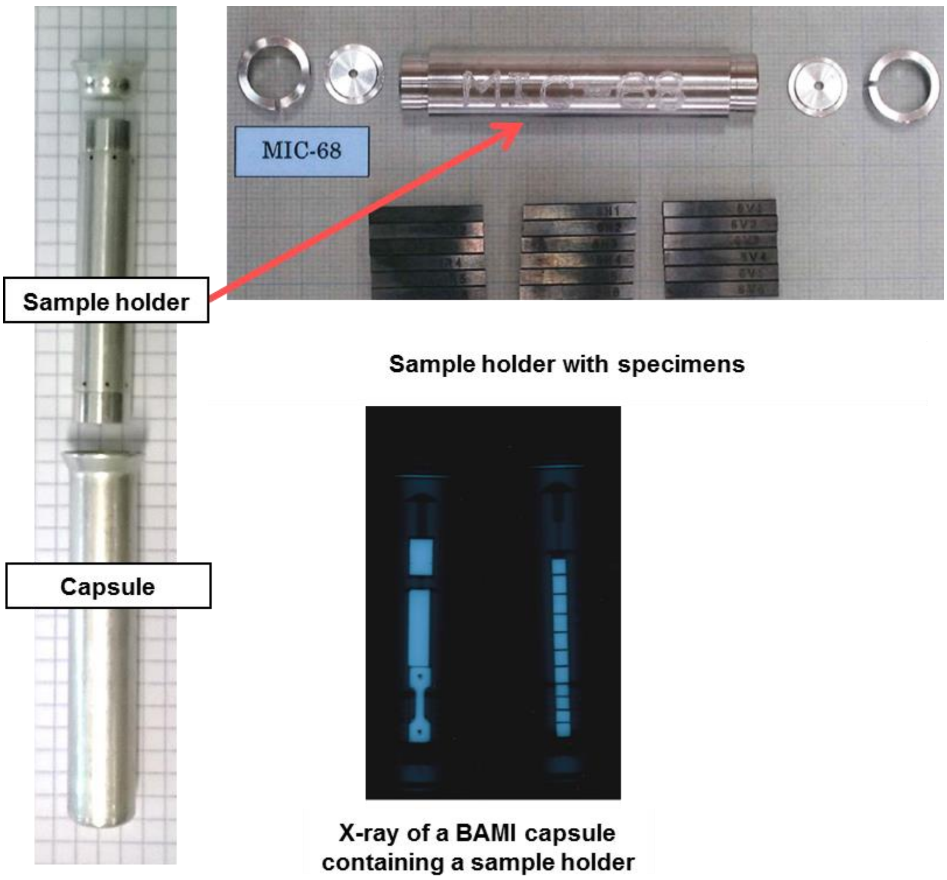

Figure 6: BAMI capsule with typical sample holder and samples.

3.2.2. ROBIN

The ROBIN device is loaded in a thimble tube, inserted in a standard channel (S) (flexible irradiation time). The specimens are encapsulated in closed needles (9 needles of diameter 11mm, see figure 7); the irradiation temperature is determined by the design of the needles and is controlled by adjusting the water flow in the thimble. In order to avoid boiling, the positioning of the experiment is limited to relatively low flux positions (thermal and fast flux 0.7 and 0.3×10^{14}n/cm²s, respectively). The temperature in the samples is monitored by adding an instrumented dummy capsule with identical design as the specimen needles.

The characteristics of ROBIN are:

Number of pins	9 (∅ : 11 mm)	**Sample size**	design dependent
Environment	gas	**Fluxes**	th: 0.7×10^{14}n/cm²s fast: 0.3×10^{14}n/cm²s
Pressure	variable	**Reuseable**	yes
Temperature	active control 80-500°C		
Irradiation position	Thimble tube in S		

Figure 7: drawing of the ROBIN device, showing 3 of the 9 sample holders.

