REFERENCES

[1] Gorin, N.V., et.al. Review of research results for IGR impulse graphite reactor [electronic resource] // News of Chelyabinsk scientific center: electron. scien.-tech. period. – issue 1(22). – 2004 – URL: http://csc.ac.ru/news/2004_1/2004_1_3_1.zip (date: 04.10.2018)

BR2 FUEL ELEMENT HYDRAULIC ANALYSES FOR REACTOR CONVERSION

H-C LIN, A. RYKHLEVSKII, P. GARNER, A. OLSON, AND J. LICHT
Nuclear Science & Engineering Division, Argonne National Laboratory
9700 S. Cass Ave, 60439 Lemont, U.S.A

F. WOLS
Belgian Reactor 2, SCK CEN
Boeretang 200, 2400 Mol, Belgium

ABSTRACT

Argonne actively supports SCK CEN in the conversion of the BR2 reactor from highly enriched uranium (HEU) to low-enriched uranium (LEU) fuel. In addition to the use of U_3Si_2-Al fuel, the transition to LEU fuel also required minor modifications to the fuel element geometry. As a result, the hydraulic models used in the safety analysis software, including PLTEMP/ANL, RELAP5-3D, and PARET/ANL, required updates. Hydraulic analyses of the BR2 fuel element were conducted and compared with historically measured data for flow distribution and recent measurements of flow versus pressure drop. Independent subchannel models for the three codes were created to demonstrate consistency with experimental data. The comparisons demonstrate accuracy of the coolant flow distribution, which provides confidence in the models utilized for further safety analyses of reactor conversion.

1. Introduction

Argonne National Laboratory is supporting SCK CEN (Belgian Nuclear Research Centre) with the conversion of the Belgian Reactor 2 (BR2) from highly enriched uranium (HEU) to low-enriched uranium (LEU) fuel. To support the conversion process, new codes and methods have been implemented to update the BR2 Safety Analysis Report (SAR) as part of the 2016 periodic safety review (PSR). In particular, three thermal-hydraulics codes PLTEMP/ANL [1], RELAP5-3D [2], and PARET/ANL [3] have been used to perform BR2 safety analyses.

The LEU fuel for the BR2 conversion consists of a 1) transition from UAl_x-Al to U_3Si_2-Al dispersion fuel plus 2) geometric changes compared to the standard HEU fuel element [4] and other burnable absorber (gadolinium instead of boron-samarium) to better accommodate the LEU fuel type. To simplify the modification and qualification process, the standard HEU fuel element was first replaced in the BR2 reactor by the current COBRA HEU fuel element which already incorporated the geometric changes and burnable absorber foreseen for the eventual conversion to LEU. As a result, the COBRA HEU vs LEU conversion analyses can focus solely on the impacts of the change in the fuel system. However, due to geometric changes, updates to the models used for the 2016 PSR that incorporated the former standard fuel element are necessary to perform safety analyses in the framework of both the fuel conversion process and the upcoming 2026 PSR. Modelling improvements and additional consistency across the models used in each of the codes are also implemented.

The BR2 reactor is versatile and core load configurations are designed for each cycle to meet the needs for fuel experiments, medical isotope production, and silicon doping, etc. Thus, the total flow rate is not fixed; instead, the reactor is operated to maintain a constant core pressure drop of 2.1 kg/cm^2 to ensure adequate core cooling. For safety analyses, the fuel element inlet pressure is maintained at 12.6 kg/cm^2 (1.24 MPa) and the inlet coolant temperature is set to 40 °C [5]. The implementation of the fuel element geometry differs among the three different codes, as will be described in Section 3. To demonstrate consistency with the different approaches, independent calculations with the differing geometric models were performed and compared with available flow measurements (Section 4). This also serves as a validation of the independent calculations which are then used to define flow distribution and pressure boundary input to the codes used to perform BR2 safety analyses (Section 5).

2. BR2 fuel elements and measurement data

2.1 COBRA fuel element

Fig 1 shows a cross-section of the COBRA fuel element in a standard, 84 mm beryllium (Be) channel. The fuel elements are composed of concentric fuel plates that are divided by three aluminium spacers into three identical sectors. A central aluminium rod is mounted within the fuel element to direct the flow of cooling water through the coolant channels between the plates. Six of the channels are bound by the central aluminium rod and fuel plates, while the seventh is bound by the outside of plate 6 and inside of the Be channel. To accommodate the transition to LEU fuel, the nominal fuel plate thickness increased from 1.27 mm (HEU standard fuel) to 1.33 mm (COBRA geometry). The (minimum) Be channel radius used for safety analyses is also decreased from 42.1 mm to 41.85 mm due to replacement of the Be matrix. The spacing of 6 fuel plates for COBRA fuel remained the same as the standard fuel, subsequently, the outermost coolant channel (channel seven) thickness is lowered from 3.52 mm to 2.91 mm. The lengths of fuel plates (970 mm) and fuel meats (762 mm) are the same for the standard and the COBRA fuel. Note that the HEU and LEU COBRA elements have the same geometry. However, based on the uranium mass specifications, the width of the fueled zone differs slightly between the HEU and LEU COBRA elements.

