BR2 FUEL EVOLUTION TOWARD SUSTAINABLE FUEL CYCLE

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In Memory of Edgar Koonen

BR2 Reactor
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ABSTRACT

This paper describes the evolution and the corresponding optimization process of the different types of fuel used at the BR2 reactor since the early beginning of its operation in the 1960s. The evolution of the BR2 fuel towards a sustainable fuel cycle is demonstrated by comparison of the reactivity vs burn-up evolution of the different types of fuel used in the past and present, or under consideration for future BR2 reactor operation. The burn-up and criticality calculations for each type of fuel are executed using an MCNP6 based methodology developed by the BR2 core load management unit. The paper also summarizes the main results and conclusions of tests and qualification irradiations performed at the BR2 reactor for several of these types of fuel.

1 Introduction

This paper describes the evolution and the optimization of the BR2 fuel since the start of the BR2 reactor operation in the '60s. The first fuel material, utilized until 1969, was UAl_4 alloy enriched at 90% ^{235}U with 244 g ^{235}U per standard BR2 fuel element. Later, the use of cermet composite UAl_x powder blended with aluminium powder allowed to increase the ^{235}U content to 330 g per fuel element and to add burnable absorbers (B_4C and Sm_2O_3) homogeneously mixed in the fuel meat. In a further step, the uranium content of the cermet fuel was increased up to the metallurgical limit of that time and now the standard BR2 fuel element contains 400 g ^{235}U.

Around 1994, the possible storage of HEU fuel from US-DOE origin has initiated an experimental program to use HEU reprocessed BR2 spent fuel. Fuel elements of type VIn C containing 330 g ^{235}U have been successfully fabricated at UKAEA and irradiated until a burnup of 47% to study the economy of a BR2 reactor cycle using BR2 reprocessed uranium. Another experimental program involved the fabrication of 72% ^{235}U enriched fuel with an increased density of 1.4 gU_{tot}/cc and 413 g ^{235}U per fuel element.

In the late 1970s, after the INFCE conference, concerns were raised about the nuclear proliferation potential of MTRs using HEU (>90% ^{235}U). In 1978, the Reduced Enrichment for Research and Test Reactors (RERTR) program was established by the US-DOE and operated by ANL in cooperation with the main suppliers of test reactor fuel and various test reactor operators. The first LEU (<20% ^{235}U) fuel studied was U_3Si_2 which allowed to increase the uranium density beyond 1.3 gU_{tot}/cc used for the HEU fuel. Feasibility studies in the 1980s have shown that, in order to maintain similar fuel and experimental performances, the density needed for the U_3Si_2 LEU fuel was about 7.2 gU_{tot}/cc. At that time and up to now, the highest experimentally tested uranium density of U_3Si_2 is 4.8 gU_{tot}/cc.

The presence of burnable absorbers in the fuel meat makes it difficult to recover the uranium from scrap material. Therefore, as an alternative solution, burnable absorbers were considered in various geometry designs out of the fuel meat, e.g. plates, wires or homogeneously distributed in the aluminium stiffeners of the fuel element. The joint efforts of BR2 & ANL resulted in an extensive feasibility study program in the framework of the conversion project of the BR2 reactor from HEU to LEU. This program started in 2007 and still continues today. Different high density fuels (U7-10Mo, U_3Si_2) in different fuel element geometries (BR2 standard geometry, 'COBRA' geometry), with various burnable absorber materials (inside fuel meat or outside fuel meat) have been considered as possible future fuels for the BR2 reactor.

The evolution of the BR2 fuel towards a sustainable fuel cycle is demonstrated by comparison of the reactivity vs burn-up evolution of the different types of fuel used in the past and present, or under consideration for future BR2 reactor operation. The paper also summarizes the main results and conclusions of tests and qualification irradiations performed at the BR2 reactor for several of these types of fuel.

2 BR2 Reactor Core Evolution Simulation with MCNP

2.1 Description of the BR2 Reactor

The Belgian Material Test Reactor BR2 is a strongly heterogeneous high flux reactor operated by SCK•CEN at the Mol site in Belgium. This tank-in-pool reactor is cooled by light water and has a compact HEU core (>90% ^{235}U) positioned in and reflected by a beryllium matrix. The beryllium matrix is an assembly of a large number of irregular skew hexagonal prisms forming a set of concentric twisted hyperboloid bundles around the central ∅200mm H1 channel. The reactor is presently operated at power levels of 50–100 MW for 130 to 150 full power days per year reaching thermal neutron fluxes of 1.2×10^{15} /cm^2·s and fast neutron fluxes of 1.0×10^{15} /cm^2·s.

2.2 3-D Geometry Model of the BR2 Reactor

A 3-D geometry and burn-up model of the BR2 core has been developed by the SCK•CEN reactor core load management unit using the latest versions of the Monte Carlo transport code MCNP [1,2]. The model is a complete 3-D description of BR2's concentric hyperboloid bundles of inclined reactor channels, whereby each channel is modelled separately with its individual position and inclination (see Fig. 1). The fuel assemblies, beryllium plugs, experimental devices and control rods loaded in the channels are modeled with the same level of detail. Fuel elements are composed of 18 fuel plates arranged in 6 concentric rings. The fuel region of each of the 6 fuel rings of each individual fuel element is axially divided into 10 material cells of 6 cm height plus 2 extra material cells of 8.1 cm height at the extremities.