3.2.3. LIBERTY

The LIBERTY device is also loaded inside a thimble tube in a standard channel (S). The main difference with the ROBIN device is that there can only be 5 sample containing needles, but the needles are larger in diameter (16mm inside) and can be equipped with active temperature control by integrated electrical heating and temperature measurement (see figure 8). In this way, specimens can be preheated before the start of irradiation. The fluxes in LIBERTY are similar to the ones in ROBIN.

The characteristics of LIBERTY are:

Number of capsules	5 (∅ : 16 mm)	**Sample size**	design dependent
Environment	gas	**Fluxes**	th: 0.7×10^{14}n/cm^{2}s fast: 0.3×10^{14}n/cm^{2}s
Pressure	variable	**Reuseable**	yes
Temperature	active control 80-500°C		
Irradiation position	thimble tube in S		

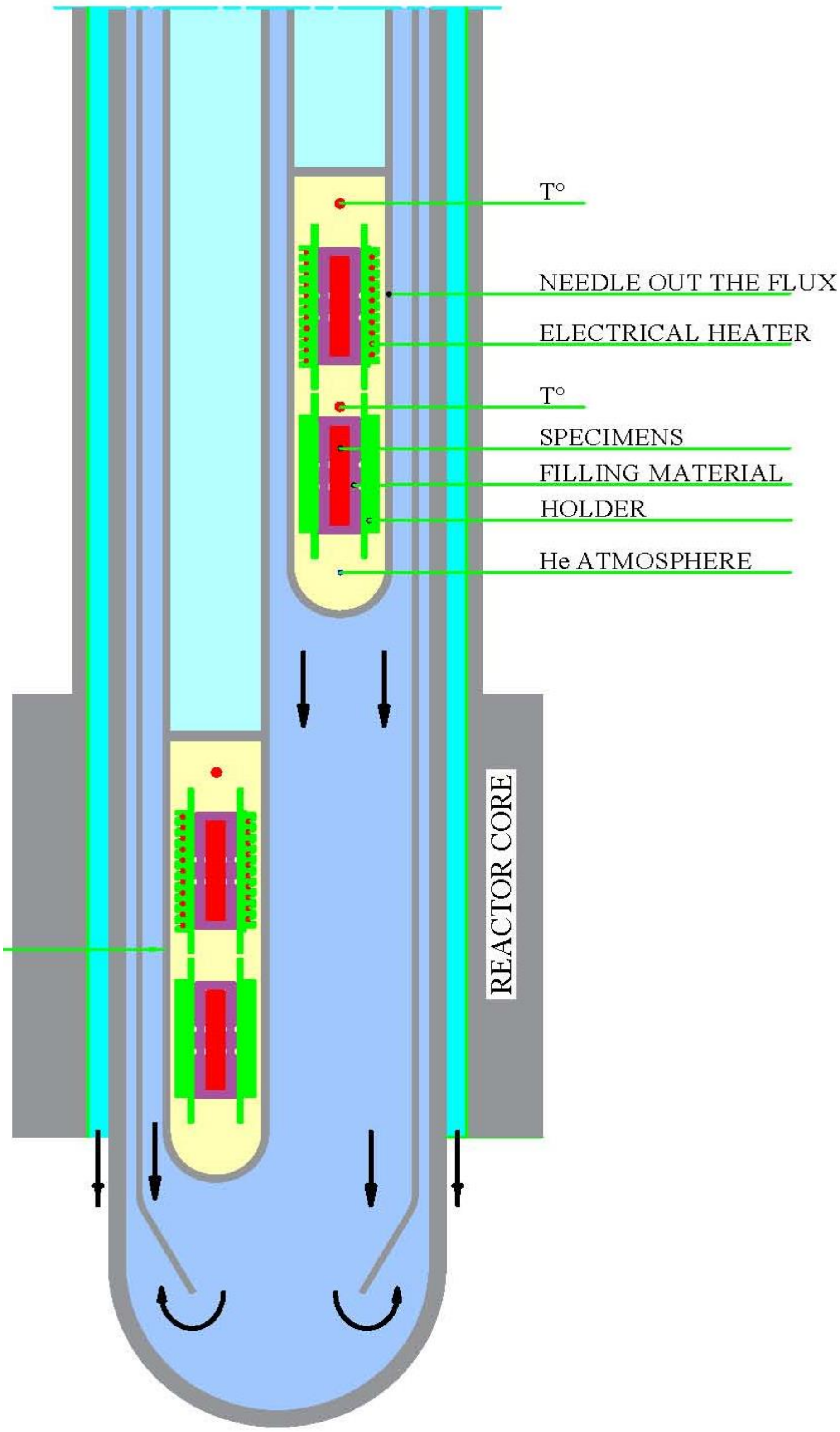

Figure 8: schematic of the LIBERTY device.

3.2.4. RECALL

The RECALL device is a pressurized water capsule device, loaded in a standard reflector channel (S), with small flow rate (figure9). The device allows accurate active temperature control in the range from 250 to 320°C, before as well as during irradiation. The device is loaded for the entire reactor cycle and allows to irradiate 24 standard Charpy V specimens within a homogeneous flux zone (+/-15% axial deviation). 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 characteristics of RECALL are:

Number of samples	<24	**Sample size**	Standard Charpy
Environment	pressurized water	**Damage rate**	0.05-0.15 dpa/cycle
Pressure	PWR/BWR	**Reuseable**	yes
Temperature	active control 250-320°C		
Irradiation position	S		

