RERTR 2012 — 34th INTERNATIONAL MEETING ON
REDUCED ENRICHMENT FOR RESEARCH AND TEST REACTORS

October 14-17, 2012
Warsaw Marriott Hotel
Warsaw, Poland

Steady-State Safety Basis and Performance Evaluation of the BR2 Core Using UMo Dispersion Fuel

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ABSTRACT

To establish the steady-state safety basis of the Belgian Reactor 2 (BR2) using LEU UMo dispersion fuel, the impact of the conversion on the neutronics and thermal-hydraulics safety criteria at steady-state was studied by the BR2 and Argonne National Laboratory (ANL) teams in close collaboration. The analyses of the excess reactivity, shutdown margin, power peaking, and thermal-hydraulic safety margins confirmed that the selected UMo fuel design could be used safely in the BR2 core. Performance metrics such as cycle length, fuel utilization and key irradiation capabilities were also studied and shown to remain within acceptable ranges. The experimental qualification for the use of this LEU fuel under high performance research reactor's operating conditions is still in progress.

1. Introduction

By 2009 a series of preliminary, but sufficiently detailed, studies had been performed by the BR2 engineering staff to declare that it was feasible[1] to convert the reactor from highly-enriched uranium (HEU) UAl_x dispersion fuel to low-enriched uranium (LEU) UMo dispersion fuel. Since then BR2 and ANL have been collaborating closely to establish a solid steady-state safety basis by extending and improving the preliminary methodologies and analyses to become part of an updated BR2 safety analysis report. In addition to the creation of the safety basis, a series of

[1] Under the caveat that the proposed fuel could be manufactured and qualified for the BR2 operating conditions.

analyses were also performed to evaluate the impact of the conversion on various performance metrics.

This paper is intended as a summary of the current state of all these efforts and is organized as follows. Section 2 presents an overview of the BR2 core and fuel assemblies. Section 3 describes the criteria used to demonstrate the safety of a given BR2 core configuration at steady-state (safety basis). Sections 4 and 5 present selected results from the steady-state safety analyses and the performance evaluation, respectively.

2. BR2 core and LEU fuel assembly

BR2 is a water-cooled thermal reactor moderated by water and beryllium. The beryllium moderator consists of a matrix of hexagonal prisms each having a central bore which can contain either: a fuel assembly, a control rod, an experimental device, or an aluminum plug. The core is located inside an aluminum pressure vessel. At nominal conditions the vessel inlet and outlet pressure are 13.6 atm and 10.1 atm, respectively, while the inlet water temperature varies from 30 to 40°C. During normal operation, the coolant flows downward through the core. Figure 1 shows a schematic of the BR2 reactor.

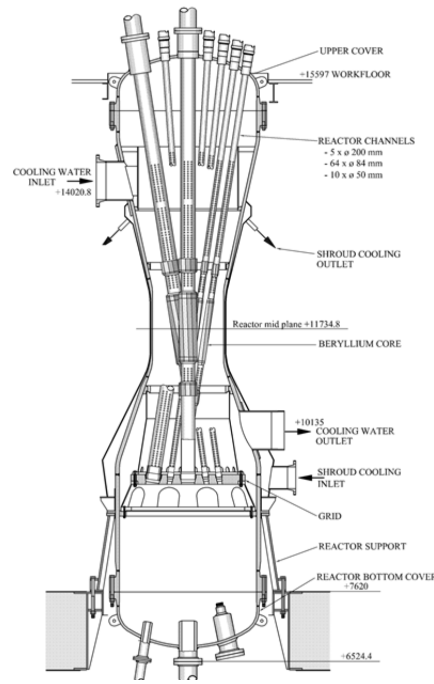

Figure 1. BR2 Reactor Schematic

Each fuel assembly is composed of six concentric "tubes" with a central aluminum plug which can be removed to provide an additional irradiation location. Each "tube" is made of three curved fuel plates (fuel meat clad in aluminum) separated by aluminum stiffeners. The current fuel uses UAl_x (~1.3 gU/cm^3) with B_4C and Sm_2O_3 (burnable absorbers) dispersed in an aluminum matrix. All the dimensions of the proposed LEU fuel assembly are unchanged but its fuel meat consists of U8Mo (7.5 gU/cm^3) dispersed in an aluminum matrix with, as burnable absorbers, 36 cadmium wires (possibly 0.4mm or 0.5mm in diam.) located in the stiffeners (see Figure 2).