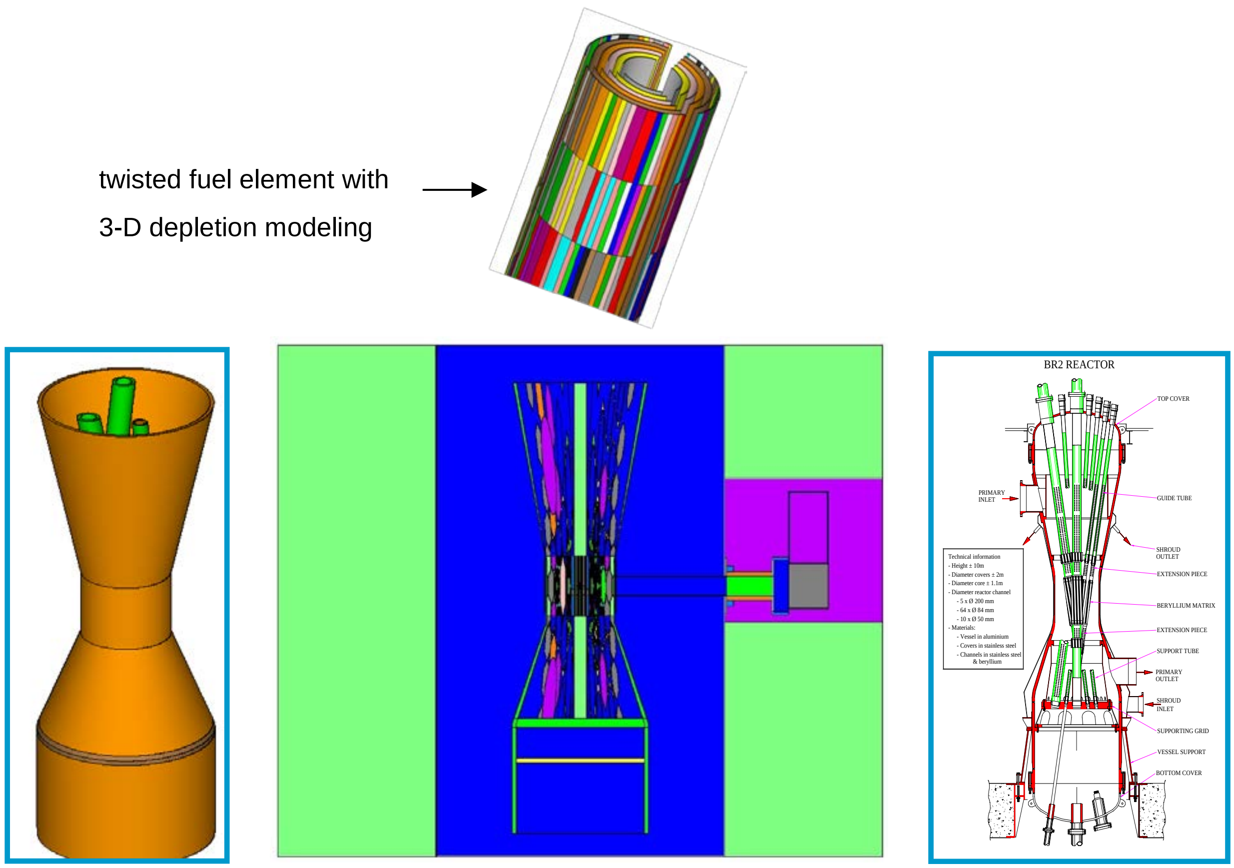
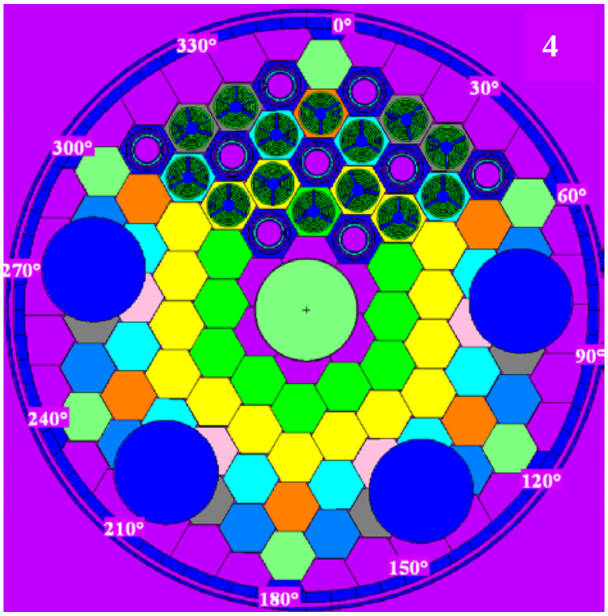


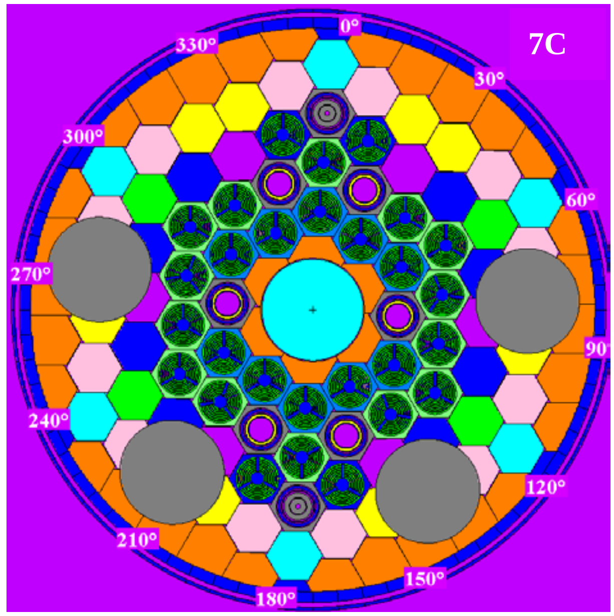
Figure 1. MCNP model of the BR2 reactor including the vessel and the bio-shield and embedded in the picture, a representation of the fuel cells of an inclined fuel element.

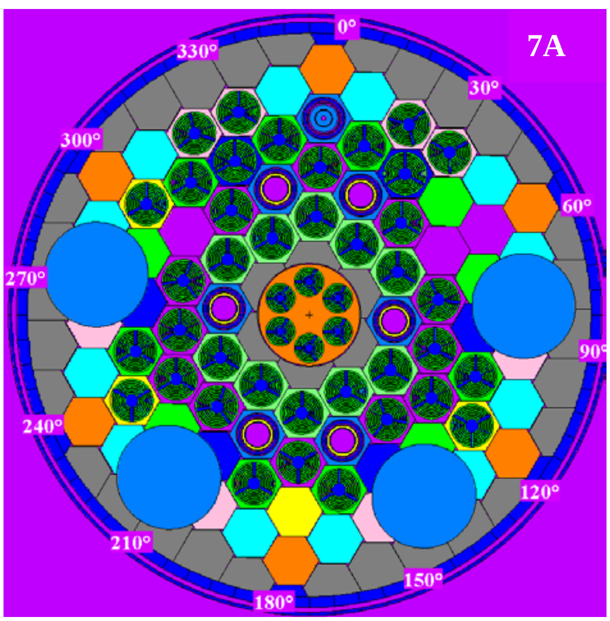
2.3 MCNP models of typical BR2 core loadings

