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Revision 0

Steady-State Thermal-Hydraulics Feasibility Study for the Conversion of the BR2 Reactor to LEU

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Nuclear Engineering Division

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prepared by

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1. Introduction

As part of the conversion from highly-enriched uranium (HEU) to low-enriched uranium (LEU) fuel, it is necessary to verify that an LEU core can operate safely at the same maximum nominal heat flux. Therefore, the main goal of this chapter is to determine the impact of using LEU fuel on the thermal performance and thermal limits of the BR2 core. More specifically, this chapter will present analyses performed to evaluate the margins to onset of nucleate boiling (ONB), fully developed nucleate boiling (FDNB) and flow instability (FI) at steady-state using the PLTEMP/ANL v4.1 code (referred as PLTEMP from here on). [1]. Section 2 describes the basis for the current thermal limits. Section 3 provides a brief description of the BR2 core and fuel assemblies. Section 4 contains a description of the computational methodology used to perform the analysis. Section 5 presents the results while Section 6 summarizes the analysis and presents some conclusions.

2. Basis of the maximum nominal heat flux

The heat removal at BR2 must satisfy the requirement that the integrity of fuel plates is ensured during steady-state operation and after a Loss-Of-Flow/Loss-Of-Pressure (LOF/LOP) accident [2]. In order to maintain the integrity of the fuel, it is necessary to ensure that no flow-related problems such as flow instability (FI) and departure from nucleate boiling (DNB) can occur. Typically, this is accomplished by demonstrating that the power at which the selected safety criterion occurs exceeds the operating power with sufficient margins.

However, in the case of the BR2 core, using an allowed core power is not useful since it would vary for each possible core configuration (different numbers of fuel assemblies as well as different locations for the fuel assemblies and experimental devices) and loadings (fuel assemblies with different burnups). An allowed heat flux (referred to herein as the maximum nominal heat flux) is a more useful safety parameter since it can be analyzed independently of the core configuration and it can be related to the operating power for a given core configuration by a neutronics calculation.

For the BR2 core, this maximum nominal heat flux is defined, at steady-state, in relation to the occurrence of ONB. By preventing any form of boiling, i.e., by ensuring that the reactor is operated below ONB, it is impossible for FI and DNB to occur.

Historically, the BR2 steady-state thermal limits determined using the FABREGA code [3] showed that ONB, FDNB and FI occurred at the following heat fluxes [4]:

- ONB occurred at 603 W/cm^2
- FDNB occurred at 675 W/cm^2
- FI occurred at 709 W/cm^2

As mentioned above, the fuel integrity must also be maintained during a LOF/LOP accident. Therefore, based on the BR2 core thermal-hydraulic performance during a LOF/LOP accident, as tested in 1963, the maximum nominal heat flux was set to 430 W/cm^2 for routine operation (operating license Royal Decree N.0024 of June 30, 1986, article 4.11) in order to protect against boiling risk when flow inversion occurs during this transient. Since 1986, 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). For a specific case, subject to an experimental demonstration (or a detailed analysis) that a total LOP event would not damage the fuel plates for this case, a maximum heat flux of 600 W/cm^2 can be temporarily allowed [5].

A preliminary comparison between the FABREGA and PLTEMP codes was performed and documented [6]. Learning from this experience, the current analysis refines and expands on this prior work.

3. Description of the BR2 core and fuel assemblies

BR2 is a water-cooled reactor moderated by beryllium and water. The core, in the form of a twisted hyperboloid bundle, is located inside an aluminum pressure vessel. The beryllium consists of a matrix of hexagonal prisms, each with a central bore forming a channel. The flexibility of the BR2 core design allows for a variety of core loadings since each channel can contain one of the following: a control or regulating rod, an experimental device, a beryllium plug or a fuel assembly. Figure 1 shows a schematic of the BR2 reactor.

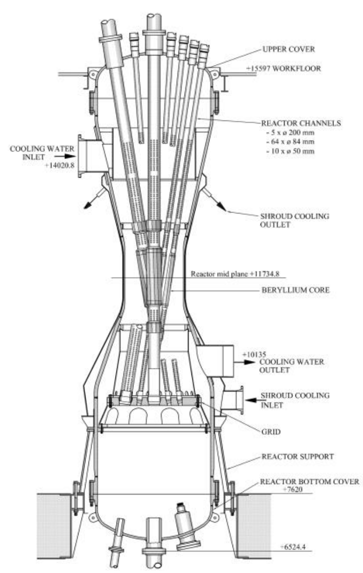

Figure 1. BR2 reactor schematic.

A standard BR2 fuel assembly is composed of 18 fuel plates arranged into six concentric fuel “tubes” divided by aluminum stiffeners into three sectors (see Fig. 2). Each fuel plate consists of a fuel meat (UAl_x-Al for HEU, UMo-Al for LEU) clad by aluminum (AG3NE). The central location of the fuel assembly can contain either an experimental device or a plug. More information about the BR2 core and fuel assemblies is presented in Ref. 7.

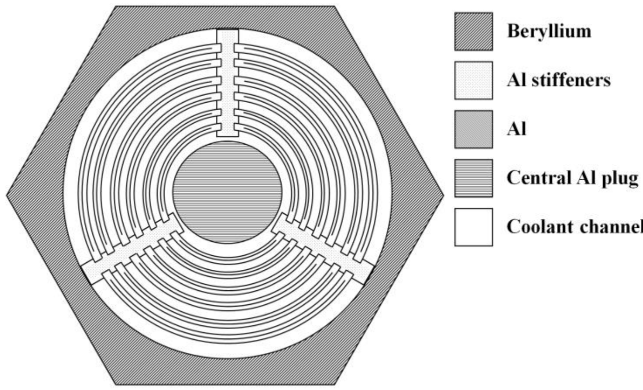

Figure 2. Section of a BR2 standard fuel assembly.

4. Computational methodology

This section presents the overall approach to determining the thermal performance of the BR2 core as well as descriptions of the PLTEMP model, the reactor operating conditions, the power distributions and the engineering hot channel factors. More information about the applicability of PLTEMP to perform this type of analysis for BR2 is provided in Ref. 8.