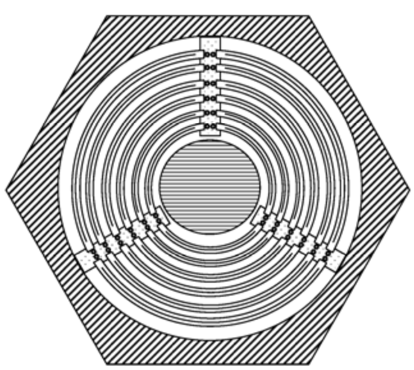

Figure 2. LEU Fuel Assembly Horizontal Cross Section

3. Description of the Steady-State Safety Basis

The current safety analysis report [1] states that in order to get approval to operate with a given core configuration, the following safety criteria must be met:

1. The maximum nominal heat flux calculated using the approved neutronics code does not exceed the routine authorized value of 470 W/cm^2.
2. The amount of negative reactivity available must exceeds 4.5$ (for a typical reactivity worth of the shim rods of 12$ ± 1$) at any time during the cycle.

To demonstrate that a core loading using the LEU fuel assemblies is safe, it is necessary to understand the technical bases of these requirements and verify that they remain applicable. Since, as part of the safety basis update, an effort was undertaken to modernize the codes and methodologies used to perform safety analyses, it is also necessary to reanalyze the HEU core.

3.1. Basis for the maximum nominal heat flux

During steady-state operation, the heat removal at BR2 must maintain the cladding and fuel temperatures well below the blistering threshold temperature. This is achieved by ensuring sufficient margins to Onset of Nucleate Boiling (ONB) which, in turn, ensures that neither flow instability nor departure from nucleate boiling will occur and damage the fuel.

Defining an allowed reactor power is not useful to ensure margins for all BR2 core configurations since the number of fuel assemblies as well as their burnup and location on the grid plate can vary significantly. A maximum nominal heat flux is a more appropriate safety parameter since the associated safety margins can be evaluated independently of any specific core configuration. Therefore, the BR2 maximum nominal heat flux is defined as the heat flux at which ONB occurs.

Historically [2], the heat flux at which ONB occurs was determined to be 603 W/cm^2. However, based on loss-of-flow/loss-of-pressure tests performed in 1963, the authorized maximum heat flux was set to 430 W/cm^2 for routine operation in order to maintain fuel integrity after such an event. Currently, a permanent deviation for a heat flux up to 470 W/cm^2 is authorized (note GF/PGo/gd/86-783/F175 van 15 juli 1986).

3.2. Basis for the amount of negative reactivity available during the cycle

The purpose of this requirement is to ensure that sufficient reactivity is available to shutdown the reactor and maintain it subcritical after shutdown in the event of a control rod ejection. The value of 4.5$ is derived from assuming the complete ejection of the most effective control rod from its fully inserted position (reactivity worth of 2.5$ for a typical arrangement of control rods) plus a 2$ safety margin [3]. This evaluation is typically performed for the following core states: 1) during the approach to criticality, 2) at startup, 3) at the minimum control rods position during the cycle, and 4) at the minimum of the Xe-Sm transient following a reactor shutdown from the minimum control rods position.

In other words, the total control rods reactivity worth evaluated from the minimum critical rods position must be greater than 4.5$ at any time during the cycle. This criterion also requires that the reactor remains subcritical (with a safety margin of 2$) in the event of control rod ejection at cold conditions and at the minimum of the Xe-Sm transient. The Xe-Sm transient is an important consideration when the minimum critical rods position occurs at or after xenon equilibrium has been established due to the use of burnable poisons. In that case, the reactivity worth of the Xe-135 is not fully compensated by the withdrawal of the control rods and consequently, a positive reactivity contribution is introduced after shutdown as the reactivity worth of Xe-135 is reduced below the equilibrium level. Note that part of that positive reactivity contribution is compensated by the buildup of Sm-129. This criterion is analogous to ensuring that the shutdown margin[2] is always greater than 2$.