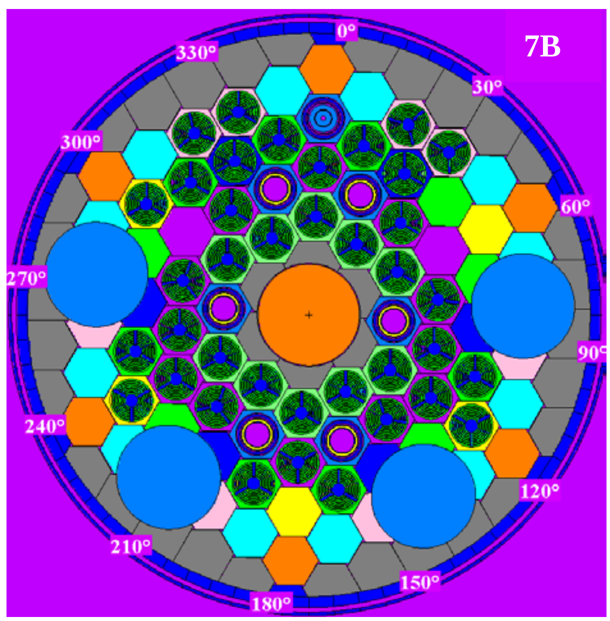
During the BR2 reactor operation with the 1st and the 2nd beryllium matrix between 1963 and 1995, about 200 to 300 reactor core loads have been assembled. To evaluate the neutron fluences accumulated in the Aluminium vessel, these core loads were grouped into 8 typical configurations (see [3-5]). The MCNP models of the 8 configurations are shown in Fig. 2, including the configuration 10N which is similar to the cores used during the 3rd beryllium matrix. The arrangement of the fuel elements, control rods and various experiments in the cores was determined on the information for the reactor core loads available in the documents of the BR2 archives. The fuel types used for the fuel elements of the 8 configurations are taken from [4-5]. The comparison between the neutron fluencies evaluated using the Monte Carlo method and the neutron fluencies estimated by deterministic, diffusion and experimental methods was reported in [3].

The core configurations used since 2016 during operation with the 4th beryllium matrix are shown in in Fig. 3. The left figure shows a typical configuration with 6 axial symmetrically placed shim-control rods and 30-34 fuel elements, similar to the configurations used matrix between 2011 and 2015 during operation with the 3rd Be-matrix. The right picture shows a new compact configuration with 4 shim-control rods and 20-25 fuel elements operating at a lower power, which was successfully tested during cycles 03/2017A.2, 04/2017A.3 and 05/2017A.2. Both cores have their advantages and disadvantages. The advantage of the compact core is that the PRF and DG irradiation devices are loaded in channels close to core center and receive therefore higher flux doses. Also, the compact core allows to save some fuel, however, highly burnt fuel elements (> 45% ^{235}U burn-up) are not suitable for use in this compact core. Therefore, a balanced use of both cores seems to be preferable for future BR2 reactor operation.









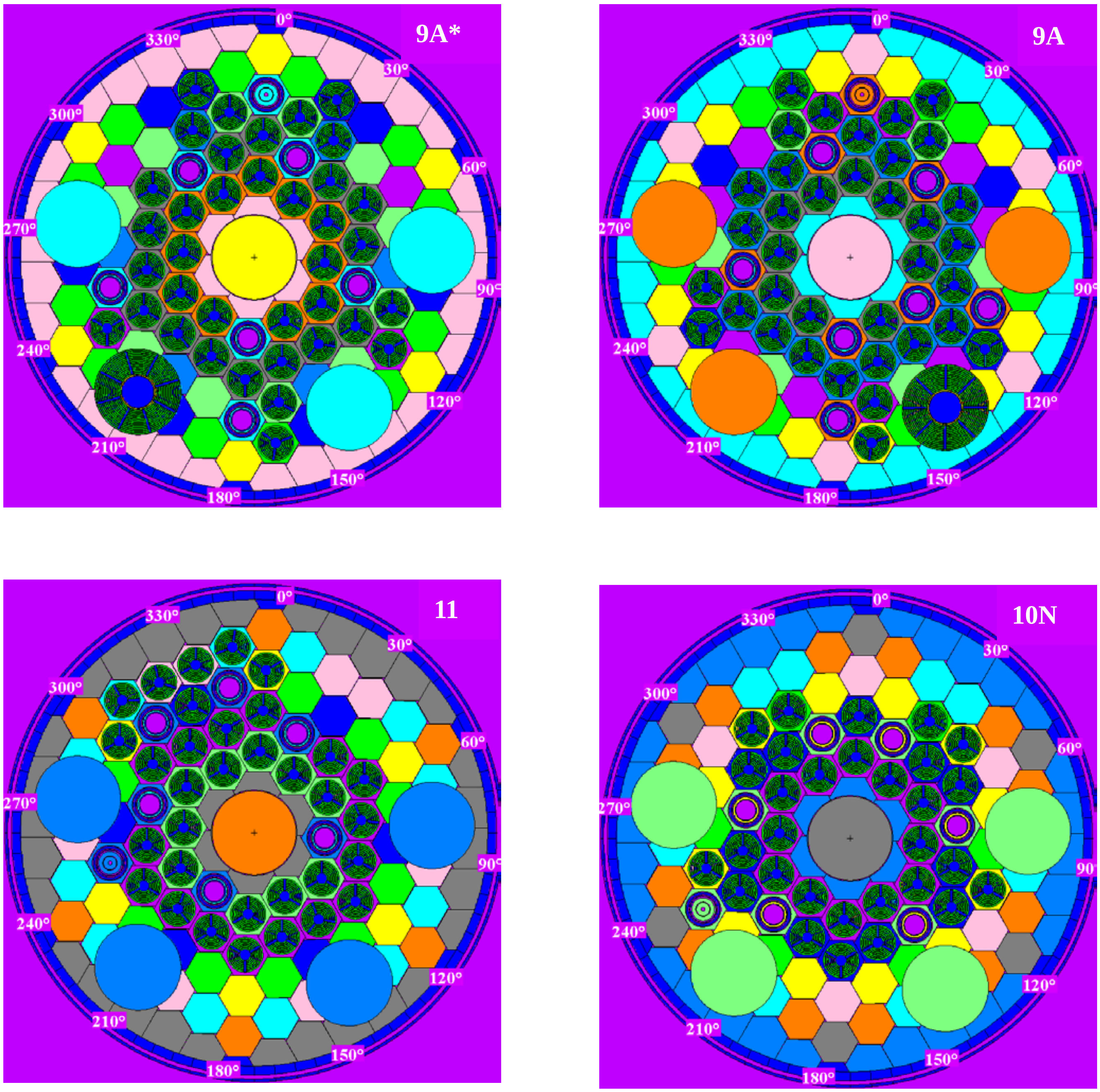


Figure 2. MCNP 3-D heterogeneous whole core models of 8 configurations used between 1963 and 1995 [4-5].