4.1. Overall approach

The maximum heat flux criterion described in Section 2 is equivalent to stating that under all allowed operating conditions, the margin to ONB, known as the ONB ratio (ratio of the reactor power at which ONB occurs, to the power at which the reactor is operating), exceeds 1.0 with sufficient margins. Similar ratios are defined to represent margins to FDNB and FI (FDNBR and FIR).

For this analysis, the HEU and LEU representative cores are assumed to be at beginning-of-cycle (BOC). Only the fuel assembly with the highest heat flux (fresh fuel assembly C-259) is analyzed. For this hot fuel assembly, the steady-state margins to the limiting conditions[1] from the maximum nominal heat flux (470 W/cm^2) and temporary maximum heat flux (600 W/cm^2) are evaluated, yielding the peak cladding and fuel temperatures for the various limits. For a range of true flow values, the fuel assembly true powers (and heat flux) to reach an ONBR = 1.0 (or FDNBR and FIR) are calculated. The true flow

[1] ONBR = 1.0, FDNBR = 1.0, and FIR = 1.0

and true power refer to the analyzed values and do not take into account measurement uncertainties.

In this work, the three limiting conditions (see footnote 1) are calculated based on the Bergles & Rohsenow correlation [9], the Forster & Greif correlation [10] and Whittle & Forgan correlation [11], respectively.

4.2. PLTEMP model

The PLTEMP model uses a detailed geometric description of the fuel assembly, including fuel plate materials, dimensions such as radius of curvature, clad thickness, meat thickness, plate full and heated length, as well as coolant channel thicknesses. Even though the code can model the flow redistribution to fuel assemblies at different powers, the present analysis considers the limiting hot assembly. The details about the BR2 HEU and LEU representative cores are presented in Refs 7 and 12.

The hot fuel assembly is modeled as 18 fuel plates and 21 heated coolant channels. All the plates and channels of a single sector are thermally coupled in the radial direction. No heat conduction is modeled in the azimuthal and axial directions. The central plug, the stiffeners, and the beryllium are modeled as adiabatic boundary conditions. Key inout parameters for the PLTEMP model are derived from the data provided in Refs 7 and 8.

Under steady-state conditions, it is necessary to model and analyze three axial regions of the fuel assembly and its enclosure:

1. The unheated section at the assembly inlet;
2. The heated section;
3. The unheated section at the outlet end of the assembly.

PLTEMP uses temperature-independent conductivities for the solid materials. The water properties are determined automatically by the code as required from temperature, pressure and enthalpy. The solid material (fuel meat and clad) thermal properties used in the analysis are presented in Table 2.

Table 2. Temperature-independent values for the thermal conductivities [13]

	Thermal conductivity (W/m-K)
AG3NE cladding	130
UAl_x-Al dispersion (fresh)	80
U-7Mo-Al dispersion (fresh)	66

4.3. Reactor operating conditions

Power and flow are not specified as operating conditions since ONBR, FDNBR and FIR are evaluated for a range of values of true flow and true power in order to obtain the allowed operating envelop.

The four reactor operating parameters of interest to analyze the BR2 maximum heat flux with PLTEMP are the pressure and temperature at the inlet of the fuel assembly, the pressure drop over the fuel assembly and the nominal mass flow rate through a fuel assembly.

4.3.1. Inlet temperature and pressure

To obtain the fuel inlet pressure, the measurement from PRCA 4-1302 is corrected to obtain the absolute pressure and take into account the pressure drop from the pressure vessel (PV) inlet to the fuel inlet. The fuel assembly inlet temperature is assumed to be the same as the coolant PV inlet temperature since direct heating of the coolant between the PV and fuel inlet is negligible.

Table 3 gives the inlet temperature and pressure considered in this analysis.

Table 3. PLTEMP inlet pressure and coolant temperature (nominal conditions)

	Value
Coolant temperature	40 °C
Pressure	1.240 MPa (12.6 kg'/cm^2)

Calculation of the inlet pressure used in PLTEMP is given in Appendix C.

4.3.2. Calibration of the entrance and exit loss factors

In order to properly model the total pressure drop across the fuel plates, it is necessary to take into account the losses due to the change in geometry at the entrance and exit of the fuel assembly. Entrance and exit loss factors were set to match the PLTEMP pressure drop to the measured pressure drop over the fuel plates [2, 4, 5], i.e., 2.1 kg'/cm^2 (0.2059 MPa). This calibration was performed for nominal operating conditions, i.e., 40 °C, 1.24 MPa and an average coolant speed of 10.4 m/s [14]. This calibration is assumed to hold for all operating conditions.

4.3.3. Pressure drop versus mass flow rate

To perform the analysis at different mass flow rates (coolant speed), it is necessary to evaluate the change in pressure drop across the fuel plates as a function of the mass flow rates. PLTEMP is used to evaluate this change in pressure drop and the results are illustrated in Fig. 3 for "cold" conditions (0.1 MW).