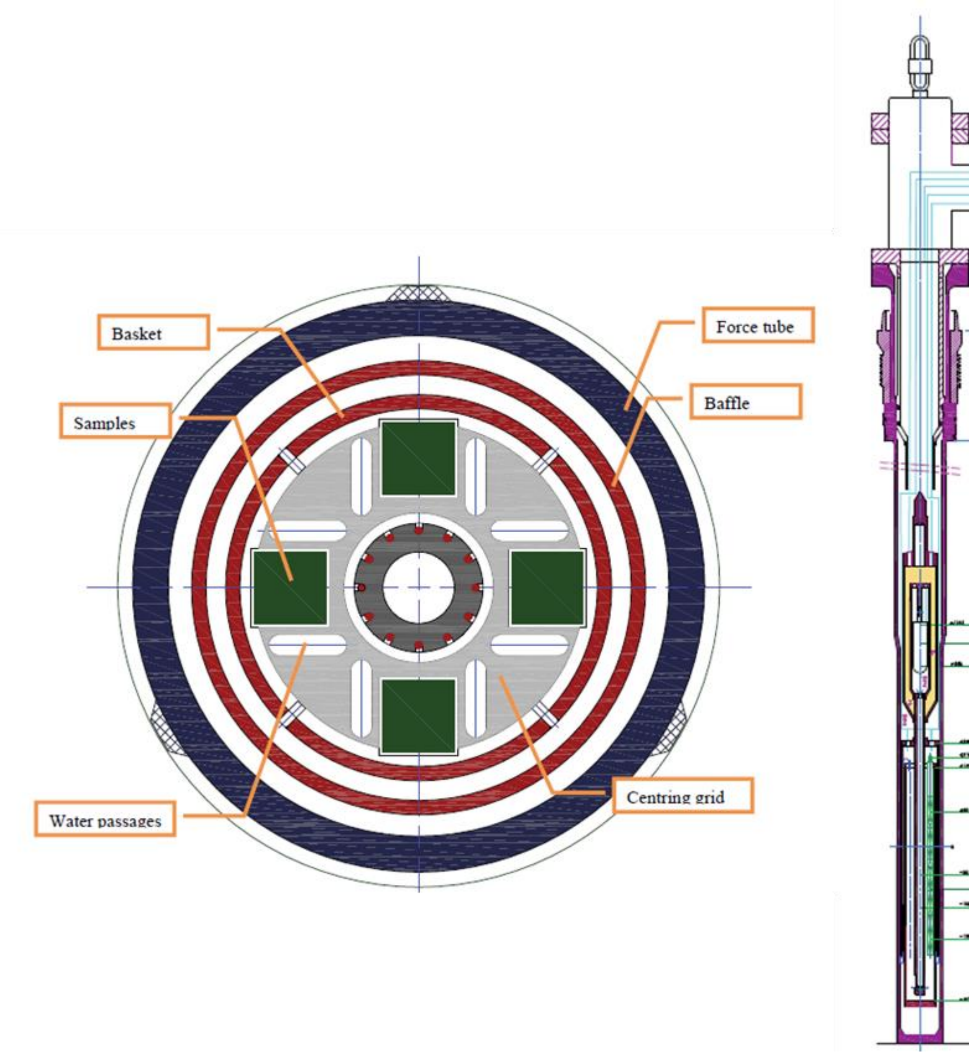

Figure 9: schematic of the RECALL device.

3.2.5. MISTRAL

The MISTRAL device is inserted in a 5 plate fuel element (F2) and offers active temperature control in a boiling water environment (figure 10). The MISTRAL device is designed to irradiate a large number (87) of miniature specimens (5mm diameter or 3x4mm² cross section and length of 27mm) in stable temperature conditions (160°C-350°C) with medium to high fast flux level (up to 2.5×10^{14} n/cm²s, E>1MeV). The rig can be reloaded, so lead times for experiments are limited as well as the rig costs. Of the 87 specimens, 26 are located in the zone having over 90% of the maximum flux in the