# IRRADIATION OF MATERIAL TEST REACTOR FUEL AT THE BR2 REACTOR

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The BR2 reactor, operated by the Belgian Nuclear Research Centre SCK CEN in Mol, Belgium, is a high performance reactor with ample capabilities for material testing. An important type of material testing is the irradiation of fuels for use in test and research reactors. Such irradiation tests are typically performed directly in the primary coolant of the BR2 reactor, which is circulated in a closed loop, pressurized to 1.2MPa in order to provide a capacity for high heat fluxes. Various irradiation vehicles can be loaded in the reactor core, allowing to irradiate fuels either as individual plates, in the standard geometry of the BR2 driver fuel elements or as prototypic elements for other reactors. This paper focusses on the recent progress in qualification of high density fuel, based on low enriched uranium silicide, for high performance reactors such as BR2 and the preparation of a new generic irradiation device, designed to be able to irradiate prototypic fuel elements of different geometry in adaptable hydraulic conditions inside BR2.

## 1. The BR2 material test reactor

The BR 2 reactor is a high flux testing reactor for materials. It was designed by the Nuclear Development Corporation of America (NDA) and operated by the Belgian Nuclear Research center SCK CEN since 1963. The high performance of the reactor is achieved by the combination of the following factors:

- High overall cooling power: the primary loop can evacuate 100MW thermal power from the core. The secondary loop has a capacity of 125MW, 25 MW can be evacuated by an independent loop, available to experiments in the reactor building.
- A compact core design: the core height and diameter are about 1 m each. However, in order to maintain good accessibility, the reactor channels are arranged in a hyperboloid of revolution (see figure 1). This arrangement provides good access to the channels at the reactor cover, which has a diameter of 2 m.
- The design of the fuel: the fuel is of plate type, with a standard fuel element consisting of six concentric cylinders with an outer diameter of about 80 mm. Due to cooling by pressurized water at high flow rates, a heat flux up to 470W/cm² is allowed in standard operation.
- The choice of materials: the irradiation channels are constructed in metallic beryllium at the core level. The reactor fuel is metallic and highly enriched. The combination of these factors yields a highly efficient neutronic design. The reactor vessel has been constructed in aluminum, as initially, the design of the installation included neutron beams. In addition, the primary loop and heat exchangers have been constructed in aluminum alloy.

The resulting design characteristics are summarized in table 1. The available volumes for irradiation depend on the irradiation channel and the design of the irradiation rig. The beryllium channels exist in three sizes: 200, 84 and 50 mm diameter. The fueled zone is 800 mm long, while the beryllium matrix is 1m long.

The reactor is operated in cycles up to 35 days long. The configuration of the reactor and the overall power are optimized in order to satisfy the requirements of the different users or irradiations and to obtain the scheduled cycle length. The number and burn up of fuel elements, their position and the number and position of the control-shim rods are selected to accommodate the required number of irradiation devices and the target flux level.