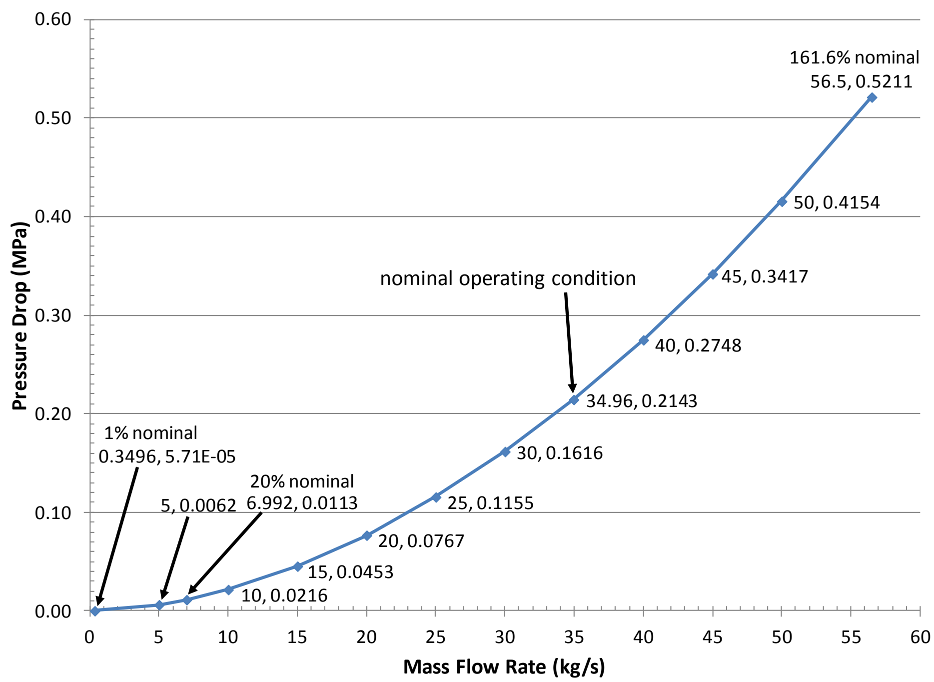

Figure 3. PLTEMP pressure drop versus mass flow rate in a BR2 fuel assembly

In Fig. 3, the mass flow rate upper bound is defined as the flow producing a pressure drop over the fuel assembly near the pressure drop trip (5.2 bars (0.52 MPa), DPRCA 4-1301) [2, 5]. Note that since the DPRCA 4-1301 measurement includes pressure drops occurring above and below the fuel assemblies, the maximum mass flow rate achievable in BR2 is lower than the upper bound used in this analysis.

4.4. Power distributions

The power distributions used in the PLTEMP models are obtained from MCNPX calculations with the HEU and LEU representative cores model [12]. An azimuthally-average power distribution is obtained for each plate of the C-259 fuel assembly. Since PLTEMP v4.1 uses a single axial distribution for all fuel plates, the most liming axial shape is obtained from the power distribution. The azimuthal power peaking is treated through a hot stripe approach using hot channel factors.

Tables 4 and 5 show the fuel assembly local-to-average power peaking for each axial segment of each plate of the HEU and LEU C-259 fuel assembly, respectively. For the HEU and LEU representative cores, the fuel assemblies C-259 have radial power peak-to-average ratios of 1.13 and 1.16, respectively.

Tables 4 and 5 also provide the local-to-average power peaking factors for each plate.

Table 4. BR2 HEU fuel assembly local-to-average power peaking [12]

	Local-to-average power peaking					
Axial position (cm)	1st plate (inner)	2nd plate	3rd plate	4th plate	5th plate	6th plate (outer)
-34.05	0.747	0.765	0.736	0.772	0.847	0.978
-27	0.937	0.971	0.949	0.998	1.103	1.275
-21	1.120	1.163	1.133	1.186	1.309	1.521
-15	1.227	1.275	1.238	1.304	1.436	1.655
-9	1.272	1.316	1.278	1.351	1.490	1.714
-3	1.249	1.292	1.253	1.319	1.455	1.674
3	1.156	1.197	1.158	1.215	1.335	1.526
9	0.998	1.037	1.004	1.053	1.140	1.291
15	0.817	0.838	0.809	0.842	0.910	1.013
21	0.637	0.659	0.636	0.660	0.704	0.782
27	0.490	0.501	0.476	0.500	0.534	0.589
34.05	0.350	0.354	0.34	0.351	0.372	0.416
Plate peaking	0.917	0.947	0.918	0.963	1.053	1.203

Table 5. BR2 LEU fuel assembly local-to-average power peaking [12]

	Local-to-average power peaking					
Axial position (cm)	1st plate (inner)	2nd plate	3rd plate	4th plate	5th plate	6th plate (outer)
-34.05	0.684	0.717	0.705	0.752	0.828	0.951
-27	0.861	0.908	0.904	0.969	1.078	1.243
-21	1.014	1.085	1.080	1.159	1.280	1.477
-15	1.137	1.206	1.191	1.270	1.412	1.631
-9	1.179	1.256	1.241	1.328	1.474	1.701
-3	1.170	1.248	1.237	1.319	1.455	1.681
3	1.116	1.183	1.171	1.240	1.369	1.576
9	0.978	1.033	1.027	1.090	1.189	1.347
15	0.822	0.880	0.855	0.898	0.967	1.079
21	0.669	0.708	0.690	0.720	0.779	0.852
27	0.524	0.546	0.541	0.560	0.605	0.665
34.05	0.382	0.399	0.388	0.406	0.436	0.480
Plate peaking	0.878	0.931	0.919	0.976	1.073	1.224

Figure 4 shows the azimuthal local-to-average peaking across plate 6 of the hot sector of the HEU and LEU C-259 fuel assemblies. The 1σ statistical uncertainty is also shown on the figure by the error bars.

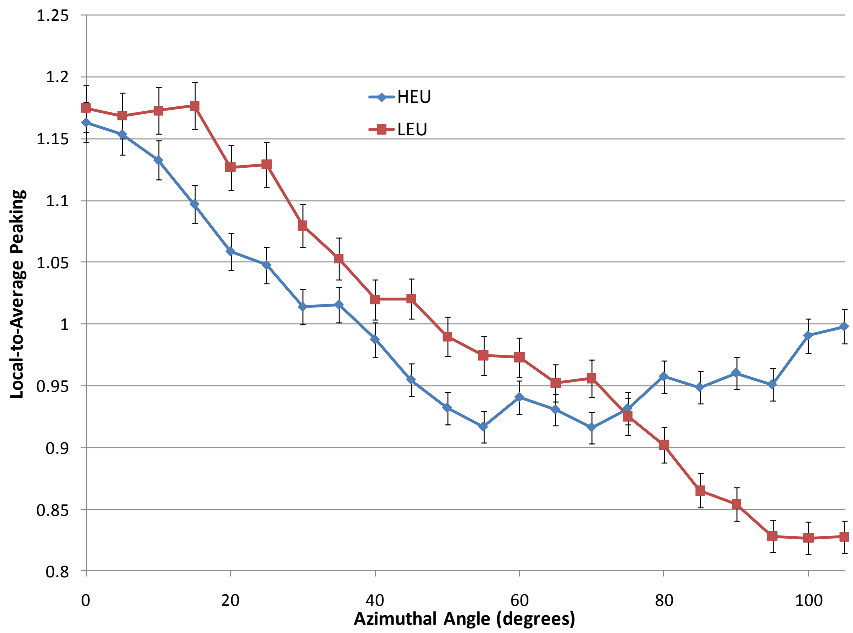

Figure 4. Azimuthal local-to-average power peaking across plate 6 of the hot sector

Experience analyzing the current BR2 core shows that the azimuthal power peak can be located at any angle along the arc length of a fuel plate based on its orientation with respect to the core centerline.