rig. The irradiation temperature is monitored by measurement inside dummy specimens and the irradiation temperature is fixed by setting the saturation pressure in the rig and sustaining boiling by electrical heating if the nuclear heating is insufficient to maintain boiling (during start up and shut down of the reactor).

The characteristics of MISTRAL are:

Number of samples	<87	**Sample size**	∅5 mm or $3\times4\times27$ mm³
Environment	boiling water	**Fluxes**	fast:<2.5×10^{14}n/cm²s
Pressure	boiling	**Reuseable**	yes
Temperature	active control 160-350°C		
Irradiation position	F2		

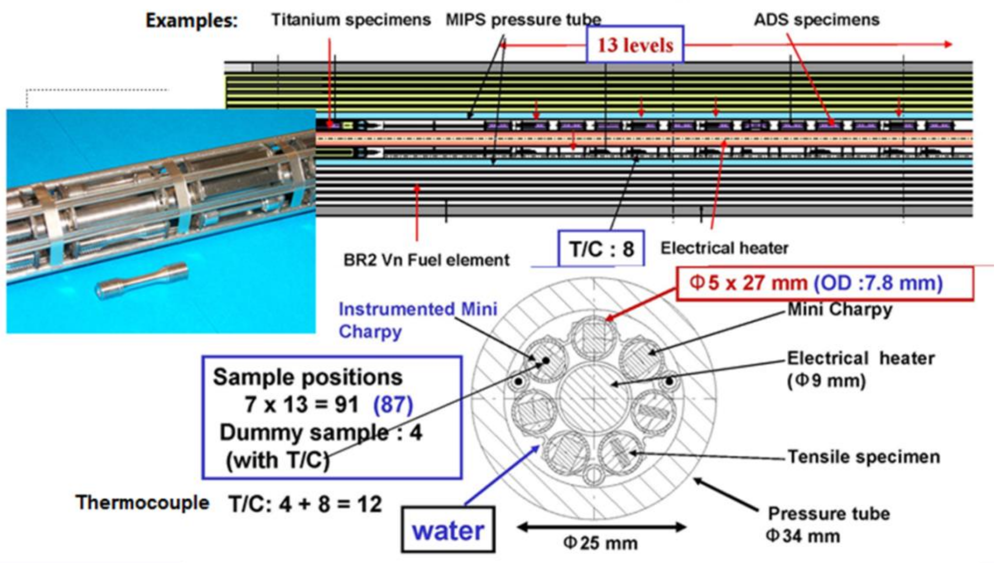

Figure 10: picture and schematic of the MISTRAL capsule.

