THE RESTART OF THE BR2 REACTOR AFTER ITS THIRD REFURBISHMENT

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ABSTRACT

From March 2015 until July 2016, the BR2 reactor underwent its third refurbishment operation. The reactor was returned to service successfully on July 19, 2016, according to the announced planning. In preparation of the restart, a number of recommissioning tests has been performed in order to validate the changes made to the reactor and its supporting system before returning to full-power operation. These tests included following items: hydraulic testing of the new reactor core and functional testing of the primary cooling circuit after revision of one of the main coolant pumps, nuclear measurements of the nuclear behaviour of the new Beryllium matrix at zero power and low power and functional testing of the refurbished secondary cooling system. This paper describes the findings of the recommissioning tests of the BR2 reactor. After a successful restart, the reactor has run for 3 cycles in 2016, retaking its key position in the global supply of medical radio-isotopes. In the mean time, the experimental devices for the reactor are updated in order to meet the demands of the research community for the coming decade. The BR2 operating license has been reviewed in the framework of periodic safety reassessment, the results of which were reported to the safety authority in July 2016. With this review, the base is set for at least one more decade of operation of the BR2 reactor.

1. The third refurbishment of the BR2 reactor

The BR2 materials test reactor has undergone its third refurbishment in the 2015-2016 period and has resumed its operation on July 19 2016 for its next period of continued service to the nuclear research community and industry. 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 and up to 600 W/cm² in experimental-set ups cooled by the primary water.

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

- Irradiation positions inside fuel elements. The standard fuel elements (F1) are tubular with 6 concentric tubes, each made of 3 circular formed fuel plates. In the centre of the fuel elements, there is space (diameter 25.4 mm) for irradiation devices. If more space is needed dedicated 5 plate elements (F2) (diameter 32 mm) can be used. 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 (R): 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 the 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.

Table 1: typical flux values in different types of irradiation channels in BR2

Channel type	thermal flux range (10^{14}n/cm²s)	fast flux range (10^{14}n/cm²s) (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*
R	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.

The third refurbishment programme of the BR2 reactor was defined in accordance to the analysis results of the plant asset management programme. This programme replies to the requirements of the periodic safety reassessment of the BR2 reactor, submitted in July 2016.

The refurbishment programme included the replacement of components prone to ageing (such as the Beryllium matrix, underground piping and electronic and instrumentation components), major maintenance and inspection campaigns (reactor vessel and primary loop, primary pumps, ventilation ducts, hot cell, …) and upgrades of systems in order to comply to modern safety requirements (improved testing and inspection capabilities, higher independence and defence in depth, as well as higher resistance to external events, as postulated in the stress test).

As the focus point of the refurbishment programme involved the replacement of the entire reactor internals, a requalification programme was defined and executed before the permission to resume routine operation could be obtained. The BR2 reactor resumed operation on July 19, 2016 and the 3 operating cycles for 2016 were executed according to schedule.

2. The recommissioning programme of 2016

2.1. Geometric requalification of the matrix

The reactor internals consist of 79 channels, in which fuel elements, control rods and experiments are inserted (see figure 1). These channels consist of a central Beryllium block, upper and lower stainless steel extension pieces and upper guide tube and lower support tubes. The Beryllium parts have a central cylindrical cavity (except for the 12 “S” pieces, which serve as positioning reference for all the channels). Following the design specifications, the clearance between two beryllium elements is of the order of 0.1mm, in order to force the primary coolant flow through the irradiation channels and optimise the moderating effect of the Beryllium metal. The stainless steel extension pieces contact the neighbouring channels through contact springs and provide mechanical stability to the matrix. The lower extension tubes are welded to the lower extension piece and are positioned in the core support plate. The upper extension tubes are freely inserted in the top extension pieces and connect to the access of the irradiation channels in the reactor top cover. They allow also for thermal expansion of the irradiation channels during service.