Experience also shows that the magnitude of the peak is rather insensitive to the orientation or to the type of dispersed fuel meat. Therefore, the power peak is assumed to occur at the azimuthal center of the fuel plate where the lateral heat conduction is minimal. Under that assumption, the azimuthal power peak-to-average ratio can be used to model the heat flux distribution.

Finally, this analysis assumes that the fraction of the fission energy deposited in any structures other than the fuel meat (beryllium, aluminum, etc.) is deposited in the coolant in addition to the coolant direct heating. Therefore, 12.2% of the fission energy is assumed deposited directly in the coolant [12]. The remainder of the fission energy is conducted through the clad into the coolant.

4.5. Determination of the hot channel factors; F_{flux}, F_h, F_{bulk}, and F_{film}

Hot channel factors (HCFs) are needed in order to account for fuel assembly manufacturing tolerances and various other uncertainties. Manufacturing tolerances are known for the HEU fuel currently in use at BR2. However, it is anticipated that manufacturing tolerances will be similar for LEU fuel since the fuel assembly and the fuel plate design are almost identical. Therefore, it is reasonable to assume that the uncertainties and manufacturing tolerances that apply to the HEU fuel assembly can be used for the LEU fuel assembly.

Tables 6 and 7 give the manufacturing tolerances and uncertainties considered in this analysis.

Table 6. Manufacturing tolerances considered by HCF.

	Tolerance
Water gap	±0.3 mm [15]
^{235}U homogeneity on 1 cm^2	±20% [15]
^{235}U plate loading	-2.7%, +2% [16]

Table 7. Uncertainties in power and flow measurements.

	Uncertainty
Total core power	±3% [15]
Total flow	±2% [15]

The following subsections describe each of the random and systematic components of the following HCFs: heat flux HCF (F_{flux}), heat transfer coefficient HCF (F_h), bulk temperature rise HCF (F_{bulk}) and the film temperature rise HCF (F_{film}).

The random combination of the components of each HCF reflects that it is unlikely that all local tolerances/uncertainties apply to the hot channel, at the most limiting axial location and at their worst possible values. Therefore, the components F^i of each HCF are combined statistically using $F = 1 + \sqrt{\sum_i (1 - F^i)^2}$, i.e., assuming that they are independent and normally distributed. To obtain the final HCFs, the random HCFs are then multiplied by components reflecting systematic effects. Details about the PLTEMP HCF methodology are provided in the PLTEMP licensing file [8] and PLTEMP User's Guide [1].

<u>^{235}U plate loading (random)</u>

The uncertainty in the ^{235}U loading of a fuel plate is typically in the range of a few percent. Ref. 16 states that, for a BR2 fuel assembly, the manufacturing tolerances on loading are [-2.7%, +2%]. Therefore, for this analysis, a conservative uncertainty of ±2% is assumed. Note that only one of the two plates on each side of the hot channel is assumed to have a higher ^{235}U loading hence the factor of 0.5 when evaluating the contribution to F_{bulk}. The impact of this uncertainty on the evaluation of the F_{bulk} HCF does not take credit for the fact that a larger fraction of the heat generated in plate 6 will flow into channel 7 (colder channel) instead of the hot channel (channel 6).

^{235}U homogeneity (random)

The BR2 HEU and proposed LEU fuels are composed of fuel particles (UAl_x or UMo) dispersed in an aluminum matrix. The ^{235}U homogeneity reflects the fact that the fuel particles (corresponding to a given mass of ^{235}U) are not perfectly mixed throughout the meat and therefore can produce a local increase in ^{235}U content. This local effect does not significantly increase the total energy in the hot channel (no impact on F_{bulk}) but does contribute to F_{film}, F_h and F_{flux}. An uncertainty of 20% (over a 1 cm^2 region) [2, 15] is used in this analysis.

Power density calculation (random)

This component addresses the uncertainties of the reactor physics calculations of local power densities. It reflects the fact that more power could be generated at the hot spot than calculated. It combines uncertainties in the calculation of the power sharing between fuel assemblies as well as the uncertainties in power shape (axial, radial and azimuthal) within a fuel assembly. The uncertainties presented in the MCNP licensing file [12] are,

- Fuel assembly power: 5%
- Axial power distribution: 10%
- Radial power distribution: 5%
- Azimuthal power distribution: 15%

For this analysis, these uncertainties are statistically combined to yield a total uncertainty of 20%.

Channel spacing (random)

This component reflects the impact of the manufacturing tolerances on the coolant channel gap on the flow and consequently, on the three HCFs. A tolerance fraction of 0.11 was obtained by dividing the coolant channel nominal thickness (t_{nom} = 3.0mm) by the minimum thickness ($t_{min} = t_{nom}$ – 0.3mm, see Table 6).

For turbulent flow in plate geometry (also applicable for a BR2 fuel assembly coolant channel) where the hydraulic diameter can be approximated as twice the channel thickness, the formulas [17] for obtaining F_{bulk} and F_{film} as a function of t_{nom}/t_{min} are

$$F_{bulk} = \left(t_{nom}/t_{min}\right)^{3/(2-\alpha)} \tag{1}$$

$$F_{film} = \left(t_{nom}/t_{min}\right)^{(0.4+\alpha)/(2-\alpha)} \tag{2}$$

where t_{nom} and t_{min} are the nominal channel thickness and the minimum channel thickness, respectively, and α is the Reynolds number exponent in the friction factor relationship. The value of α is typically between 0.2 and 0.25. For this analysis, an α of 0.25 is selected.

Flow distribution (random)

This uncertainty is the result of the hydraulic analysis that is used to determine the flow distribution among the coolant channels. This is a local effect that does not systematically affect all coolant channels. The determination of this uncertainty was based on the measurement of the flow speeds in the different coolant channels of a BR2 fuel assembly [18]. Appendix A shows that this uncertainty is of the order of 9%. Moreover, Ref. 14 states that for a given pressure drop over the vessel, the mass flow rate in a given fuel assembly has a small dependency on the loading of the core. For an unfavorable but credible loading, the mass flow rate in a FA could be reduced by 4%. For this analysis, these two uncertainties are statistically combined and a total uncertainty of 10% is used.