4. Steady-State Safety Evaluation

Due the variable configuration of the BR2 core, the steady-state safety and performance evaluations were performed using a series of hypothetical core loadings that are representative of the current and expected utilization of the reactor. The results presented in this paper are based on the representative core load shown in Figure 3. This reference core has the following characteristics:

- an irradiated beryllium matrix (yellow) with a projected (mid-2018) helium-3 reactivity worth based on current utilization (~6.5$ at BOC),
- 32 fuel assemblies (pale blue) with, at BOC, 6 fresh fuel assemblies in the C-channels and either 16%, 32% or 46% average burnup for the other fuel assemblies,
- cadmium wires of 0.5mm diameter as burnable absorbers in the LEU fuel assemblies,
- 2 cadmium regulating rods (pink), 8 hafnium shim and safety rods (red),
- various irradiation devices (PRFs, DGs, SIDONIE, CALLISTO, IPSs) (other colors),
- a typical steady-state power of 59 MW.

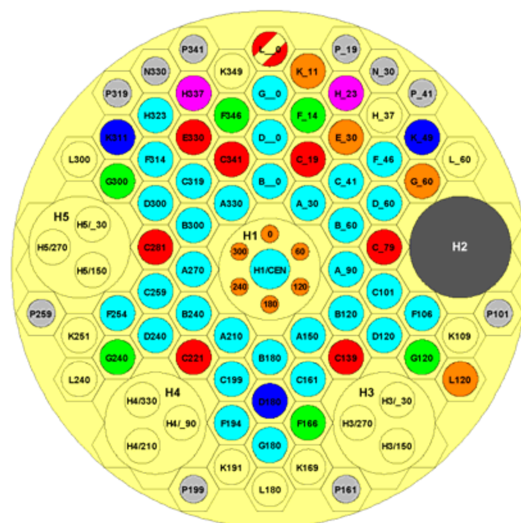

Figure 3. Representative Core Loading

Other core loadings have also been studied to analyze the impact of parameters such as the use of a fresh beryllium matrix, different cadmium wire diameters, different experimental loadings as well as mixed HEU/LEU transition cores. More details about all these representative cores are presented in Ref. 4.

For all the core loadings, detailed MCNPX [5] models have been developed and are used to: 1) estimate the control rods position at BOC, 2) perform whole-core depletion calculation [6] to predict control rods motion during the cycle, 3) calculate power distributions for thermal-hydraulics calculations, 4) evaluate the control rods reactivity worth, and 4) estimate the neutron fluxes in various irradiation devices.

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[2] The amount of reactivity by which the reactor is subcritical or would be subcritical from its present condition assuming all control rods are fully inserted except for the rod of highest reactivity worth that is assumed to be fully withdrawn.

4.1. Applicability of the maximum nominal heat flux criterion

To evaluate the applicability of the maximum nominal heat flux criterion (470 W/cm^2) to an LEU core, a PLTEMP [6] analysis of the limiting fuel assembly was performed to determine the margins to ONB when operating at steady-state.

The results presented in this paper were obtained for a fresh fuel assembly in a C-channel since these fuel assemblies have the highest heat flux at beginning-of-cycle (BOC) in both HEU and LEU cores. Engineering hot channel factors are used to take into account the impact of the manufacturing tolerances and uncertainties on the bulk coolant temperature rise, film temperature rise, local heat flux, and the heat transfer coefficient. A factor is also used to model the azimuthal power peaking through a hot stripe approach [7]. Details about the PLTEMP models and analysis methodology are presented in Refs. 4.

Using PLTEMP search capabilities, the fuel assembly power (and heat flux) at which ONB occurs is obtained[3]. Table 1 gives the heat fluxes at ONBR = 1.0 obtained with the updated methodology at nominal flow (10.4 m/s). It can be seen that these values are similar to the historical value (603W/cm^2) and that they do not differ significantly between the HEU and LEU fuel assemblies. To estimate the safety margins, heat fluxes at ONBR = 1.0 are evaluated for a series of fuel assembly average coolant speed as shown in Figure 4.