Fig 1. COBRA fuel element in an 84 mm beryllium reactor channel

2.2 Measurement data

Two sources of experimental data are used in this study to support the model development of the standard and COBRA BR2 fuel elements. First, out of pile hydraulic tests were performed to measure flow distribution in different BR2 fuel elements [6]. Several different fuel element designs were tested, but only the results of the standard SVIn BR2 fuel element are used in this study. The measured flow velocities in all channels of all three sectors are listed in Tab 1.

Tab 1. Measured velocities from hydraulic tests of standard (SVIn) BR2 fuel element.

Channel	Velocity (m/s)			Average Velocity (m/s)	Standard deviation %
	Sector 1	Sector 2	Sector 3		
1	9.74	10.00	10.00	9.91	1.23
2	9.87	9.63	9.62	9.71	1.23
3	10.13	10.50	11.55	10.73	5.61
4	10.92	10.72	10.79	10.81	0.75
5	10.67	10.63	10.18	10.49	2.13
6	10.05	--	10.71	10.38	3.21
7	10.80	10.86	9.80	10.49	4.65
Fuel Element				10.36	8.46

The second set of data comprises the out-of-pile hydraulic tests for pressure drop as a function of flow rate for the standard and COBRA fuel element geometries [7] (Fig 2). Dummy fuel elements are fabricated to meet fuel element specifications. The mean coolant temperature was 25 °C and nominal pressure of 12 bar. At the same pressure drop, the smaller flow rate in the COBRA fuel is due to the smaller total flow area compared to the standard fuel element.

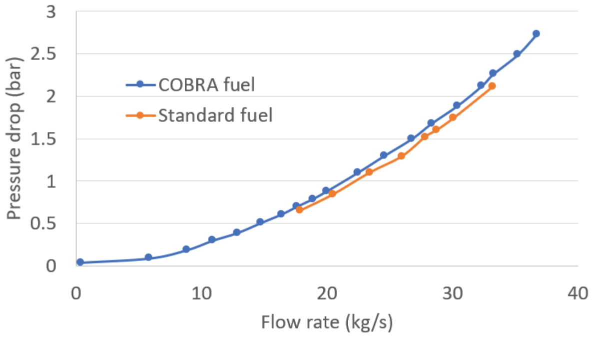


Fig 2. Flow rate and pressure drop measurements for standard and COBRA fuel elements.

3. Software

3.1 PLTEMP/ANL

PLTEMP/ANL is a steady-state thermal-hydraulics code. The PLTEMP/ANL BR2 model is created for one of the three sectors of the BR2 fuel element, consisting of seven coolant channels and six fuel plates. These channels and plates are represented by three axial regions: upper and lower unfueled region and fueled region. The seven channels are thermally coupled via the fuel plates within the fueled region. The outer surface of the aluminium plug and inner surface of Be channel are considered adiabatic. PLTEMP/ANL can perform calculations in either flow or pressure driven mode. In pressure-driven mode, the user provides the pressure boundary conditions at the channel inlet and outlet surfaces. The flow distribution and the total flow rate are iteratively determined based on flow area and calculated flow resistance. The pressure drop is calculated as follows:

$$dP = DENOF(W^2/2\rho)\ ,\ \ DENOF = \sum (K_{loss} + fL/D_h)/A^2 \qquad \text{Equation 1}$$

Where terms W and ρ represent the mass flow rate and density, evaluated at the channel average temperature and pressure. K_{loss} is minor loss coefficient and f is friction factor. L, D_h, and A are the length, equivalent hydraulic diameter and total flow area of a region, respectively. Note that users specify K_{loss} and wall roughness values only for each fueled or unfueled region. However, this limits flexibility when different K_{loss} and wall roughness need to be attributed to separate channels. A summary of the friction factor correlations used in PLTEMP/ANL is provided Tab 2, where ε is the surface roughness. The shape factors (Φ_{PLTEMP}) are calculated by PLTEMP/ANL based on the coolant channel geometries. For thin rectangular channels this is implemented in PLTEMP/ANL as follows [8]:

$$\Phi_{PLTEMP} = (1 - 1.3553x + 1.9467x^2 - 1.7012x^3 + 0.9564x^4 - 0.2537x^5) \qquad \text{Equation 2}$$

where x is the channel thickness to width ratio. Although BR2 coolant channels are not rectangular, the geometry differences have minimal impact using Equation 2. Taking channel six of the standard BR2 fuel element as an example, the shape factor is found to be 0.945 (i.e., $f = \frac{90.7}{Re}$). However, because of the modelling limitations described above in PLTEMP/ANL imposing only one value of wall roughness and K_{loss} for all channels of a fuel element, the use of the flow-driven mode is preferred for the BR2 safety analyses. The flow-driven mode requires the user to specify the mass flow rate of each channel, along with a pressure value at the inlet and outlet of the fuel element in the heated region.