Single phase heat transfer correlation (systematic)

Heat transfer correlations typically predict heat transfer coefficients that are accurate to within 10 to 15%. A study [19] comparing the heat transfer coefficients predicted by various correlations and CFD clearly showed that, for thermal-hydraulic conditions similar to a BR2 channel near ONB, the selected heat transfer correlation must take into account the variation in water viscosity between the bulk coolant and the coolant adjacent to the channel wall. The same study also shows that the correlations using variable properties (Seider-Tate [20], Dittus-Boelter-Modified (i.e., corrected for viscosity changes) [19] and Petukhov & Popov [21]) and the CFD predict heat transfer coefficients within a range of ±10%. Since it is difficult to evaluate the true accuracy of any correlations for a configuration and regime (geometry, flow, power, pressure, etc.) representative of a BR2 channel near limiting conditions (ONBR, FDNBR and FIR near 1.0), a systematic error of 15% is applied in this analysis.

Hot stripe (systematic)

Since, i) the azimuthal peak shown in Fig. 4 can occur near the azimuthal center of a plate, ii) the azimuthal heat conduction has a limited effect in reducing the heat flux at that location [19], and iii) the coolant mixing effect is minimal in a BR2 channel [19]; a hot stripe approach is appropriate to taken into account the azimuthal power peak in PLTEMP. To model the hot stripe in PLTEMP, the azimuthal peak-to-average from Fig. 4 is used as a systematic HCF on F_q, F_{bulk} and F_{film}. Note that the azimuthal peaking of plate 6 is assumed to also apply to plate 5. Table 8 summarizes the HCFs used in this analysis.

Table 8. Hot Channel Factors for ONB – HEU and LEU fuel assemblies

				Hot Channel Factors			
Uncertainty	Type of tolerance	Effect on bulk ΔT (fraction)	Tolerance or uncertainty (fraction)	Heat flux, F_q	Heat transf. coef., F_h	Chan. temp. rise, F_{bulk}	Film temp. rise, F_{film}
U5 homog. (over 1 cm^2)	random		0.20	1.20			1.20
U5 loading per plate		0.5	0.02	1.02		1.01	1.02
Power density calculation		0.5	0.22	1.22		1.10	1.20
Channel spacing		1.0	1.11			1.20	1.04
Flow distribution		1.0	1.10			1.10	1.10
Random errors combined				*1.30*		*1.25*	*1.30*
Heat transfer coef.	systematic		1.15		1.15		
Hot stripe [a]			1.16 /1.18	1.16 /1.18		1.16 /1.18	1.16 /1.18
Final HCF - product of random and systematic errors (HEU/LEU)				**1.51 /1.53**	**1.15**	**1.45 /1.48**	**1.51 /1.53**

[a] HEU/LEU azimuthal peaking for the hot sector of fuel assembly C-259 in representative cores

5. Computational results

5.1. Impact of single-phase heat transfer correlation

Evaluating the margins to the three limiting conditions using PLTEMP requires the use of a single-phase heat transfer correlation. It is therefore useful to compare the heat flux (for ONBR = 1.0) predicted by PLTEMP using the three correlations discussed in Section 4.5. Table 9 shows the predicted heat flux at ONBR = 1.0 for the HEU core using the three correlations taking into account the variation of viscosity between the bulk coolant and the coolant adjacent to the channel wall.

Table 9. Heat flux for ONBR = 1.0 in the HEU core for three heat transfer correlations.

Limiting Condition	Heat flux (W/cm^2)		
	Sieder-Tate	Dittus-Boelter (modified)	Petukhov & Popov
ONBR = 1.0	687.4	620.2	724.6

Table 9 shows that the most conservative of the three heat transfer correlations predicts a margin to ONB of about 20 W/cm^2 above the 600 W/cm^2 temporary limit (including the systematic HCF of 15% applied on the heat transfer coefficient). The remainder of the analyses will use the Dittus-Boelter-Modified heat transfer correlation.

5.2. Comparison of the HEU and LEU thermal performance

In order to evaluate the thermal performance of the HEU and LEU cores, the three limiting conditions (ONBR, FDNBR, FIR) are determined for four percentages of the nominal true flow: 1%, 20%, 100% and 161.6%.

Figures 5 and 6 show the calculated heat flux and associated true fuel assembly power as a function of true average coolant speed and associated true mass flow rate. The allowed operating regions are also illustrated for both thermal limits: 470 W/cm^2 (short dashes) and 600 W/cm^2 (long dashes).

From Figs. 5 and 6, it can be seen that the margins to FI are large for either maximum heat flux (470 W/cm^2 and 600 W/cm^2) for mass flow rates above about 50% nominal. It can also be seen that the most conservative criterion, that is preventing ONB, is met for both heat flux limits when the mass flow rate is above the minimum flow lines.