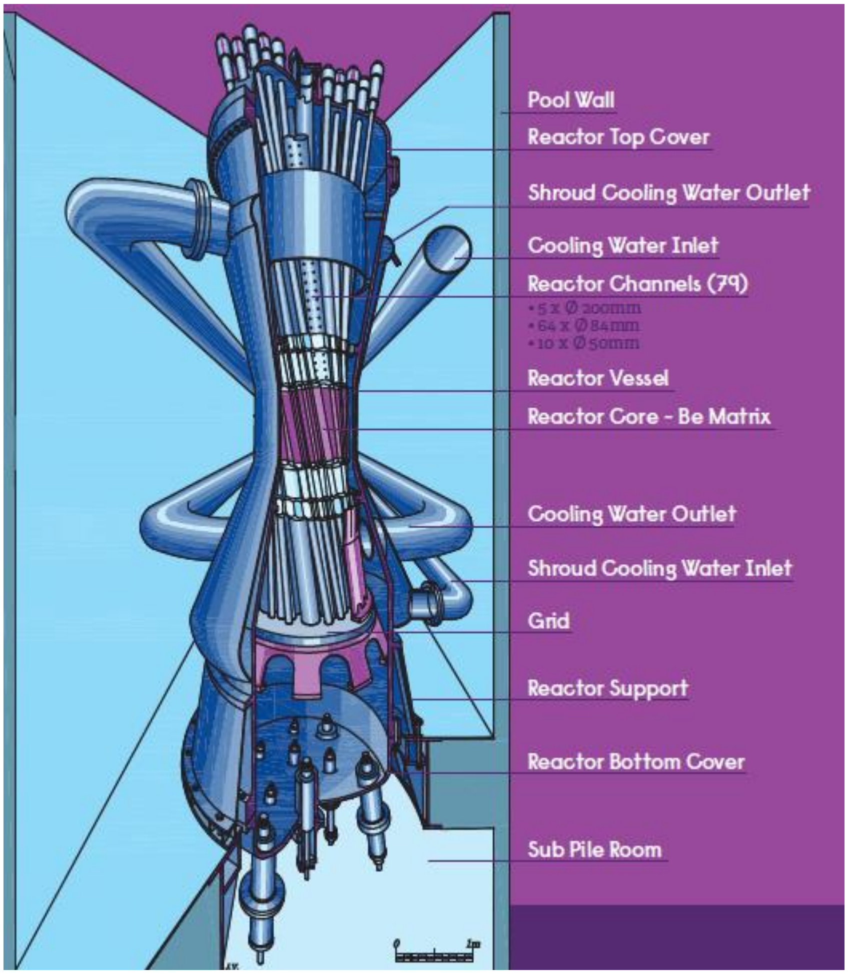

Figure 1: Lay out of the BR2 reactor, with visualisation of the 79 irradiation channels, the primary piping and the shroud cooling.

**Table 1: Nuclear characteristics of the irradiation channels**

| 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* |
| 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.

The main applications currently active at the BR2 reactor are [1]

- Production of radio-isotopes by fission of uranium: with 7 irradiation devices, the BR2 has the highest irradiation capacity for producing $^{99}$Mo among the OECD member states. Up to 9100Ci of 6 day calibrated $^{99}$Mo can be produced per week; with an annual availability of the reactor of 200 days, over 230 000 Ci annually can be produced.
- Production of radio-isotopes by activation: either full cycle irradiation in primary water can be performed or irradiation in thimble tube devices for shorter duration. The most important isotopes are $^{177}$Lu and $^{192}$Ir. Due to the high performance of the BR2, specific activity levels up to 1000Ci/g can be achieved in iridium.
- Neutron transmutation doping (NTD) of silicon: the BR2 is equipped with two set-ups for NTD. Crystals up to 5-inch diameter can be irradiated in vessel (batch length up to 800 mm); five positions for irradiation of 6 or 8-inch diameter crystals are available in a pool side facility (batch length of 500 mm). The total annual irradiation capacity is about 40 tons (15 in vessel, 25 in pool side facility).
- Irradiation testing of fuel for test reactors: the BR2 is a key facility in the development of fuels for test reactors. Standard irradiation baskets for plate irradiation are available and a proven experience exists for the irradiation of prototype fuel assemblies. For such experiments in the primary coolant of BR2, heat fluxes up to 600W/cm² can be achieved.
- Irradiation testing of power reactor fuel: either steady state irradiation or transient testing in capsule environment is possible. The current focus is on transient testing for determination of cladding resistance to pellet clad mechanical interaction of pre-irradiated fuel segments from pressurized water reactors. Typical tests have 100% peak power increase up to levels of about 400 to 500W/cm. The maximal allowable heat flux in this device is 750W/cm, the typical ramp rate is 100W/cm per minute.
- Irradiation testing of construction and cladding materials: different capsules are available for irradiation of materials in water or inert gas. Designs with liquid metal environment have been applied also, but such capsules are not reusable. The

irradiation temperature in the different capsule designs can range from 50°C to 1000°C. The damage accumulation in one reactor cycle is typically from 0.05 dpa (in steel) to 0.1 dpa in a reflector position and up to 0.75 dpa when the irradiation capsule is inserted into the central cavity of a fuel element.

## 2. Experimental set-ups for material test reactor fuels

For the irradiation of plate type material test reactor fuels, different experimental rig types are available.