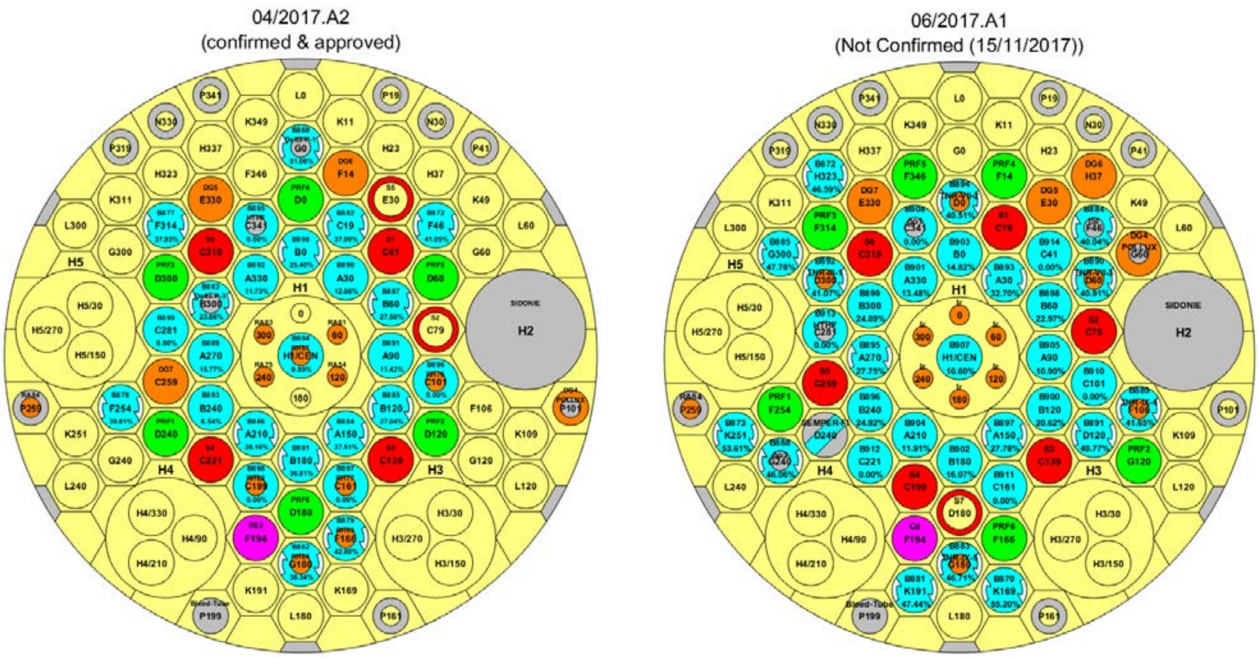


Figure 3. Typical configurations used with the 4th beryllium matrix: extended core (left) and compact core (right).

2.4 MCNP6 methodology

For burn-up calculations the MCNP6 model is coupled with CINDER90, which is included in the MCNP code. The credibility of the MCNP model was demonstrated by multiple comparisons of code predictions with available experimental data, such as control rod worth, neutron fluxes, gamma heating and linear power [6]. The burn-up and criticality capabilities of the different fuel types is calculated by MCNP6 in an infinite lattice. After that the fuel compositions with a ^{235}U burn-up between 0% (fresh FE) and 80% with 2% burn-up steps are distributed in the different fuel assemblies in the whole core 3-D MCNP model using pre-calculated power peaking factors. For details of the MCNP methodology developed by the BR2 core load management unit see Ref. [7].

3 Description of fuel parameters

The parameters of the different fuel types used during BR2 operation since 1963 are summarized in Table I. The HEU fuel (93% ^{235}U enrichment, 400 g ^{235}U per fuel element, with B and Sm as burnable absorbers in the fuel meat) labeled as VIn G is the standard BR2 fuel which is used since the '70s until now. Around 1994, the possible storage of HEU fuel from US-DOE origin has initiated an experimental program to use HEU reprocessed BR2 spent fuel. Fuel elements of type VIn C containing 330 g ^{235}U were successfully fabricated at UKAEA and irradiated till a burnup of 47% giving the parameters for studying the economy of a BR2 reactor cycle re-using BR2 reprocessed uranium. Another experimental program resulted in the fabrication of 72% ^{235}U enriched fuel with an increased density of 1.4 gU_{tot}/cc and 413 g ^{235}U per fuel element.
Other fuel types which were used in the feasibility studies for the conversion of the BR2 reactor from HEU to LEU are given in Table II.

A series of feasibility studies to convert the BR2 reactor from HEU to LEU fuel with different burnable absorber were performed from 2008 to 2011 [8-9]. The choice made for the new burnable absorber at that time was placing 36 cadmium wires in the 12 grooves of the 3 Al side-plates of a standard

BR2 fuel element. The optimum wire diameter was 0.4–0.5 mm for U-7Mo LEU (20% ^{235}U) with a density of 7.5–8.5 g U_{tot}/cm^3.

Table I. HEU fuel system parameters of fuel types used/considered for BR2 operation since 1963.

	VIn G (standard)	VIn A	VIn C	VIn E (test)	VIn E' (objectives)	VIn L (objectives)	VI H (ideal)
fuel type	UAl_x	UAl_4	UAl_x	UAl_x	UAl_x	U_3Si_2	UAl_x
Enr. [%]	90.0	90.0	90.0	72.0	72.0	19.9	90.0
Density [g U_{tot}/cm^3]	1.31	0.80	1.11	1.31	1.70	7.10	1.7
^{235}U mass [g]	400	244	330	330	413	480	520
U_{total} mass [g]	430	263	355	458	574	2412	578
Fuel meat thickness [mm]	0.508	0.508	0.508	0.508	0.508	0.508	0.508
Cladding thickness [mm]	0.38	0.38	0.38	0.38	0.38	0.38	0.38
Water gap [mm]	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Fuel meat length [mm]	762	762	762	762	762	762	762
Boron in form of B_4C [g/FE]	3.8	0	2.8	1.8	3.8	3.0	3.8
Sm in form of Sm_2O_3 [g/FE]	1.4	0	1.3	1.3	1.4	1.4	1.4

The highest density LEU fuel currently qualified is U_3Si_2 dispersed in an aluminium matrix with a maximum density of 4.8 g U_{tot}/cm^3 and 20% ^{235}U enrichment. Additional studies for the feasibility to convert the BR2 core with U_3Si_2 fuel type with various densities and few fuel enrichments (19.7% and 27.0%) have been performed in 2012–2013 [10]. Two series of studies have confirmed that the only at that time qualified U_3Si_2 fuel with a density 4.8 g U_{tot}/cm^3 (≤ 20% ^{235}U enrichment) was not feasible for the BR2 core conversion. The first series of studies performed in the past by ANL (Snelgrove, Deen, J. Matos) have shown that an only high density U_3Si_2 fuel (~ 7.2 g U_{tot}/cm^3, < 20% ^{235}U enrichment) with a diameter of cadmium wires of ~ 0.6 mm is feasible for the BR2 reactor operation. The second series of studies performed at BR2 in 2008 [11] has shown that U_3Si_2 fuel with a density of 4.8 g U_{tot}/cm^3 (< 20% ^{235}U enrichment) and with a diameter of the cadmium wires ≥ 0.2 mm is also not feasible from the reactivity point of view for the standard BR2 core load configurations.