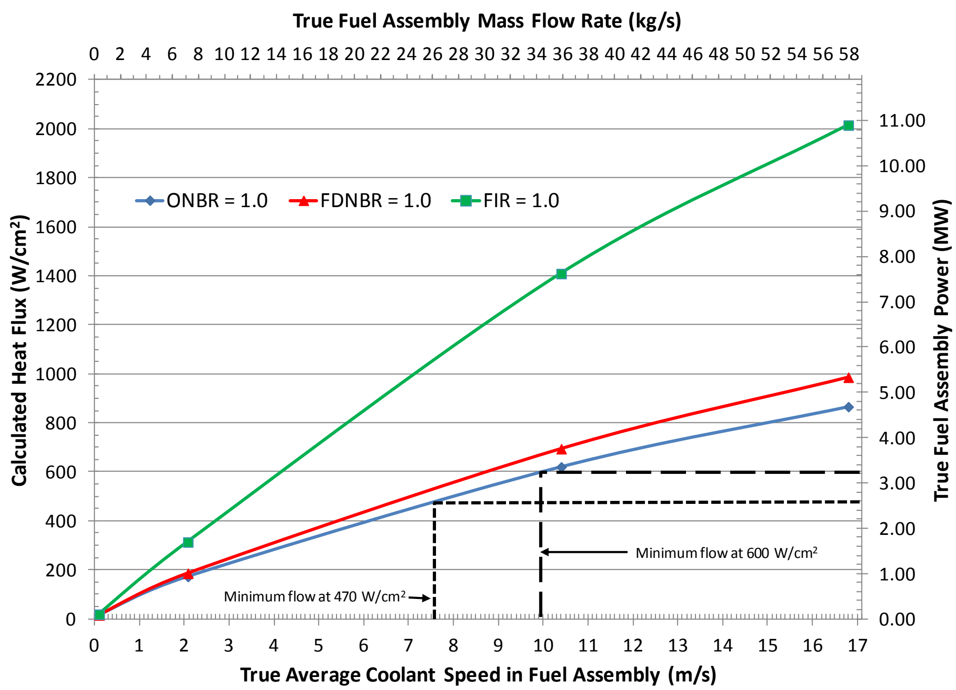

Figure 5. HEU core limiting conditions as a function of true average coolant speed

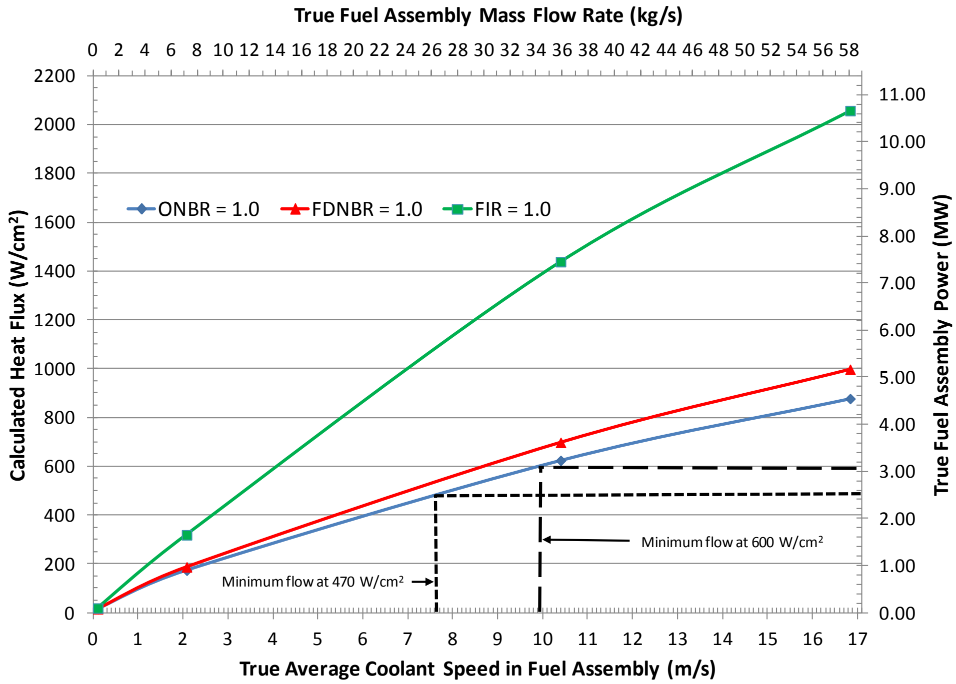

Figure 6. LEU core limiting conditions as a function of true average coolant speed

Figure 7 compares the thermal performance of the HEU and LEU cores with respect to ONB.

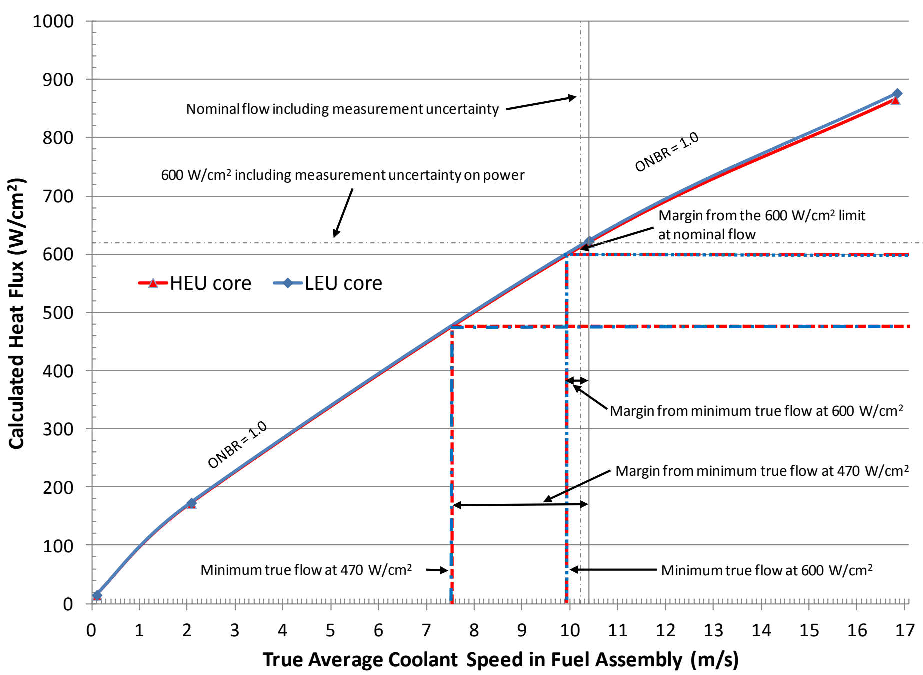

Figure 7. Thermal performance comparison for the HEU and LEU cores (ONBR = 1.0)

From Fig. 7 it can be seen that, for both the HEU and LEU cores: i) ONB occurs at nearly the same heat flux, ii) the allowed operational regions are almost identical, iii) the margins from nominal to minimum true flows (about 28% at 470 W/cm^2 and 5% at 600 W/cm^2) are larger than the uncertainty on flow measurement (2%, see Table 7), iv) at 470 W/cm^2 and nominal flow, the margin to ONBR = 1.0 (about 11%) is larger than the uncertainty in power measurement (3%, see Table 7), and v) at 600 W/cm^2 and nominal flow, the margin to ONBR = 1.0 (about 3%) is of the order of the uncertainty in power measurement (3%, see Table 7). Table 10 gives limiting fuel assembly heat flux and associated fuel assembly power at ONBR = 1.0.