3.2.6. HTHF

For irradiating materials at maximum fast flux (2.8×10^{14} 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 11). This capsule is constructed 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 number 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 HTHF devices, for example to compare different materials or generate data at different irradiation temperatures.

Number of samples	<87	**Sample size**	adjustable
Environment	gas	**Fluxes**	fast: 2.8×10^{14}n/cm²s
Pressure	n/a	**Reuseable**	no, except out-of-pile instruments
Temperature	active control <1000°C		
Irradiation position	F1		

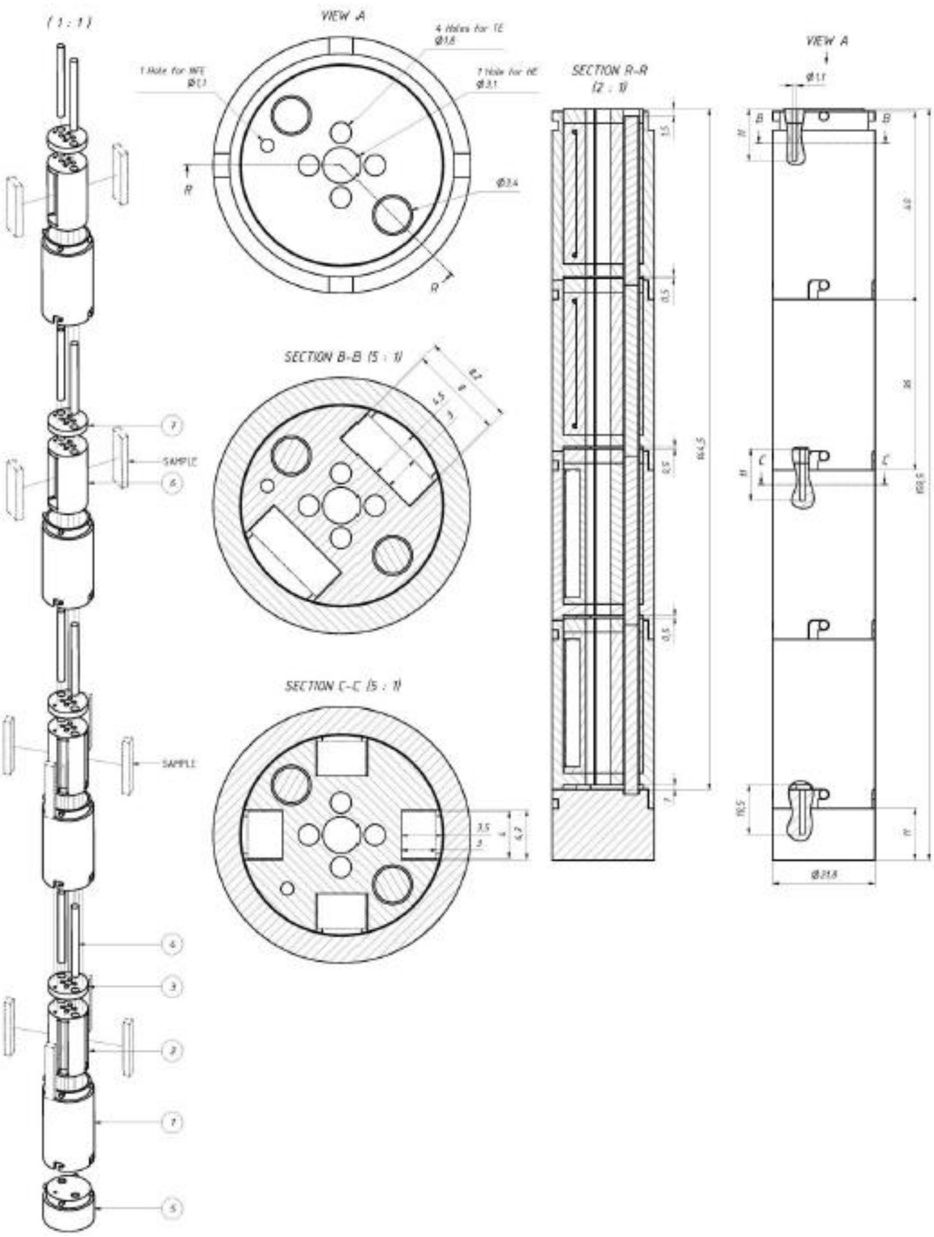

Figure 11: schematic of the HTHF capsule.