In the report [10] it was shown that an EVITA fuel type (4.8 g U_{tot}/cm^3, 27% ^{235}U) had the best reactivity and experimental performances, similar to the high density UMo fuel types. At the same time, the studied U_3Si_2 fuel type with 6.0 g U_{tot}/cm^3 (≤ 20% ^{235}U enrichment) showed worse reactivity performances (short cycle length) compared to all other fuel types (HEU, UMo, EVITA).

Table II. Considered LEU and HEU fuel system parameters in the conversion feasibility studies.

	HEU			UMo		U_3Si_2									
	Standard	COBRA		LEONIDAS		COBRA					MILKA				EVITA
Enr. [%]	93.0	93.0	93.0	19.7	19.7	19.7	19.7	19.7	19.7	19.7	19.7	19.7	19.7	19.7	27.0
Density [g U_{tot}/cm^3]	1.3	1.05	1.05	7.5	7.5	5.3	5.3	5.3	5.3	5.3	5.3	6.0	6.5	6.5	4.8
^{235}U mass [g]	400	405	405	482	482	433	433	433	433	433	343	389	421	421	426
^{238}U mass [g]	30	31	31	1978	1978	1755	1755	1755	1755	1755	1391	1577	1707	1707	1145
Fuel meat volume [cm^3]	329	415	415	329	329	415	415	415	415	415	329	329	329	329	329
Fuel meat thickness [mm]	0.51	0.63	0.63	0.51	0.51	0.63	0.63	0.63	0.63	0.63	0.51	0.51	0.51	0.51	0.51
Cladding thickness [mm]	0.38	0.36	0.36	0.38	0.38	0.36	0.36	0.36	0.36	0.36	0.38	0.38	0.38	0.38	0.38
Water gaps (inner) [mm]	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Water gap (outer) [mm]	3.52	3.00	3.00	3.52	3.52	3.00	3.00	3.00	3.00	3.00	3.52	3.52	3.52	3.52	3.52
Fuel meat length [mm]	762	762	762	762	762	762	762	762	762	762	762	762	762	762	762
Cd-wire diameter [mm]	–	–	–	0.4	0.5	–	–	–	0.3	0.4	0.3	0.3	0.3	0.4	0.4
Number Cd-wires per FE	–	–	–	36/Al grooves	36/Al grooves	–	–	–	18/Al grooves	18/Al grooves	18/Al grooves	18/Al grooves	18/Al grooves	18/Al grooves	36/Al grooves
Boron in form of B_4C	3.8 g./fuel meat	3.8 g./fuel meat	–	–	–	1.6 g./fuel meat	1.6 g./fuel meat	–	–	–	–	–	–	–	–
Sm in form of Sm_2O_3	1.4 g./fuel meat	1.4 g./fuel meat	–	–	–	1.4 g./fuel meat	0.88 g./fuel meat	–	–	–	–	–	–	–	–
Gd in form of Gd_2O_3	–	–	2.5-4.5 g./fuel meat	–	–	–	–	1.73 g./fuel meat	–	–	–	–	–	–	–

Later studies for the 'COBRA' project were performed for a modified geometry of the BR2 fuel assembly. In these studies, the fuel meat thickness is increased from 0.508 mm (standard geometry) to 0.630 mm. The nominal Al-cladding thickness is slightly reduced from 0.38 mm to 0.36 mm. The thickness of the water gap is preserved (3.00 mm), except for the outer water gap, which is reduced from 3.52 mm to 3.00 mm. Studies with this geometry were performed and compared for both LEU (U_3Si_2) and HEU fuel types [10].

4 Importance of the burnable absorbers used in the BR2 fuel types

The burnable absorbers used in past, current and future fuel types play(ed) an important role for the sustainability of the BR2 fuel cycle. Therefore, a brief review of these burnable absorbers is presented in this Section. The burn-up rates of the major burnable isotopes were calculated by MCNP6 [1] during one operation cycle with a duration ~ 24 days and reported in [12-13]. As seen in Fig. 4, ^{157}Gd acts similarly to ^{149}Sm, burning almost totally in the first 5 days. The burn-up rate of ^{155}Gd, compared to ^{157}Gd, is slower, but after 20 days is also totally burnt. The burn up rate of the major cadmium isotope ^{113}Cd strongly depends on the wire diameter, being higher for smaller diameters. The major boron isotope ^{10}B has the slowest burn up rate, burning almost linearly with time.

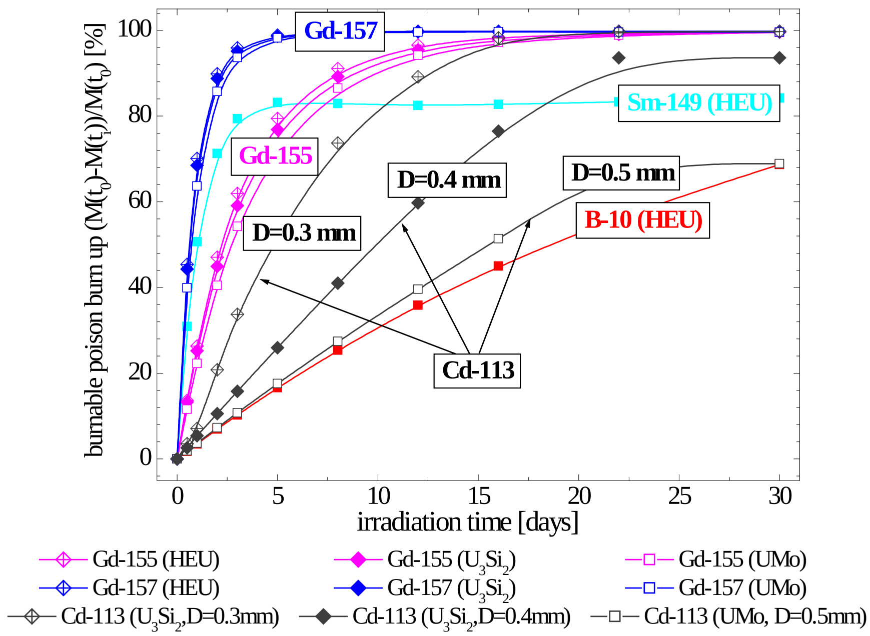


Figure 4. Comparison of the burn-up rate of different burnable absorbers used in HEU and LEU fuel assemblies.

5 Reactivity performances of different fuel types

5.1 Infinite lattice

Simulations of criticality and depletion of different fuel types in an infinite lattice have been performed by MCNP6. The fuel evolution is followed during 20 time steps for total 126 irradiation days at typical power 2 MW of the fuel element in the infinite lattice. The comparison of infinite multiplication factors for different fuel types are given in the graphs in Fig. 5a.