Table 1. Calculated Heat Flux at ONBR = 1.0

Limiting Condition	Heat flux (W/cm^2)	
	HEU	LEU
ONBR = 1.0	620.2	623.6

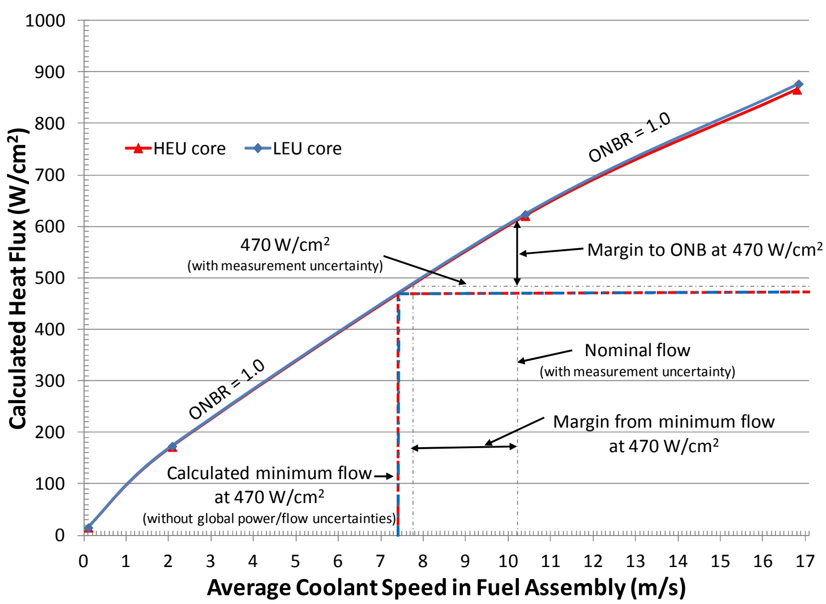

Figure 4. Calculated Heat Flux at ONBR = 1.0 as a Function Average Coolant Speed

[3] PLTEMP searches for the power at which the smallest ratio of the local heat flux to the ONB heat flux (ONBR) equals 1.0.

In Figure 4, the horizontal colored dashed lines are the maximum nominal heat fluxes without the measurement uncertainty on total core power (3%) for the HEU (red) and LEU (blue) cores. The vertical colored dashed lines are the calculated minimal flow[4] without measurement uncertainties to total core flow (2%). From that figure, it can be seen that: i) the margins from nominal flow to the minimum flow and from maximum nominal flux to ONBR = 1.0 are much larger than the uncertainties on total flow and power measurements (2% and 3% respectively), and, ii) the margins to ONB are essentially the same for both fuels. Based on these results, it can be concluded that a maximum nominal heat flux of 470 W/cm^2 remains an applicable criterion for the routine operation of the BR2 core using the proposed LEU fuel assembly.

Figure 5 shows that for the typical steady-state power of 59MW, the peak heat flux in a fresh fuel assembly is far from the maximum nominal heat flux. In the representative core configuration, the maximum nominal heat flux is reached for steady-state powers of 88 MW (HEU core) and 82 MW (LEU core). The difference observed is a result of the higher peaking in the LEU fuel assembly as shown in Figure 5.