4. Evaluation of experiments

4.1. Project evaluation

An irradiation project request is submitted to the reactor manager (contact information on http://science.sckcen.be/en/Facilities/BR2). The project is evaluated according to the following criteria

- compliance to mission and strategy of the institute: the project has to fit the statutury mission of the institute.

- scientific & technological excellence: the objectives of the irradiation have to demonstrate the scientific or technological excellence of the proposed irradiation project.

- technical compliance: the project has to be technically compliant to the capability and license of the installation.

Following this stage, a contractual arrangement is set-up defining the project schedule and resources, including the front and back-end liabilities and intellectual property rights.

4.2. Safety evaluation

The project's safety evaluation is required in order to obtain permission for irradiation. It is performed in 4 steps:

1) Phase 1: Investigation of feasibility
2) Phase 2: Investigation of the detail design
3) Phase 3: Investigation of the testing and commissioning results
4) Phase 4: Discussion of the experimental results in view of using the experience gained for future irradiation programs

Feasibility Study

The Feasibility Study outlines the scope of the project and proves that it can be realized effectively and safely in the reactor environment and within the limits of the exploitation license. The study investigates the problems and identifies the solutions. It identifies the risks and the way to cope with them. In broad outline it will deal with the irradiation, dismantling and disposal procedures.

In particular following information will be given:

- Description of the experiment. Schematic diagram of the in-pile section and the Out-of-Pile equipment
- Required space in the reactor (in-pile section) and in the reactor building (Out-of-Pile equipment).
- The postulated irradiation conditions (type of reactor channel, neutron flux, gamma heating, duration of the irradiation, waste production during operation)

- Required connections to the reactor circuits: electrical power, water, gasses, compressed air.
- General view of the irradiation program: anticipated start and duration of the irradiation. Special requirements with respect to start-up and power level.
- Required actions after the irradiation, cooling time, hot cell occupation, PIE and waste production.
- Concise evaluation of the risks associated with the irradiation and potential measures to be taken.

2.2. Detail Design

The detailed design translates a set of experimental requirements into the development of the necessary tools to realize the specified goals. It complements and details the points discussed in the feasibility study. The main points to be dealt with are:

2.2.1. General

- Objectives: material to be irradiated (metal, fuel), required nuclear characteristics, required medium (gas, water, liquid metal), compatibility of samples with medium, required space, required temperature and pressure.
- The technologies incorporated in the design and the construction are proven by experience or testing

2.2.2. Choice of Materials

- Exclusion of materials which are incompatible with the reactor or fuel cladding
- Exclusion of hazardous materials
- Limitation on materials with strong neutron absorption
- Identification of construction materials and their fabrication standards

2.2.3. Nuclear characteristics

- Nuclear characteristics: required flux level and spectrum, axial and radial flux gradient, gamma heating. The anti-reactivity effect is to be evaluated. All these factors determine the choice of the reactor channel and the reactor loading. If a hard spectrum is required, the use of a thermal neutron screen (e.g. Cd or Gd) is to be considered.
- If applicable: inventory of fissile material and inventory of dangerous products, fission products generated during the irradiation.
- The activation of the materials at the end of the irradiation will be calculated. It determines the type of shielded containers to be used for the evacuation of the dismantled experiment.