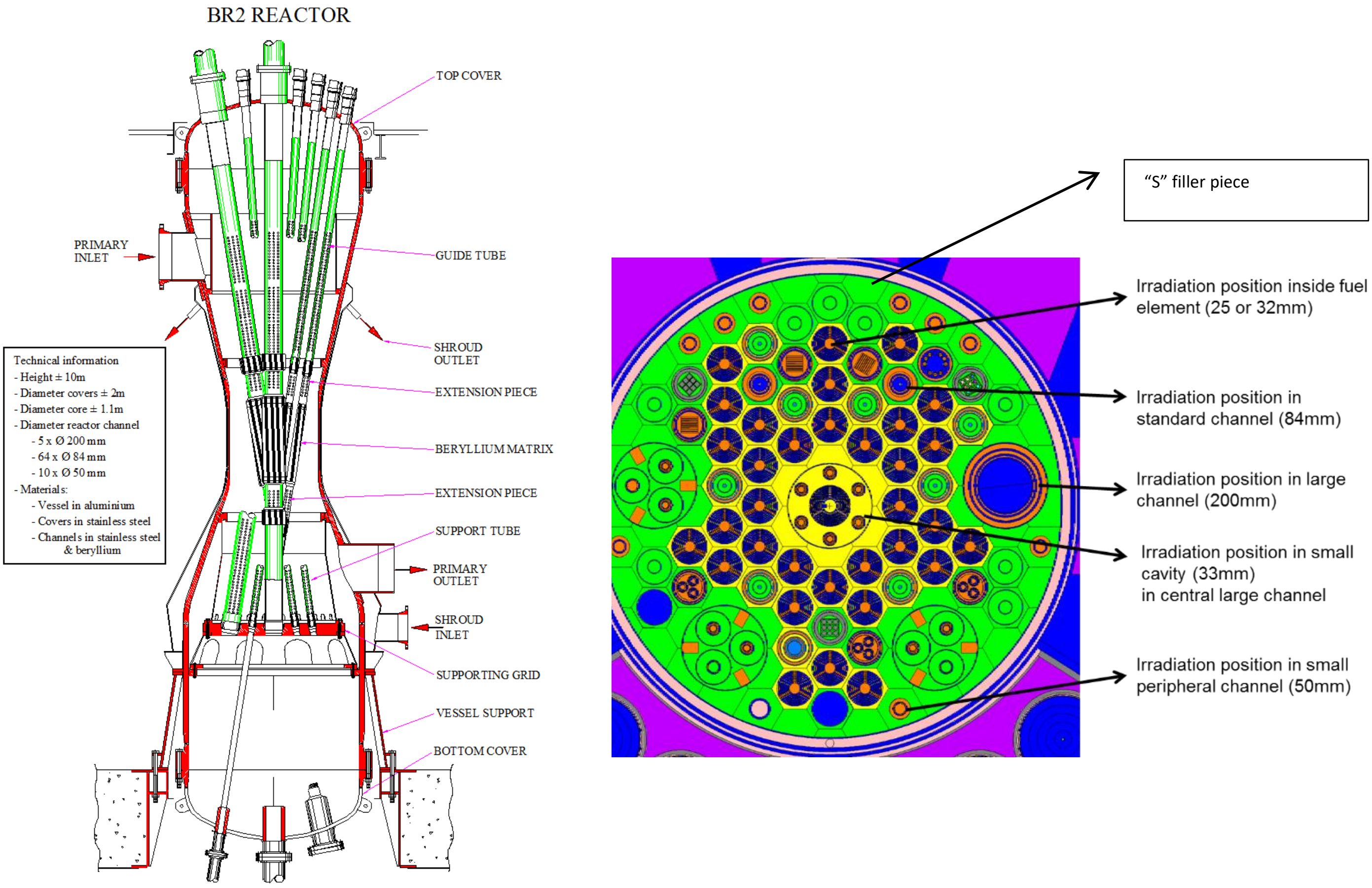

Figure 1: general lay out of the reactor vessel and internals of the BR2 reactor (left) and cross section of the core at mid plane (right).

The matrix is qualified from the geometrical point of view in different stages:

- On the component level, each component is verified to comply to the dimensional specifications of the design. This verification is part of the factory acceptance tests for the components.

- On the channel level, the alignment of the composing parts is verified with go--no-go calibres in order to verify the straightness of the channels and validate the reference inner dimensions of the channels for design purposes of future experiments.