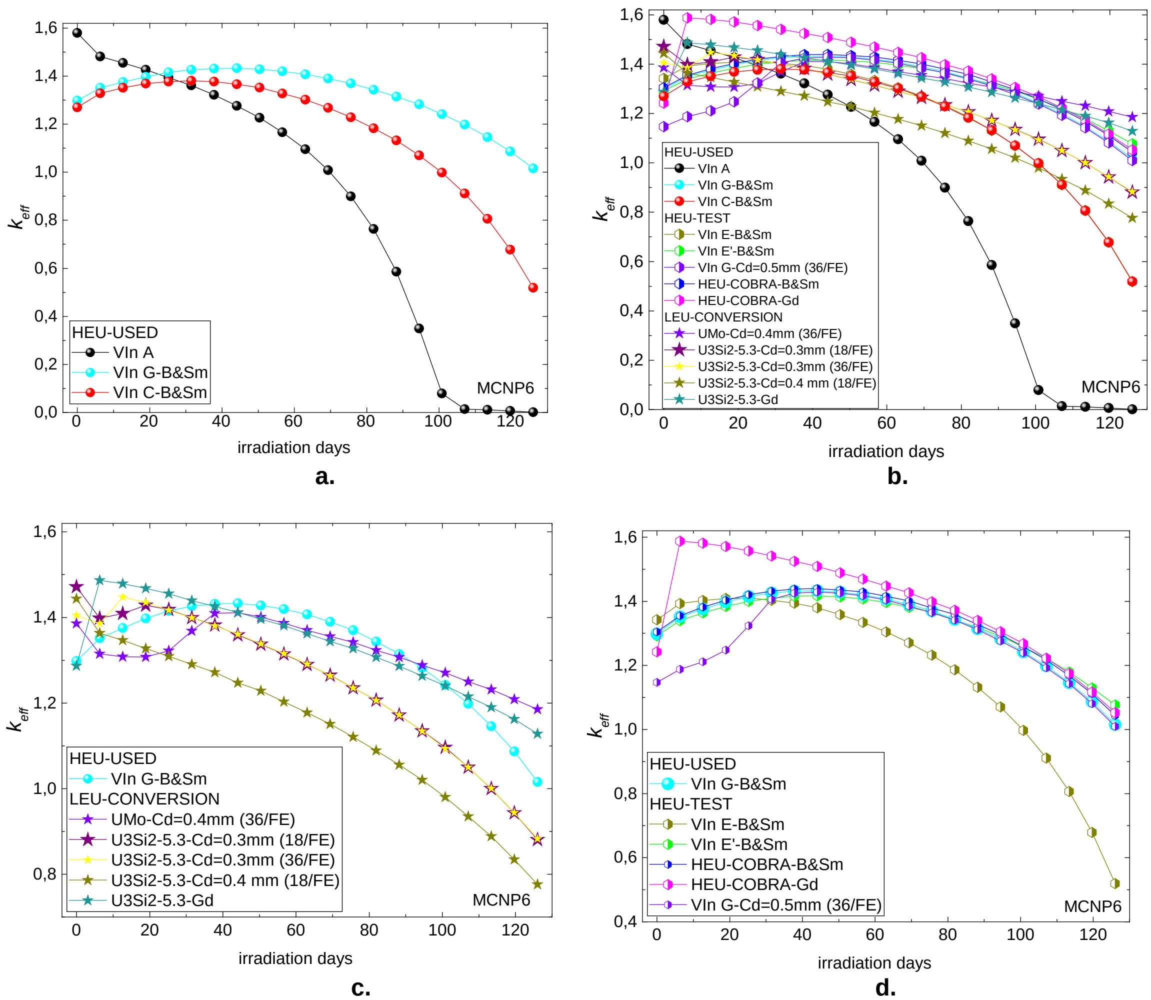


Figure 5. Comparison of infinite multiplication factors of fuel types in BR2 hexagonal lattice.

The used (or test) fuel types in the past and at the present/future time are compared separately in Fig. 5b and Fig. 5c. It is seen that the reactivity of the standard BR2 HEU standard fuel element (VIn G) is significantly higher compared to all used and some of the test fuel types with the reactivity of the oldest fuel type VIn A being the lowest due to absence of burnable absorbers and also small ^{235}U mass (244 g). The HEU-COBRA-B&Sm fuel type has almost identical reactivity behavior compared to the standard HEU fuel element VIn G. The highest reactivity effects assuming continuous irradiation during 50-60 days in the infinite lattice has the COBRA-HEU-Gd with gadolinium as burnable absorber in the fuel meat. For irradiation longer than 50-60 days the HEU fuel types – the standard fuel VIn G, the test fuel VIn E', both COBRA fuels with B&Sm and with Gd absorbers and the fuel Cd wires have similar reactivity effects. The LEU fuel types are compared in Fig. 5d. Fuel types using U_3Si_2 fuel with density 5.3 g/cc are only feasible with gadolinium absorber in the fuel meat, while the various considerations with Cd-wires have shown significantly lower reactivity effects. Moreover, the reactivity of the U_3Si_2 fuel with Gd absorber is almost comparable to the high density (7-7.5 g/cc) UMo fuel with Cd-wires.

5.2 In whole core

The performance graph of the reactivity [$] of a FE as function of mean ^{235}U burn-up [%] has been calculated for the standard HEU fuel and for the various LEU fuels (see Fig. 6) and reported in [14-15]. The load of a representative HEU core for situation at Mid-2020 has been used in the calculations. The calculation methodology is as follows: a FE with different mean ^{235}U burn-up is loaded in one and the same channel A270. The reactivity of each HEU FE and each LEU FE is determined relatively to the reactivity of the fresh [0%] standard HEU FE loaded in the same channel. The reactivity of the *fresh* LEU FE is significantly higher than the reactivity of the *fresh* BR2 HEU FE, because of the significantly higher absorption cross section of ^{10}B and ^{149}Sm in the fresh BR2 standard HEU fuel in comparison with the cross section in the Cd wires in the LEU/HEU FE. During the first irradiation days, the reactivity of the HEU FE increases in contrast of the LEU/HEU FE with Cd-wires which is caused by the faster burn-up of the standard absorber (^{149}Sm) in comparison with the cadmium (^{113}Cd) burn-up rate (see also [10]). After that, the performance graphs for HEU and LEU follow similar behavior, however the reactivity of the UMo FE is always higher than the reactivity of the standard HEU FE.

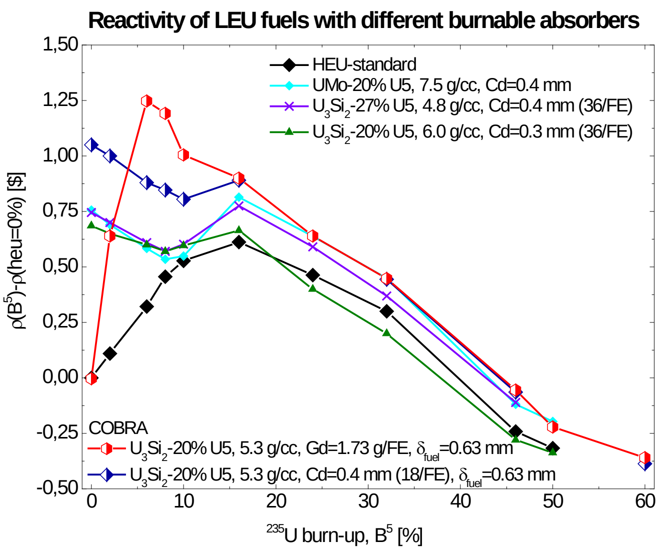


Figure 6. Performance graphs of reactivity of HEU FE and various LEU FE vs. ^{235}U burn-up calculated in channel A270.