2.2.4. Design aspects – Safety analysis

- Description of the test facility: in-pile section, out-of-pile equipment, instrumentation.
- Strength calculations according to a chosen standard e.g. ASME VIII
- Overpressure protection: The experiment has to be protected against overpressure. The maximum allowable working pressure (MAWP, often taken equal to the design pressure) is usually equal to 110% of the operating pressure. In any case the design pressure of the experiment equals at least the design pressure of the BR2 vessel (14.5 bar rel).
- Thermal design: how to obtain the required temperatures and thermal gradients. Surface heat flux during operation and during inversion of reactor cooling water with reactor scram. Thermal stresses as a result of heat losses and gamma heating. If the experiment is loaded in a fuel element, the surface heat flux, in case of inversion of the reactor water flow, is limited to 25 W/cm².
- Risk evaluation: it is to be demonstrated that the experiment does not add any supplementary risk to the staff and the general public outside of the SCK•CEN site.
- Accident analysis:
    - LOCA (Loss of Cooling Accident)
    - Loss of Power
    - Consequences of rupture of samples especially in case of fuel irradiation (Fuel leakage or rupture)
    - Failure of instrumentation: Minimum required Instrumentation for a meaningful and safe operation of the experiment
    - Failure of Control System
- The experiment should not impede the cooling conditions in the reactor, especially if the test section of the experiment is surrounded by a fuel element, it is to be verified that the water flow in that channel is sufficient.
- The design must take account of dismantling needs, hot cell occupation and the removal of waste. Especially when intermediate unloading and reloading of samples is to be done in the hot cell, the design of the closures is to be discussed with the hot cell operators, e.g. socket head bolts are preferred to hex head bolts and it is common practice to use pneumatic-driven tools.
- For large loops a seismic analysis could be required.
- Experiments done in a thimble: The thimble itself is designed according to the rules applied for normal irradiations devices. Experiments inside such a thimble should be compatible with the pool water. The control is limited to visual inspection, accordance with the drawings, and geometrical control with a ring calibre. If the experiment inside the thimble is cooled by forced convection, some parts of the experiments must be capable of withstanding the pump outlet pressure.

2.2.5. Electrical Power supply and Instrumentation.

- Redundancy for reliability and safety related components is aimed at. For instance use two pumps with independent power supply if feasible. The power supply for safety related components should be divided over the normal and the vital network.
- Instrumentation is required for recording experimental data, control of operating conditions and safety of the experiment, the reactor and the environment.
- Safety limits shall be set to protect the integrity of the experimental device. They shall be set on important parameters such as temperate, pressure, flow rate, radiation level. The safety limits will be chosen equal to or lower than the design specifications.
- The safety actions should be triggered automatically and preceded by an alarm set with a certain margin relative to the action limit (e.g. 5% lower). Possibly actions on the reactor are required. As a general rule a 2/3 logic is applied. Instrumentation for safety actions shall not be used for control.
- Measuring circuits that generate safety actions are made "fail safe" i.e. a high level or low level signal is produced, in case of failure of the sensor or an apparatus, whatever is the safe direction. Valves, solenoid, electric air or air operated, will return to its safe position in case of air or electrical power loss.

2.2.6. Reactor interface, Reactor Building integrity

- Interference with reactor operation and the connections to building circuits. Required electrical power, water, and gas consumption are to be listed in detail.
- Required bottom or wall penetrations for the connection of the in-pile section to the out-of-pile equipment and the reactor building facilities. Wall penetrations should be made at a level higher than the reactor cover (fourth floor). Preferably the wall penetrations are filled with pool water to prevent a radiation beam at the containment building side when manipulating objects with high radiation level such as used fuel elements in the pool. The seals used for all penetrations, also in through-loops, are to be protected against excessive temperature and high radiation levels.
- Required connections to ventilation (contaminated or not) and liquid waste system (contaminated or not).
- If connections are to be made to the outside of the reactor building, tightness of the containment building is to be guaranteed.
- If large loads on the reactor cover are to be expected, a stress analysis should be made. The maximum allowed load is 100 kN in axial direction, 4000 Nm bending moment and 1000 Nm torsion moment.