For flat fuel plates, a basket is available to insert up to 5 plates (61mmx970mm, 1.25mm thick) with dimensions which correspond to a full size plate for the BR2 fuel assembly. This basket is loaded in a standard 84mm diameter channel of the BR2 and the fuel plates are cooled directly by the primary water flow. The water gap between the plates is 6mm, the water velocity, resulting from the pressure drop condition over the core and the geometry is about 11m/s.

The position of the experiment and its surroundings are optimized in order to achieve the irradiation goals of the experiment in terms of power density and burn-up (see section 3). This experimental set up has no on line instrumentation capability; the loose insertion of the plates in the basket allows for visual inspection under water of each plate between irradiation cycles. The basket is also compatible with the wet sipping installation of the BR2 facility, so the fuel plates can also be tested for fission product release after the irradiation cycle.

The FUTURE basket is designed to be operated up to the peak heat flux allowed in the primary coolant of the BR2, 600W/cm². The maximum allowed fuel content is 23 g of $^{235}U$ per plate. This basket has been successfully used for a number of irradiations to qualify low enriched uranium based fuels for research reactors.

SCK CEN is designing a rig to support the qualification irradiations of research reactor / material test reactor (MTR) fuel. During the final phase of qualification of MTR fuel, a fuel assembly irradiation is typically performed composed of formed (bended) fuel plates that are swaged (mechanically crimped) into side plates. The conceptual design of the generic test assembly (GTA) is MTR formed fuel plates, swaged into a box-shaped MTR-type fuel element which is inserted into a basket. These baskets convert the box-shaped fuel element to a cylindrical assembly that is intended to be irradiated in 84 mm channels like BR2 fuel elements and FUTURE-type baskets. The plates will be directly cooled by the primary coolant, which is flowing through the BR2 core, driven by a 0.32MPa pressure drop. This results in a 10m/s flow velocity on the fuel plates in the BR2 fuel assemblies. For the GTA, the geometrical design is somewhat flexible, so the local flow velocity may vary. This flexibility allows to change the number of fueled plates in the test or the coolant gap between the plates (see figure 2). The standard design can be used to test fuel plates up to a heat flux of 470W/cm², while tests up to 600W/cm² can be performed, given a detailed thermal hydraulic evaluation to demonstrate margin against departure of nucleate boiling in design base transients of the BR2 core.

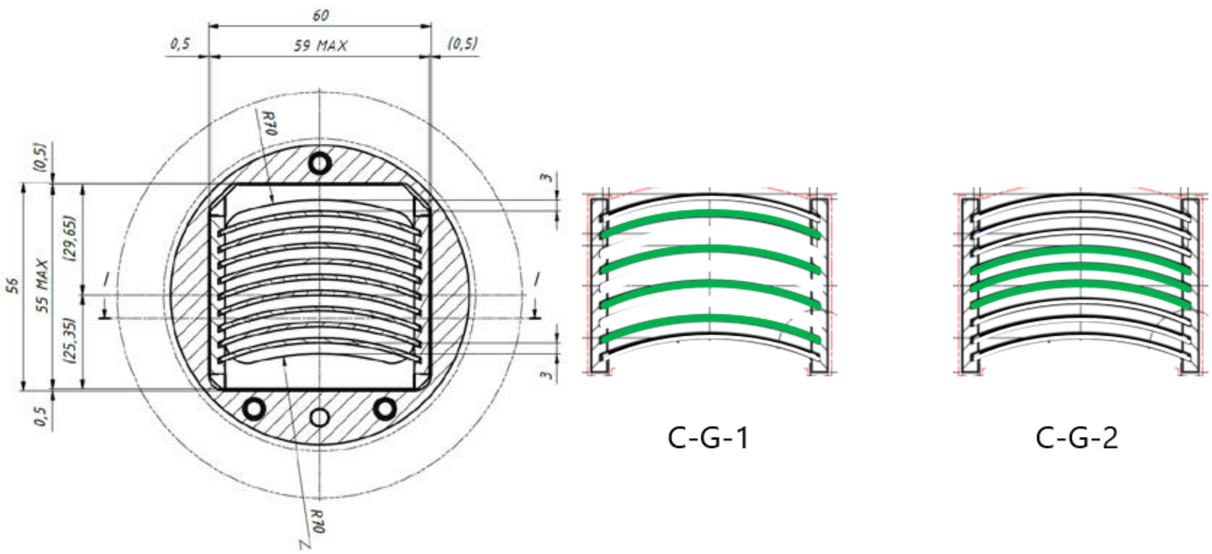


Figure 2: design of the generic test assembly cross section (left); the variants to the right allow for larger coolant flow gaps and less plates in the fueled plates.