6 Fuel cycle in different cores

The fuel cycles using burnable absorbers, homogeneously mixed with the fuel meat, follow somehow similar tendency, which is characterized with a minimum of the control rod position during the course of the operation cycle. However, the minimum of the CR position in fuel types with Gd_2O_3 in the fuel meat is observed earlier in time (about 3-4 days after BOC) due to the faster burn up of the gadolinium compared to boron and samarium. HEU fuel type with 2.5 g/FE Gd in the meat is very reactive (low critical control rod position at BOC), characterized with a steep control rod course down during the first operational days. Therefore, in order to respect the safety reactivity margin at the minimum of the CR position, different strategies can be applied specifically for the HEU fuel type, such as:

- Loading of absorptive experiments would allow increasing minimum control rod critical position.
- Increasing the initial Gd amount in the fresh fuel elements from 2.5 g/FE up to 4.0 g/FE improves the critical height at BOC. However the minimum critical rod position during the cycle is almost not changed.
- Removing fresh and/or burnt fuel elements from the core would allow to increase significantly the minimum rod position.

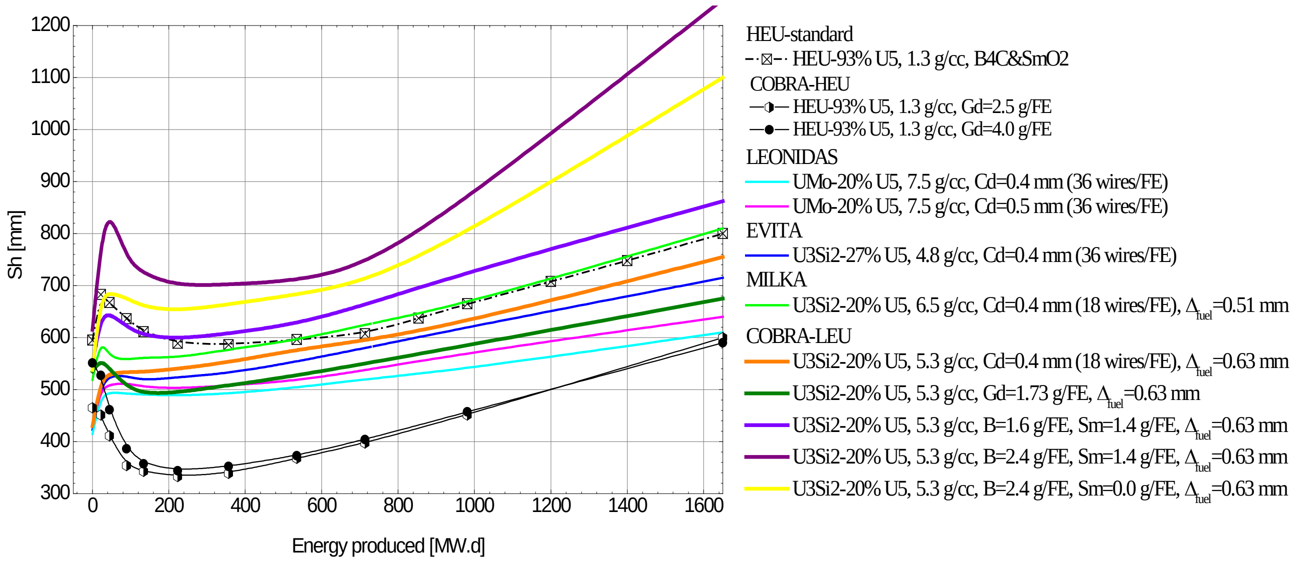


Figure 7. Control rod motion in HEU-representative core, in fully converted COBRA cores and in fully converted LEU cores.

The tendency of the control rod motion of LEU (U_3Si_2) fuel with Gd (1.73 g/cc) is similar as for the HEU fuel type, however the descending of the rods is less pronounced. The minimum control rod position for the HEU and LEU fuel types with Cd-wires is effective only at the start-up: after the first couple of days, the control rods are almost monotonically withdrawn during the reactor operation. In all cases the cycle length with Gd is significantly longer in comparison with Cd-wires.

7 Fuel test experiments

7.1 Two prototypes HEU FE with Cd-wires

Two prototypes HEU fuel elements with cadmium wires have been manufactured and irradiated during five BR2 operation cycles in 2011 under the BR2 Conversion Project [14]. The purpose of these irradiations was to investigate the effect of the replacement of the standard burnable absorbers (B_4C and Sm_2O_3) in the fuel meat by cadmium wires located in the grooves of the aluminium stiffeners of a standard BR2 fuel element. A detailed MCNPX geometry and burn-up model has been developed and implemented for evaluation of the reactivity performance of the HEU-Cd elements. A Nuclear Measurement Program for the determination of the reactivity effect of the HEU-Cd fuel elements relatively to a standard fresh BR2 HEU fuel element has been conducted in the shutdown of each operation cycle. MCNPX predictions for the reactivity effects of fresh as well as for burnt HEU-Cd fuel elements were in a good agreement with the measurements (see Fig. 8). The overall conclusion is that the two cadmium-wired fuel elements behaved as expected. Therefore it can be concluded that the Cd wires are qualified as another type of burnable absorber for the BR2 driver fuel.

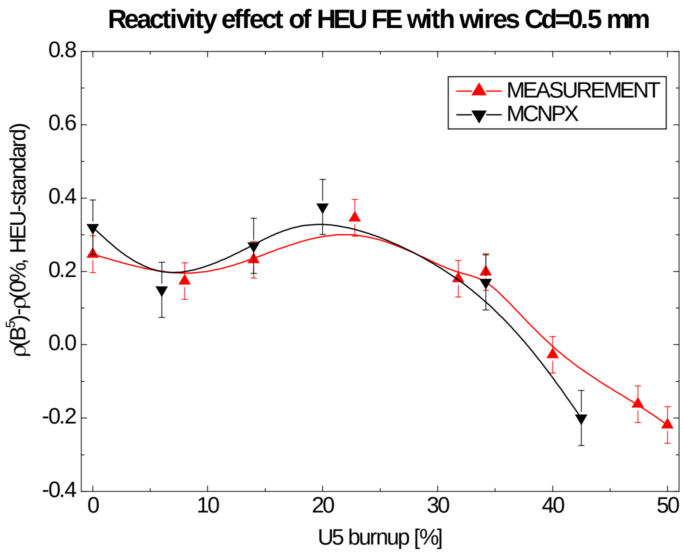


Figure 8. Reactivity effects of HEU fuel elements with Cd-wires: MCNPX predictions vs. measurements.