Table 10. Limiting condition comparison

Limiting Condition	Heat flux (W/cm^2)		Fuel assembly power (MW)	
	HEU	LEU	HEU	LEU
ONBR = 1.0	620.2	623.6	3.5695	3.359

It can be seen that even if ONB occurs at similar heat fluxes in both cores, the maximum allowable LEU fuel assembly power is slightly lower than the HEU due to the slightly higher power peaking using in this analysis (see Section 4.4).

Finally, it is instructive to compare the predicted peak cladding surface and peak fuel temperatures at 1) the maximum nominal heat flux (470 W/cm^2), 2) the temporary maximum heat flux (600 W/cm^2), and 3) ONBR = 1.0 conditions. The peak clad surface and peak fuel temperatures shown in Table 11 where calculated with all HCFs (see Table 8). Note that for peak temperatures, a sensitivity study of the uncertainty associated with fuel and clad thermal conductivity should be performed. This aspect will be more important when considering depleted fuel assemblies due to the uncertainties in the change in thermal conductivities from irradiation (degradation of meat conductivity due interlayer growth, oxide growth, etc.).

Table 11. PLTEMP wall and peak fuel temperatures for three limiting conditions

Limiting Condition	Clad surface temperature (°C)		Fuel peak temperature (°C)	
	HEU	LEU	HEU	LEU
ONBR = 1.0	193.3	194.0	219.1	222.3
Temporary heat flux limit (600 W/cm^2)	188.9	188.9	213.9	216.0
Maximum nominal heat flux (470 W/cm^2)	160.0	159.8	179.4	180.9

As expected, the peak clad temperatures are almost identical for the HEU and LEU fuel assemblies since ONBR = 1.0 is reached at about the same heat flux and axial height. The slightly higher fuel peak temperature for the LEU fuel assembly is explained by the slightly lower thermal conductivity. However, this increase is small and does not limit thermal performance for fresh fuel.

6. Summary and conclusions

The objective of this analysis was to demonstrate the feasibility, from a thermal performance perspective, of converting the BR2 core using the proposed LEU fuel assembly design. More specifically, it was necessary to ensure that the safety margins would remain adequate.

To achieve this objective, a PLTEMP analysis of the limiting fuel assembly (defined as the assembly with the highest heat flux at beginning-of-cycle) was performed to evaluate the margins, when operating at steady-state at 470 W/cm^2 or 600 W/cm^2, to three limiting conditions: onset of nucleate boiling, fully developed nucleate boiling and flow instability.

The analysis showed that for the hot fuel assembly, the margins (with respect to heat flux and minimum flow) to the most conservative limit (onset of nucleate boiling) are essentially identical. Consequently, the use of the proposed LEU fuel assembly does not affect the capability to operate routinely at 470 W/cm^2 or exceptionally at 600 W/cm^2. The analysis also showed that, for these two operating heat fluxes, the margins to flow instability are large for mass flow rates above 50% of the nominal flow. Finally, an evaluation of the peak cladding and fuel temperatures of fresh fuel showed that these temperatures are not limiting conditions for reactor operation at any state below onset of nucleate boiling.

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Appendix A Evaluation of the Uncertainty on Flow Distribution

A series of coolant speed measurements in a BR2 fuel assembly is presented in Ref. 18. Table A-1 shows the speed measured in each channel.

Table A-1 Measured coolant speed in various channels of a BR2 fuel assembly

Channel	Measured Coolant speed (m/s)		
1	9.75	10.40	9.99
	10.20	10.00	10.40
2	10.20	10.17	10.50
	9.88	9.61	9.62
3	10.13	10.60	11.53
	10.50	10.50	10.69
4	10.48	10.72	10.60
	10.91	10.40	10.78
5	10.67	10.90	10.89
	10.70	10.63	10.18
6	10.47	10.60	10.40
	10.05		10.71
7	10.70	10.86	10.80
	10.80	10.40	9.80

For each channel, an average and standard deviation is calculated from the values in the above table. The largest relative error of 4.3% (standard deviation/average) is obtained for channel 3. The HCF component that reflects uncertainty in flow distribution is assumed to be twice the largest relative error. Therefore, an uncertainty of 1.09 is assumed in the evaluation of the HCFs.

Appendix B Limiting conditions as a function of flow conditions

This appendix presents, for both the HEU and LEU cores, the following quantities: heat flux, fuel assembly power, and wall (clad surface) temperature for various values of the flow: 1%, 20%, 100% and 161.6% (maximum flow based on allowed pressure drop) of nominal value. The nominal pressure and inlet temperature (1.24 MPa, 40°C) are used. It should be also noted that these values were used to derive Figs 5 and 6 in Section 5 and therefore do not include the systematic uncertainties on total power and flow.

B.1 HEU core

Table B-1. 1% of nominal flow, V=0.104 m/s, $\Delta P_{fuel\ plates}$=7.513E-5, HEU core

Limiting Condition	Heat flux (W/cm^2)	Fuel assembly power (MW)	Wall temperature (°C)
ONBR = 1.0	14.9	7.511E-2	190.7
FDNBR = 1.0	15.4	7.775E-2	195.2
FIR = 1.0	18.4	9.270E-2	220.6

Table B-2. 20% of nominal flow, V=2.08 m/s, $\Delta P_{fuel\ plates}$=0.01106 MPa, HEU core

Limiting Condition	Heat flux (W/cm^2)	Fuel assembly power (MW)	Wall temperature (°C)
ONBR = 1.0	172.0	0.96632	193.8
FDNBR = 1.0	185.7	1.0444	204.3
FIR = 1.0	313.2	1.7717	298.5

Table B-3. 100% of nominal flow, V=10.4 m/s, $\Delta P_{fuel\ plates}$=0.210 MPa, HEU core

Limiting Condition	Heat flux (W/cm^2)	Fuel assembly power (MW)	Wall temperature (°C)
ONBR = 1.0	620.2	3.5695	193.3
FDNBR = 1.0	694.1	4.0014	209.1
FIR = 1.0	1409	8.223	357.2