For BR2 reactor specific qualification irradiations (or reactors having very similar thermal hydraulic conditions), a standard BR2 fuel assembly can be produced with the outer plates replaced by the experimental fuel plates. The irradiation experiment of such mixed element requires less analysis of the thermal hydraulic aspects (as the element geometry is qualified to be irradiated to 600W/cm² in an experiment) but does obviously not offer flexibility in plate design. It also needs to be manufactured by a qualified supplier of BR2 reactor driver fuel.

The FUTURE basket, GTA and mixed element are all experiments, cooled by the unmodified BR2 primary flow. The primary flow of the BR2 reactor is controlled by the pressure drop over the core, which is set to 0.32MPa as standard condition. For standard BR2 fuel elements, this implies a flow velocity of 10m/s and pressure drop of 0.21 MPa over the length of the element. For experiments requiring higher pressure drop (for example due to smaller plate spacing than the 3mm of the BR2 driver fuel), an additional loop can be installed, providing a larger pressure drop by extracting primary water from peripheral channels and injecting it in the test channel. This concept has been implemented for the qualification irradiations in the EVITA project [2] [3]. The Enhanced Velocity Test Apparatus (EVITA) loop allows to generate a significantly higher coolant velocity (up to 15m/s) despite the smaller fuel plate spacing in the irradiated fuel element (less tahn2 mm instead of 3mm in the BR2 driver fuel). The total power evacuated by the loop can amount to 5.2MW and a maximum power density of 520W/cm². This allowed to achieve an element average burn up in the tested fuel element of 60% in 20 weeks of irradiation. The specific requirements of the experiment necessitated a number of additional safety provisions:

- Forced cooling in the loop needed to be available for 1 hour after reactor stop. Given the power consumption of the loop's pump, an additional UPS was installed inside the reactor building to provide this power instead of connecting it to the emergency power supply system of the reactor.
- Automatic actions to stop the reactor were implemented upon detection of loss of flow or pressure in the loop.

- A specific loading procedure was applied in order to verify the reactivity effect of the loop and fuel because of the high quantity of fissile material, loaded in the center of the reactor.

The concept of a fully submerged loop (see figure 3) in the reactor pool offered a number of safety benefits:

- There is no additional risk of loss of coolant or loss of cold source (the reactor pool).
- No large additional shielding due to water activation in the loop or incidental fission product release from the experimental fuel.
- The BR2 coolant pumps and the loop cooling pump are complementary for residual heat removal from the tested fuel element, so no redundancy in the loop was required.

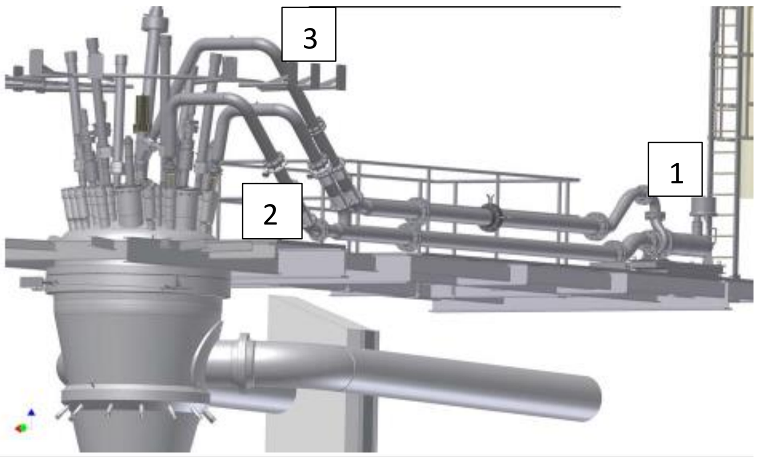


Figure 3: the EVITA loop installed in the BR2 reactor with the pump (1), the 2 feed lines and the discharge line (3) connected to the central reactor channel, containing the test section.