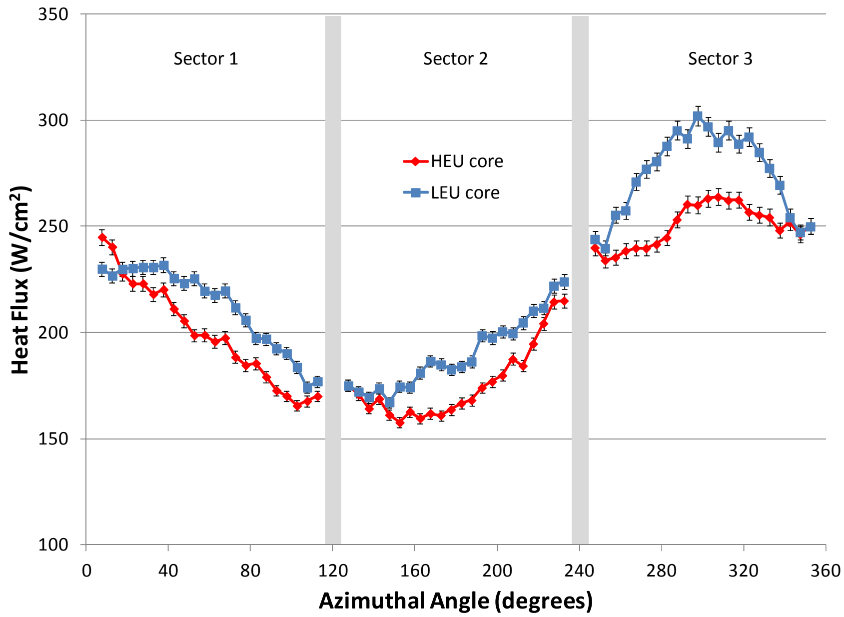

Figure 5. Azimuthal Heat Flux (peak) for the HEU and LEU cores at 59 MW

From the results presented in Figure 5 in can also be concluded that at, at equal power, the LEU core will have a slightly reduced margin to ONB.

4.2. Applicability of the minimum negative reactivity criterion

To remain brief, this section will focus on demonstrating the applicability of the minimum negative criterion at the minimum control rods position and following shutdown from that position. To perform this evaluation, the control rods reactivity worth and their motion during the cycle were evaluated using the MCNPX model. Figure 6 shows the control rods motion during the first 16 days of a typical cycle operated at 59MW.

[4] The minimum flow is defined as the flow where ONB occurs for the maximum authorized heat flux (470W/cm^2)

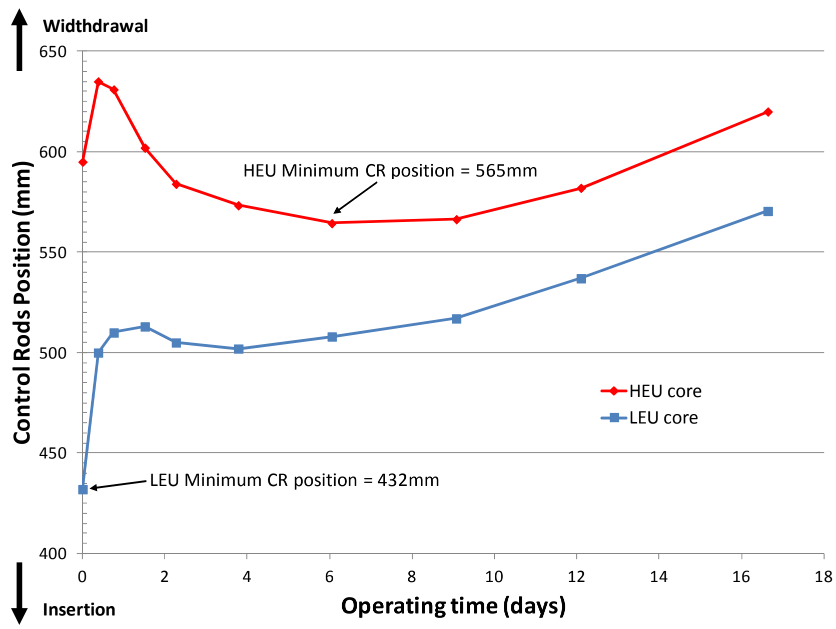

Figure 6. Control Rods Critical Position during a Cycle Operated at 59 MW

Figure 6 shows that the control rods are inserted farther at BOC for the LEU core than the HEU core. This can be explained by fact that the LEU core excess reactivity at BOC is about 3.5$ higher than for the HEU core due to the higher U-235 loading and the change in the burnable absorber design. It can also be seen that minimum control rods position occurs at the BOC for the LEU core rather than later in the cycle as with the HEU core. This is a result of the careful selection of the burnable absorber material and geometry in the proposed LEU fuel assembly in order to match more evenly the fuel and absorber burnup rates.

Table 3 shows the different components used to evaluate the applicability of the minimum negative reactivity criterion.