7.2 Three COBRA Lead Test Assemblies (LTA)

Three Lead Test Assemblies (LTA) with HEU fuel in the new 'COBRA' geometry have been manufactured and will be irradiated in several BR2 operation cycles during 2018. Two equal LTA's have Gd as burnable absorber inside the fuel meat, and one LTA has boron and samarium absorber inside the fuel meat as for the standard BR2 HEU fuel type.

Reactivity effects of the LTA’s will be calculated in advance by MCNP6 and measured at beginning of each cycle. The goal will be to compare the reactivity effects of LTA’s relatively to standard BR2 FE. In order to do this properly the comparison must be performed always in one and the same channel (preferably a channel ‘C’). *A preliminary* graph of the reactivity effects as presented in [12], [13], [15] is shown in Fig. 9.

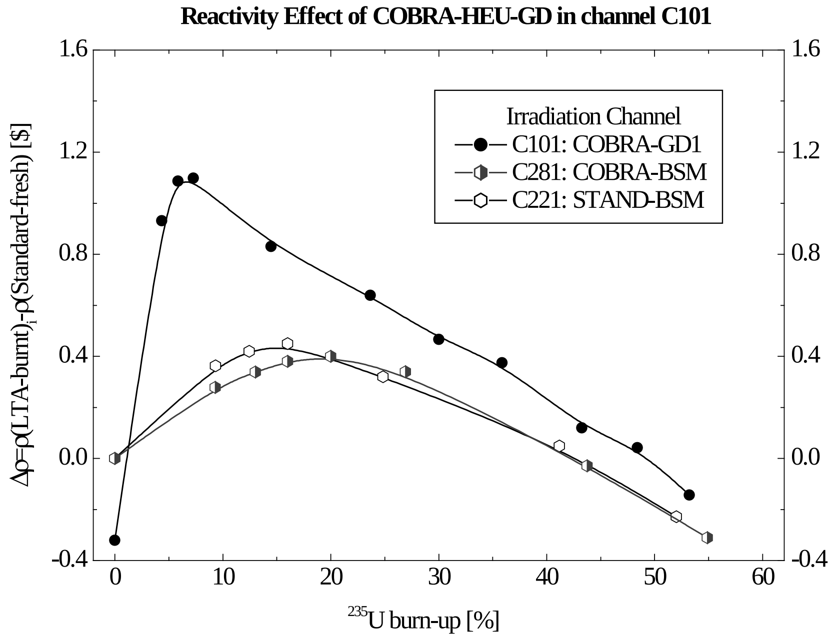


Figure 9. Comparison of *preliminary calculated* reactivity effects of LTA-COBRA-GD and LTA-COBRA-BSM vs. standard BR2 HEU fuel element in channel C101 [12], [13], [15].

The ^{235}U burnups of each LTA will be calculated by MCNP6 during each cycle and at the end of each cycle. The goal will be to load the LTA's in such way that it will be possible to achieve in some of the cycles (at least in the first 2-3 cycles) similar burnups of COBRA-GD and COBRA-BSM in order to properly compare the reactivity effects.

Heat flux distributions will be calculated in advance before beginning of each cycle. One goal will be to reach Q_{max}=470 W/cm2 in the LTA's for which different scenarios for loading of LTA's have been considered and proposed.

8 Summary

Since the start of its operation, the original fuel of the BR2 reactor has evolved from HEU fuel without burnable absorbers (≈2 weeks cycle length) toward various HEU types of fuel with burnable absorbers (3–4 weeks cycle length). The currently used standard fuel, viz. type VIn G (93% ^{235}U, 1.3 gU/cc, B = 3.8 g/assembly, Sm=1.4 g/assembly) has the best reactivity performance compared to the other used or considered fuel types.

From 2008 until 2015, a detailed comparative analysis was carried out on the efficiency of three major candidates to be used as burnable absorbers for the new BR2 LEU fuel: Cd, Gd_2O_3, and B_4C. It was shown that the cadmium wires (in the side plates outside the fuel meat) had the best performance as burnable absorber. This was due to the fact that for the minimum wire diameter which could be fabricated, i.e. 0.3–0.4 mm, cadmium has the highest burn-up rate. Gadolinium and boron are subject to higher self-shielding effects and therefore need very thin wire diameters, i.e. < 0.3 mm, in order to have a high burn-up rate.

Later (current) studies involve the analysis of various fuel types (LEU and HEU) in a COBRA geometry with various burnable absorbers, homogeneously mixed with the fuel meat: B_4C & Sm_2O_3 as in the current standard BR2 fuel, and Gd_2O_3. These studies have shown that gadolinium has the highest burn-up rate due to its two major isotopes ^{155}Gd and ^{157}Gd. The preliminary analysis has shown that an HEU core using fuel with gadolinium as a burnable absorber has a significantly longer cycle length compared to the HEU core using standard fuel with boron and samarium as burnable absorbers. The fully converted LEU core using fuel with gadolinium as a burnable absorber has also a longer cycle length compared to cadmium wires as a burnable absorber.

For the analyses of past, current and future types of fuel, an MCNP based methodology developed by the BR2 core load management unit is used [7]. The reliability of the MCNP methodology was verified by various fuel test and qualification programs conducted at BR2. Fuel assemblies of different MTR (e.g., such as the Jules Horowitz Reactor) were successfully tested under comprehensive irradiation programs. Two prototypes of HEU fuel elements with cadmium wires have been manufactured and irradiated during five BR2 reactor cycles in 2011 and the MCNPX predictions for the reactivity effects were in a good agreement with the measurements. Finally, LTAs with the COBRA geometry using Gd_2O_3 or using B_4C & Sm_2O_3 as burnable absorber will be tested during several BR2 reactor cycles in 2018.

9 Dedication

This paper is dedicated to the memory of Edgar Koonen who for almost 40 years worked at the BR2 reactor in the field of reactor safety and core load management. Edgar acquired in this period a vast knowledge of the BR2 reactor and of MTR fuel development. This knowledge combined with his sound judgement was soon not only appreciated at the BR2 reactor alone but also on different international fora on reactor safety and MTR fuel. Testimony to this were the many messages of sympathy we received after his death from all over the world. Edgar was a bright and inspiring member of the international nuclear community. His knowledge and competence are for sure sincerely missed, but, most probably, everybody who has known him will especially miss his unique sense of humour. It is therefore only fitting to end with one of Edgar's own memorable quotes: "If you want to prove the impossible, come to BR2, we will prove you are right!"

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