For irradiation conditions with reduced flow, the MUSTANG device can be used. This device offers an option to reduce the flow by an adjustable restrictor in the top section of the device. The device is inserted into a 200mm peripheral channel of the BR2 and allows to load a basket with outer diameter of 145mm, containing a fuel element, prototypic for a research reactor. The allowable flow restriction is set by hardware before start of irradiation and is limited by safety analysis of the minimum required flow for the following cases:

- Loss of flow and pressure in the primary coolant of BR2, followed by SCRAM of the reactor and flow reversal to natural convection.
- Inadvertent closing of the restrictor during normal operation.
- Reactivity injection followed by SCRAM of the reactor.

All these cases are compatible with the prototypic irradiation conditions for high performance reactors such as the reactors of the Massachusetts Institute of Technology or the National Institute of Standards and Technology.
The basket in the rig is designed for the mechanical compatibility with the fuel element to be irradiated as well as to adapt the neutronic conditions to the desired power distribution and burn-up accumulation of the elements.

## 3. Irradiation conditions for experimental fuels in the BR2 reactor

In order to provide the proper irradiation conditions to the experiments and to analyse the results of the characterization of the irradiated objects, a numerical model of the experiments and the full BR2 core is used in order to optimize the load of the core to satisfy the requests of all irradiation clients. This model supports the design of the experimental rigs as well as

the preparation of the actual core configuration for the irradiation of the experiment. This model uses the MCNP code (version 6.2), in combination with a burn-up code (Aleph) in order to predict and track the evolution of neutron (and gamma) flux, heat generation and burn up accumulation.
The predicted irradiation conditions are reassessed after the actual irradiation cycle to take into account the actual burn up rate of the reactor core load in order to define the initial condition for any consecutive irradiation cycle of the experiment. In this way, the irradiation history of the experiment is integrated in order to obtain the distribution of power and burn-up distribution in the fuel. This can then be linked to the results of the post irradiation examinations of the irradiated fuel plates or elements. As approximation, the conditions at the beginning of cycle are considered to be representative for the entire cycle, which proves to be acceptable for the calculation of the average and peak values of fission rate and burn-up (uncertainty of about 5%). This approach is also validated by the comparison of the calculated reactivity of a fuel element as a function of calculated burn up (see figure 4). The effect of the burnable absorbers and uranium burn-up is also demonstrated by the comparison of the shim rod motion prediction versus measurement with different burnable absorbers in the BR2 driver fuel.
Figure 4 shows the integrated fission density (in $10^{20}$ fissions per cc of fuel) that was accumulated in a high density silicide dispersion fuel, irradiated for 3 reactor cycles, totaling 88 days of irradiation with a peak power of 427W/cm² and average total burn up of 55%.
More complex examples can be found in ref [6]

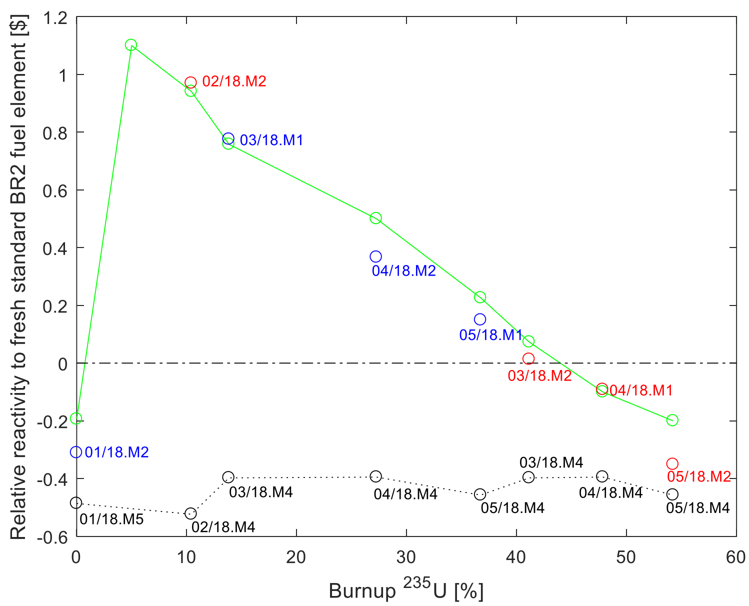


Figure 4: the calculated and measured effect of burn-up on the reactivity effect of an HEU BR2 fuel element with B and Sm as burnable absorbers versus Gd.