Table 3. Minimum Negative Reactivity Criterion Components

Core	Most effective rod worth [a] [$]	Control rods worth [b] [$]	Positive reactivity after shutdown [$]		Minimum Negative Reactivity [$]
			Cooldown	Xe-Sm transient	
HEU	-2.5	-10.4	+0.2	+2.7	-7.5
LEU	-2.3	-6.1	+0.2	0	-5.9

[a] Calculated from fully inserted to fully withdrawn
[b] Calculated from the rods' minimum critical position (see Figure 6), including shim and safety rods

The following observations can be made about the LEU core results presented in Table 3:

- The most effective control rods reactivity worth is slightly reduced due to the hardening of the neutron spectrum from the higher U-235 and U-238 loadings.
- The control rods reactivity worth from the minimum critical position (BOC) is significantly reduced due to the lower control rods position.

- The minimum control rods position occurs at BOC and therefore there is no Xe-Sm transient to consider.
- The minimum negative reactivity criterion[5] is larger than 4.5$.

Table 4 gives the shutdown margins which were estimated by subtracting the reactivity worth of the most effective rod from the total control rods worth at different core states. From this table it can be seen that the shutdown margins are always greater than the safety margin of 2$.

Table 4. Shutdown Margins for the HEU and LEU Cores at Different States

Core	Shutdown margin [$]		
	From rods position during core loading (370mm)	From minimum critical position	After shutdown from minimum critical position
HEU	-2.9	-7.9	-5.0
LEU	-2.6	-3.8	-3.6

Based on the above results, it can be concluded that the minimum negative reactivity criterion of 4.5$ is applicable but slightly more conservative for the LEU core since, based on the reactivity worth of the most effective control rod, 4.3$ could be used as the minimum negative criterion.

5. Performance Evaluation

In order to compare briefly compare the performance of the HEU and LEU cores, two important metrics are presented, 1) the thermal and fast neutron flux levels in selected irradiation devices, 1) the cycle length.

Table 5 provides the representative changes in the neutron fluxes in the hot-plane (i.e., the peak heat flux location) for selected irradiation devices.

Table 5. Representative Changes in the Neutron Flux at Selected Locations

Irradiation device	Relative change in neutron flux	
	Thermal	Fast
H1/0 (Iridium-192)	-14%	-7%
PRF (Molybdenum-99)	-13%	-12%
SIDONIE (Silicon doping)	-6%	-4%
DG (other radioisotopes)	-10%	No changes

The changes in neutron fluxes presented in Table 5 remain within an acceptable range. Moreover, given the fact that BR2 can operate at different power levels, it would be possible to compensate part of those losses by operating, on average, at a slightly higher power.

The depletion analysis of the representative core described in Section 2 predicted a cycle length of 26 days for the HEU core operated at 59MW. A cycle length of 34 days was predicted for the

[5] Calculated for each core by adding the cooldown and Xe-Sm transient positive reactivity contribution to the total control rods worth.

LEU core at that same power. Since a longer cycle length can be achieved using the proposed LEU fuel at the same power, an increase in the average operating power to compensate some of the performance loss should not result in larger fuel utilization.

6. Conclusions

As part of the modernization of the steady-state safety basis, PLTEMP and MCNPX were used to evaluate the applicability of the load approval requirements for the LEU core.

It was shown that a maximum nominal heat flux of 470W/cm^2 remains an applicable criterion for the proposed LEU fuel assembly. Progress continues on the thermal-hydraulic safety basis as the methodologies and analyses are refined to include topics such as an estimation of the peak fuel temperatures and RELAP5 modeling of loss-of-flow/low-of-pressure events for the representative cores. It was also shown that the minimum negative reactivity criterion of 4.5$ remains applicable and, consequently, that the BR2 LEU core can be shutdown and kept subcritical with its most effective rod stuck out with at least a 2$ safety margin. Note that additional studies [4] not presented in this paper demonstrated that these criteria can be met for LEU fuel assemblies using 0.4mm cadmium wires, and with slightly modified core loads for various mixed HEU/LEU transition cores or for a core with fresh beryllium matrix. Finally, the cycle length and neutron fluxes in key irradiation devices were shown to remain within acceptable ranges.

These analyses confirmed that the proposed LEU (UMo) fuel assembly design can be used safely in the BR2 core given that the experimental qualification of the fuel under high performance research reactor's operating conditions is successful.

7. References

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