2.2.7. Radiation Protection considerations

- ALARA analysis. It is to be verified that all measures have been taken to limit the radiation dose of the personnel as well as the waste produced during the operation and during dismantling.
- Release of radioactive material is done in a controlled manner. Delaying the releases of fission gases for instance by means of an active coal trap could be appropriate.

2.2.8. Manipulations

- Design of necessary tools for manipulating the experiment and the samples, loading, unloading, dismantling, PIE and transport. The equipment for the handling, dismantling and safe storage or disposal of irradiated materials and devices shall be tested before the start of the operation.
- It is to be verified that containers used in the reactor pool and the storage canal do not float.

2.3. Construction and Assembly

On basis of the detailed drawings and the specifications, the construction and assembly phase can be initiated. Following steps are to be considered:

- A LOFC (List of Operations of Fabrication and Control) will be written in cooperation with "Nuclear Safety BR2". The LOFC identifies the different operations necessary for the construction and the intermediate and final controls required for the realization of a reliable and safe experiment (witness- and hold points). Some quality controls on a component can be done at the premises of the manufacturer by a qualified inspector. This approach can only be allowed in agreement with "Nuclear Safety BR2" who can decide to assist at these tests or not.
- The operation manual has to be detailed, including procedures for the operation of the experiment in nominal and in accident conditions.
- Instructions for the reactor operator, defining the nominal operating conditions and the operation margins (minimum and maximum limits).
- Procedures for the manipulations during irradiation, during dismantling in the hot cells, PIE and removal of the experiment components.
- Periodic maintenance works and intermediated recalibrations and controls are defined, specifying the frequency of performance and the allowable deviations. A list of spare parts is made on basis of previous experience and advice from component suppliers. Spares for items subject to wear shall also be kept in stock.
- List of all reference documents (drawings, calculation notes, technical specifications, descriptive reports, applicable procedures).

- Before transferring the device to the reactor, functional testing under conditions, as realistic as possible, should be done. The test results are documented.

2.4. Operation

- Operator training of concerned people (operators and persons that will have to intervene in maintenance and manipulation tasks).
- Once the experiment loaded in the reactor, all connections are tested (pneumatic, electrical and instrumentation connections) according to the programme specified in the safety file.
- Reactor start-up profile needs of the experiment is to be defined.
- The irradiation will be done according to the written operation, calibrating, testing and maintenance procedures. The frequency of calibration, testing and preventive maintenance operation is fixed in advance.
- After reactor start-up a radiation survey shall be made that covers especially the area of the experiment.
- Observations made during the irradiation may require an updating of the procedures. If modifications to the experiment equipment (IPS or OPE) are required, they shall be fully documented and drawings, documentation and notes will be modified accordingly.
- All interventions are recorded in a logbook. All incidents, requiring corrective actions, are recorded in a "nonconformance report". For this purpose the Management System for Non Corformance Reports will be used (NCRMS). Every one (operator or any member of the staff) who observes an anomaly will make use of the NCRMS.
- All irradiation equipment has to be requalified at least every five years or according to an inspection and control program as described in the chosen construction code (e.g. ASME III imposes a test program distributed over a period of 10 years).
- If an installation is to be put out of service for a long period, a preservation program for regular checks is made. The operational limits and conditions are adjusted. Appropriate alarms are kept operational.

2.5. Dismantling, PIE and Disposal

After completion of the irradiation, the in-pile section will either be transferred to the hot cell or stored in the reactor pool. In case of a fuel irradiation, the fuel is allowed to decay sufficiently (e.g. BR2 fuel is transferred to the canal after a decay period of 100 days – transfer to the hot cell can be done earlier if the scrubber is put in operation). It has also to be verified that the temperature would not rise to unacceptable values when the experiment is transferred from a wet environment to the dry atmosphere in the hot cell.

The PIE is done according to a program, established by the experimenter before the start of the irradiation program.