- On the matrix level, the full set of channels is validated by assembly in a mock-up vessel in order to demonstrate the compatibility of the matrix with the reactor vessel. At the start of this stage, the new S-parts are installed in the mock-up vessel with the same spacing as the old pieces, which was measured in the BR2 vessel prior to removal of these parts from the vessel. Instruments, calibrated to the same calibration parts as the in-vessel measurement devices, allow to reproduce the position of the old S-pieces within +/- 0.1mm. A positive tolerance towards the theoretical distance between the S-parts in the vessel is imposed, so some margin exists in order to load the matrix parts. The open space is filled up due to the action of the leaf springs on the extension pieces of the channels. After acceptance of the new matrix in the mock-up vessel, the procedure was repeated in order to install the new S-pieces in the reactor vessel, ensuring the alignment between the new reactor channels and the reactor top and bottom cover penetrations. The final check on the reloaded internals is the stability of the top cover flange bolting and the diameter and straightness of the recycled top extension tubes.

2.2. Hydraulic requalification of the reactor and primary circuit

In parallel with the replacement of the reactor internals, one of the main primary cooling pumps had been revised in order to evaluate the general condition of the pump after over 50 years of service and to demonstrate the feasibility of such operation. Spare parts were manufactured according to the original specifications and the axis, rotor and seals were succesfully replaced. Also, a spare pump was acquired in order to serve as spare part in case of pump failure, reducing the replacement period, in line with the recommendations of the plant asset management programme.

After closure of the reactor and the revised primary pump, the primary cooling loop was inspected for leaks. The reactor was loaded with control rods, experimental devices and beryllium plugs in order to perform hydraulic tests to demonstrate the capacity of the primary circuit to deliver the required coolant flow and that the primary circuit conforms to the leak tightness criteria.

2.3. Nuclear requalification

The nuclear requalification was aimed at verifying the functionality of the nuclear instrumentation and safety systems of the reactor after the long shut down as well as the validation of the reactor core model with the fresh Beryllium matrix. The main difference in the nuclear characteristics of the reactor were expected to arise from the fact that the old beryllium matrix (Matrix 3) was neutronically poisoned by ^{6}Li and ^{3}He, while the new matrix (Matrix 4) does not contain any ^{6}Li and ^{3}He yet. However, by the use of irradiated Be plugs loaded in reflector channels, some neutron poisons are carried over to the reactor core with the new matrix. Additionally, the two remaining In-Pile-Sections of the CALLISTO loop were removed from the reactor core during the refurbishment. Given the fact that the construction material used for both IPSs at the core level was stainless steel, there was a reactivity effect to be expected by the removal of these IPSs.

The actual measurement programme consisted of the following parts:

For the unloaded core:

- check of the nuclear safety chains of the reactor control room according to the standard procedures
- measurement of the drop times of the shim-safety rods without primary flow

The checks provided sufficient proof of the operation of the safety system at zero power to allow the loading of fuel in the reactor.

At zero power:

Load the reactor core with a critical configuration of fuel elements, control rods and regular experimental devices in a safe way, validating the criticality prediction of the reactor core model. Since the nuclear characteristics were not yet determined experimentally, as was the case before the beryllium replacement, as an extra precaution, the critical approach with measured follow-up and forecasting of the reactivity value was executed with the last 12 fuel elements to be loaded instead of the last 6 fuel elements (the latter being the common practice during regular reactor cycles). After loading of the fuel, the critical height of the control rods was determined, as well as the anti-reactivity value of each control rod. Also the positive reactor period of withdrawing the control rods was measured. Each measurement is then compared to the predictions of the core physics model.

With pressure drop sensors, the pressure drop in two fuel elements was measured with variable flow and compared to previous measurements with the old Beryllium matrix. In addition, the control rod drop times were verified (according to the standard procedure) and the reactor period was measured with nominal primary flow. Finally, there were measurements of characteristics of new loading elements as preparation of possible future modifications.

The conclusions of the tests were that the critical height of the control rods prediction was sufficiently accurate (569mm measured vs 580mm predicted). The total anti-reactivity weight and the differences between the control rods were as expected from the model (12.58$ measured vs 12.62$ predicted). A small difference in axial distribution of the control rod anti-reactivity worth was noted (see figure 2). This is attributed to the elimination of the Be poisoning from the old matrix, which was proportional to the axial fluence profile. However, this small difference has no safety impact.

The nuclear measurement chambers all reacted in coherent ways; both the start-up chambers as well as the neutron flux measurement chambers gave similar signals to the situation before the Beryllium replacement. The linear ionisation chambers, protecting the reactor against overpower at start-up and ramping to nominal power showed a lower signal and the reaction of the chambers was not equally proportional for all chambers during the SCRAM tests of the control rods. One ionisation chamber showed a high level of noise due to the low power at the zero-power tests (also due to the low expected intensity of the photoneutrons because of lower radio-activity in the irradiated fuel elements after 16 month shut-down, resulting in a weaker neutron start-up source).