Table B-4. 161.6% of nominal flow (max), V=16.808 m/s, $\Delta P_{fuel\ plates}$=0.515, HEU core

Limiting Condition	Heat flux (W/cm^2)	Fuel assembly power (MW)	Wall temperature (°C)
ONBR = 1.0	865.7	5.008	187.0
FDNBR = 1.0	985.8	5.713	204.6
FIR = 1.0	2015	11.815	352.4

B.2. LEU core

Table B-5. 1% of nominal flow, V=0.104 m/s, $\Delta P_{fuel\ plates}$=7.513E-5, LEU core

Limiting Condition	Heat flux (W/cm^2)	Fuel assembly power (MW)	Wall temperature (°C)
ONBR = 1.0	14.9	7.219E-2	190.7
FDNBR = 1.0	15.5	7.474E-2	195.3
FIR = 1.0	18.4	8.899E-2	220.5

Table B-6. 20% of nominal flow, V=2.08 m/s, $\Delta P_{fuel\ plates}$=0.01106 MPa, LEU core

Limiting Condition	Heat flux (W/cm^2)	Fuel assembly power (MW)	Wall temperature (°C)
ONBR = 1.0	173.3	0.9118	193.9
FDNBR = 1.0	187.1	0.9862	204.6
FIR = 1.0	318.7	1.6933	302.2

Table B-7. 100% of nominal flow, V=10.4 m/s, $\Delta P_{fuel\ plates}$=0.210 MPa, LEU core

Limiting Condition	Heat flux (W/cm^2)	Fuel assembly power (MW)	Wall temperature (°C)
ONBR = 1.0	623.6	3.359	194.0
FDNBR = 1.0	697.5	3.763	209.9
FIR = 1.0	1438	7.857	364.3

Table B-8. 161.6% of nominal flow (max), V=16.805 m/s, $\Delta P_{fuel\ plates}$=0.515 MPa, LEU core

Limiting Condition	Heat flux (W/cm^2)	Fuel assembly power (MW)	Wall temperature (°C)
ONBR = 1.0	877.0	4.748	188.8
FDNBR = 1.0	997.0	5.407	206.6
FIR = 1.0	2057	11.28	359.5

Appendix C PLTEMP fuel inlet pressure

The set of pressure measurements made during cycle 01/2011 is used to define the reference fuel inlet pressure required by PLTEMP.

During that cycle, pressures were measured for two fuel assemblies at four axial locations. Figure C-1 illustrates the locations of the various pressure measurements (PRCA 4-1302, PS, PB and PO).

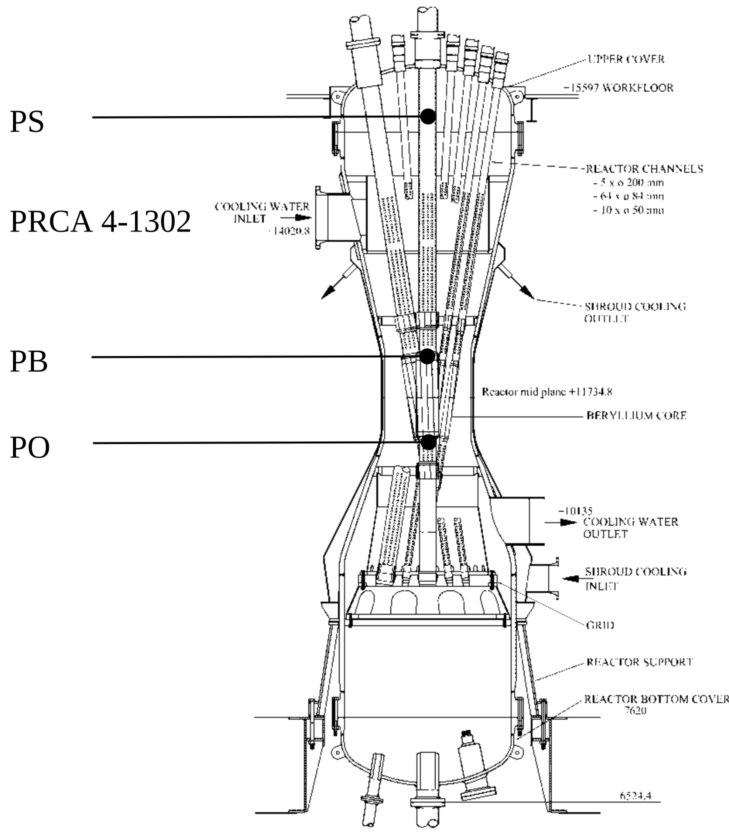

Figure C-1. Locations of pressure measurement in the BR2 core

The following list provides the measured pressures, averaged over the cycle, for the four locations shown in Fig. C-1.

- At the inlet of the PV (PRCA 4-1302): 12.2 kg'/cm^2,
- Below the reactor pressure vessel cover (PS): 11.8 kg'/cm^2,
- Above the fuel assembly (PB): 11.1 kg'/cm^2,
- Below the fuel assembly (PO): 9.0 kg'/cm^2.

The pressure gauges (measuring the difference with the local atmospheric pressure) for these measurements were located at about the same height, i.e.,

- 5.5m above PRCA 4-1302: static pressure head correction of 0.55 kg'/cm^2,
- 4.5m above PS: static pressure head correction of 0.45 kg'/cm^2,
- 7.0m above PB: static pressure head correction of 0.7 kg'/cm^2,
- 8.5m above PO: static pressure head correction of 0.85 kg'/cm^2.

Table C-1 gives the detail of the PLTEMP fuel inlet (PB) absolute pressure calculation.

Table C-1 Calculation of the PLTEMP fuel inlet absolute pressure

	Pressure	
	MPa	kg'/cm^2
Measured value at PB	1.0885	11.1
Correction: use minimum of pressure range[a]	-0.0191	-0.2
Correction: add atmospheric pressure	+0.1013	+1.03
Correction: add static pressure head	+0.0686	+0.7
PLTEMP inlet pressure	**1.24**	**12.6**

[a] Obtained by subtracting the measured pressure at the PV inlet (12.2 kg'/cm^2) from the minimum of the operating pressure range: 12.6 ± 0.6 kg'/cm^2.

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