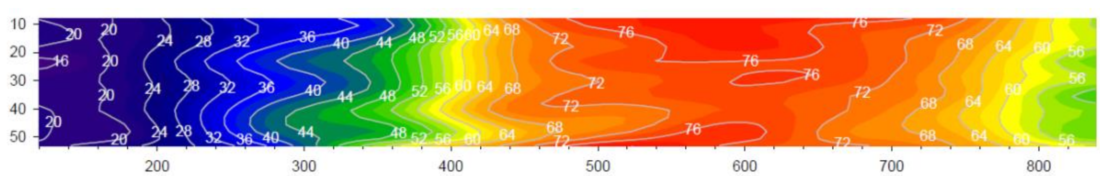

Figure 5: the calculated burn-up distribution in a high density silicide fuel plate, irradiated in the FUTURE basket for 88 days.

The thermal hydraulic conditions in the irradiation rigs depend on the irradiation rig selected and its operating mode. For rigs, irradiated in the undisturbed primary flow, the coolant flow is characterized by

- The pressure drop over the core, controlled at 0.32MPa
- The pressure at the outlet of the core, set above 1MPa
- The inlet temperature, controlled to be below 40°C
- The outlet temperature, maximum 57°C (although typically the temperature difference in the primary loop is about 10°C).

As mentioned before, this results in an average velocity of the water in the BR2 driver fuel elements of 10m/s.
Other rigs with flow control, such as the EVITA loop or the MUSTANG-R device, will exhibit different characteristics, based on the settings of the rig itself. Typically, these rigs are equipped with a measurement of the total power, generated in the rig.
The hydraulic modelling of the rig is also validated by measurement in ether mock-up loops or the reactor at zero power.

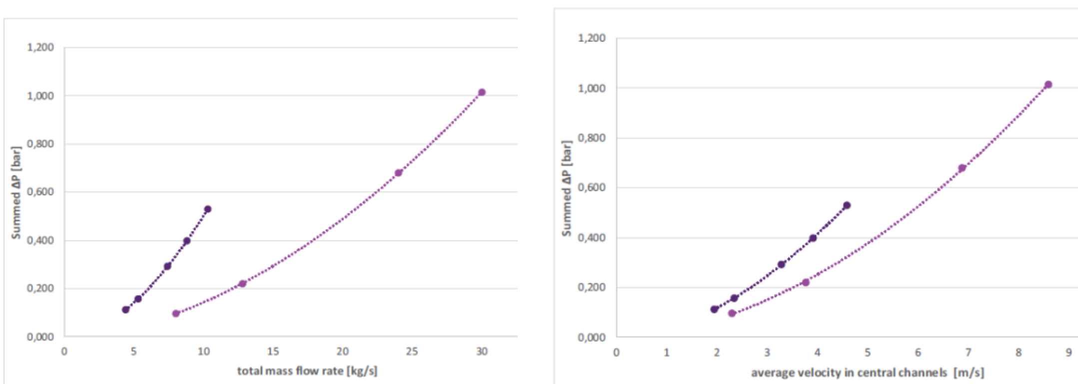


Figure 5: the calculated flow rate and velocity in 2 typical fuel assemblies in the MUSTANG-R device.

## 4. Summary and conclusions

This paper has highlighted a number of possibilities for irradiating experimental material test reactor fuel in the BR2 reactor. The reactor features allow for a wide range of irradiation conditions of individual fuel plates or experimental set-ups. For generic tests, individual plates can be irradiated in simple basket experiments in the primary coolant flow of the reactor. For qualification of production typical plates, mixed elements or generic test assemblies can be constructed to perform testing in high performance conditions, with heat flux peaks up to 600W/cm².
For more realistic test conditions for various fuel elements, the reactor can be fit with dedicated rigs which can accommodate fuel elements with dimensions, not compatible with the BR2 standard channels. For irradiating such devices, the 200mm channels are used and the local environment is adapted, such that both hydraulic as well as neutronic conditions can be created to provide suitable qualification conditions. This illustrates the unique combination of high

performance and flexibility of the BR2 reactor to support the development and qualification of material test reactor fuels.

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