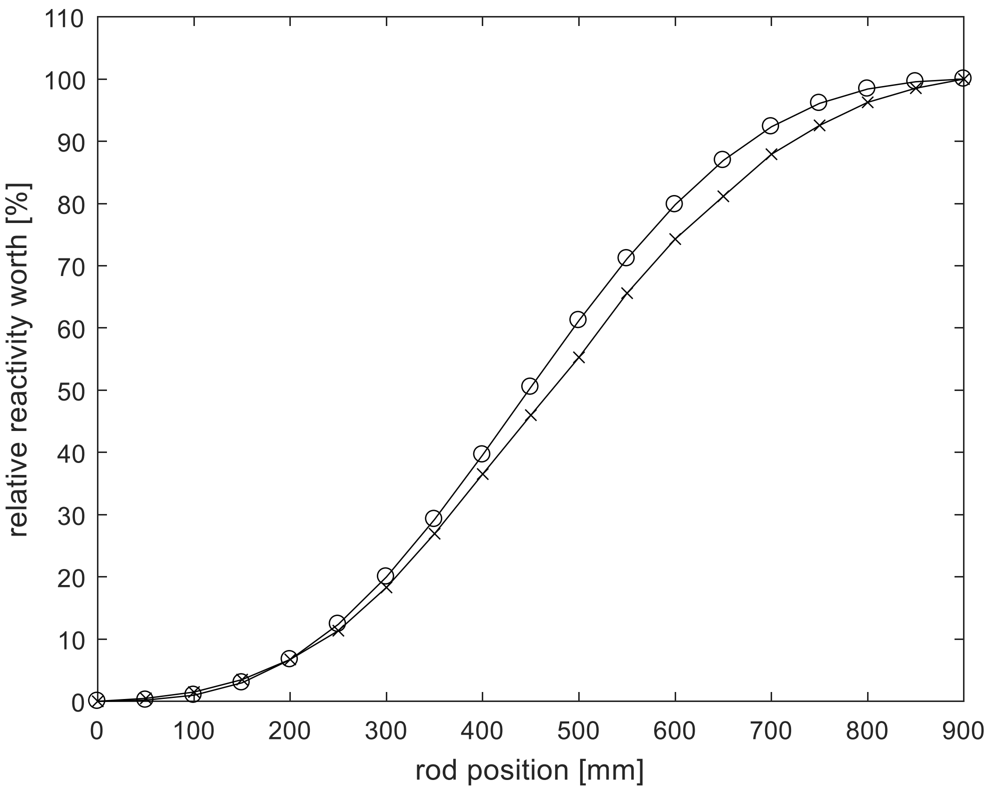

Figure 2 Evolution of the relative axial reactivity evolution of the control rod bank: o-markers common evolution before beryllium matrix replacement, x-markers as measured after the beryllium matrix replacement.

At low power (from 2 to 20MW):

- Full functional check of all systems of the reactor and coolant loops.
- Verification of integrity of pre-irradiated fuel elements at low power.
- Standard procedures for core load configuration acceptance and confirmation of the load characteristics from modelling.

The start-up to low power was initially limited due to a low signal of the linear ionisation chambers, preventing the increase in power. As noted for the zero power measurements, the chambers needed careful repositioning and revision in order to reduce noise and increase the signal. The positioning of the chambers proved to have great impact on the signal level at the lower decades of the measurement span (one order of magnitude change in signal with 5 to 10 cm change in position). The correction of the alignment was effective to normalise the functioning of the linear chambers of the reactor. Subsequent testing at low power allowed to identify a number of settings issues with renewed electrical installations. The fuel elements were investigated visually and by wet-sipping after the low power operation (maximum power density 110W/cm², compared to 470W/cm² as nominal maximum) and showed no sign of degradation after the 16 month storage.

At full power (56 MW):

Verification of predicted fluxes by activation dosimetry in fuel and reflector channels. The analysis of activation samples was targetted at determining the integrated reaction rates over the 21 day reactor cycle for both the reactions ^{59}Co (n,γ) $\rightarrow$^{60}Co (thermal neutrons) and ^{54}Fe (n,p) $\rightarrow$^{54}Mn (fast neutrons). The average deviation between the fluences deduced from measurement and the values calculated were 6.4% and 8.7% for the thermal and fast neutron reactions, respectively. Additional dosimetry measurement campaigns are carried out in following cycles in order to further analyse the origin of discrepancy between measurement and calculation.

3. Operation of the reactor in 2016

The BR2 reactor was scheduled for 3 operation cycles in 2016, totalling 10 weeks of operation. The scheduled operation time was realised for 100%, although a number of issues still emerged from the different refurbishment activities. All of these were handled without impact on the availability of the reactor, except for the failure to start all required main pumps in the secondary loop at the start of the first reactor cycle on July 19, 2016. The cause of this issue was the incompatibility between the standard settings of the power transformers and the switchboards in the feed lines for the secondary pumps. As these can only be fully tested at full power conditions, the issue was not detectable during the low power tests. The first cycle therefore started with about 10 hours of delay. For cycle 2/2016, an additional operating day was inserted in order to respond to the shortage in radio-isotope irradiation capacity in Europe in October 2016. In total, 357 targets were irradiated for ^{99}Mo-99 production in 2016.

After the restart of the reactor in July 2016, a number of refurbishment activities were continued during regular shut-down periods. The main activities were upgrades of the electrical system (project planned to extend until 2019), dismantling and waste characterisation of obsolete out-of-pile equipment, corrective and preventive replacement of all seals in the new secondary piping system and preparation to replace buried piping for evacuation of spills from the spent fuel storage channel (outside reactor building).

4. Operation outlook for 2017

The operational schedule for 2017 has been defined in close collaboration with the main stakeholders of the BR2 reactor. The schedule consists of 6 operating cycles, totalling 21 operation weeks. This schedule was defined in order to tackle the challenges in the global isotope supply chain after the closure of the OSIRIS reactor and the end of commercial ^{99}Mo production at the NRU reactor. By maximising the operational availability of the BR2 reactor within the current limits of the license, a significant contribution to the security of supply of ^{99}Mo and other radio-isotopes is made.

From the experimental point of view, the introduction of 2 new experimental rigs is scheduled for the second half of the year. These rigs target the irradiation of materials in support of two R&D areas:

- The HTHF device (High Temperature, High Flux) targets the qualification 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/cm²s, E>0.1MeV). This device has a dedicated in-pile section for each irradiation demand, but has a generic design. 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 design of the rig is such that the irradiation temperature range is influenced by the design, allowing some flexibility to set and control the irradiation temperature by electrical heating and adjusting the inert gas pressure inside the rig in order to adjust the heat loss rate. The first irradiation project is focussed on tungsten irradiation at 800°C to achieve 1dpa. 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 RECALL (replacement of CALLISTO) targets the irradiation of light water reactor pressure vessel materials in order to address long term operation issues. This device is reusable and has the unique feature to offer stable irradiation temperature (+/- 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 temperature control system is able to preheat the specimens up to the irradiation temperature before the start of the reactor by pre-heating the water which is injected into the in pile section, containing the specimens. Upon the start of the irradiation, the electric power is reduced to compensate for the nuclear heating. The stability of the irradiation temperature is reached by setting the inlet temperature of the water in the rig slightly above the saturation temperature and keeping constant pressure, corresponding to the boiling pressure at the desired temperature for the specimens. The heat input in the specimens is then mainly evacuated by boiling at constant temperature. If needed, cold water is injected in order to control the steam fraction so heat transfer occurs in a stable mode (no slug flow).

5. Conclusions

The refurbishment of the BR2 reactor has been successfully completed and the reactor was restarted according to plan on July 19, 2016. The main operation of this refurbishment was the replacement of the reactor internals, including the beryllium matrix. The new beryllium matrix was qualified in different steps, validating the design and production from the geometrical, thermal hydraulic and nuclear point of view. Gradual power ramp up tests have been performed in order to verify and optimise nuclear instrumentation, electric power and cooling loop settings and modifications. Due to the interlocks and physical limitations, specific systems and functions proved to be testable only above certain power thresholds.

The reactor resumed full operation according to planning in 2016 and now plays a key role in the global safety of supply for radio-isotopes. In the course of 2017 a significant upgrade of the available tools for material irradiation for research purposes is expected.

6. References

[1] S. Van Dyck, W. Claes, P. Leysen "The third refurbishment of the BR2 reactor", RRFM-IGORR conference procedings 2016, Berlin, March 13-17 2016, European Nuclear Society, p 498 -508.