Tab 2. PLTEMP/ANL friction factor correlations

Reynolds Number (Re)	Friction Factor Equation (f)
$Re \leq 2{,}200$	$f = 96\Phi_{PLTEMP}/Re$
$2{,}200 < Re < 3{,}000$	$f = \left(3.75 - \frac{8250}{Re}\right)(f_{Re=3000} - f_{Re=2200}) + f_{Re=2200}$
$Re \geq 3{,}000$	$f = 4f'$; $f'(smooth) = 6.25002/\left(1 - 8.68591\, Log_e \left[Re\sqrt{f'}\right] + 18.8612 \left(Log_e \left[Re\sqrt{f'}\right]\right)^2\right)$; $f'(rough) = 0.331369/\left(Log_e \left[0.27027 \frac{\varepsilon}{D_h} + 1.255/(Re\sqrt{f'})\right]\right)^2$

3.2 RELAP5-3D

RELAP5-3D is a thermal-hydraulics code used to model reactor system transients. It has greater modelling flexibility and different capabilities than PLTEMP/ANL and PARET/ANL. There are two main BR2 fuel element channels modelled in RELAP5-3D. One of these represents the limiting BR2 fuel element. It includes four subchannels, three representing a 10-degree stripe of the 5th, 6th and 7th coolant channels of one sector, and one for the remainder the fuel element (Fig 3).The second is a single-channel representing the flow area and hydraulic diameter for all other fuel elements in the reactor core. Coolant channels are defined by the hydraulic diameter and flow area, and heat structures (solid components) can be thermally coupled to the coolant channels. One of the modelling flexibilities in RELAP5-3D is that the user can specify local values for both the wall roughness (for each coolant node volume) and minor loss coefficients (for each coolant node junction). This differs from PLTEMP/ANL where only one wall roughness is supplied and one K_{loss} is supplied at the entrance, channel and exit locations for all coolant channels of a fuel element. The friction factors implemented in RELAP5-3D are summarized in Tab 3., where ε is the wall roughness and D is the hydraulic diameter.

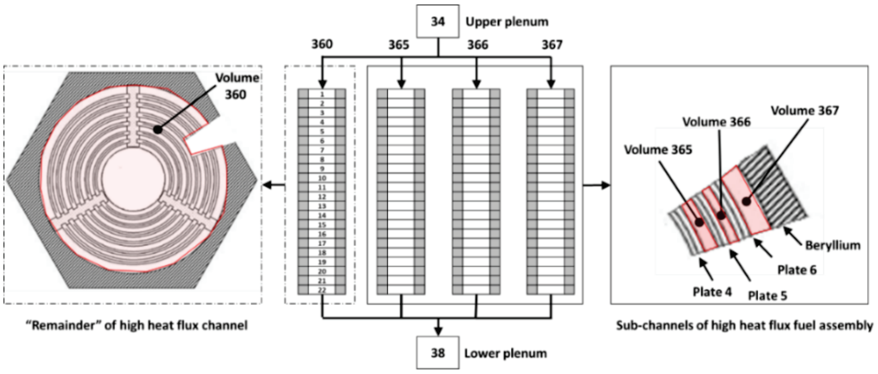


Fig 3. Discretization of the BR2 limiting fuel element used in RELAP5-3D

Tab 3. RELAP5-3D friction factor correlations

Reynolds Number (Re)	Friction Factor Equation (f)
$Re \leq 2{,}200$	$f = \frac{64}{Re\Phi_{RELAP5}}$
$2{,}200 < Re < 3{,}000$	$f = \left(3.75 - \frac{8250}{Re}\right)(f_{Re=3000} - f_{Re=2200}) + f_{Re=2200}$
$Re \geq 3{,}000$	$\frac{1}{\sqrt{f}} = -2log_{10}\left\{\frac{\varepsilon}{3.7D} + \frac{2.51}{Re}\left[1.14 - 2log_{10}\left(\frac{\varepsilon}{D} + \frac{21.25}{Re^{0.9}}\right)\right]\right\}$

RELAP5-3D allows for user-defined shape factors (Φ_{RELAP5}) to be applied to every coolant node. For K_{loss} in RELAP5-3D, the value can be either user-supplied or calculated from the code (abrupt area option) as shown in Equation 3 for contraction (Kc) and expansion (Ke). For the BR2 fuel element models in RELAP5-3D, the minor loss coefficients were calculated utilizing Equation 3. This gives Kc=0.131 and Ke=0.243 for the standard fuel element, and Kc=0.143 and Ke=0.282 for the COBRA fuel element. Note there is also a recoverable pressure change due to the change in flow area between A_1 (upstream) and A_2 (downstream).

$$K_c = \left(1 - \frac{A_2}{A_c}\right)^2; \frac{A_c}{A_2} = 0.62 + 0.38\left(\frac{A_2}{A_1}\right)^3, \quad K_e = \left(1 - \frac{A_1}{A_2}\right)^2 \qquad \text{Equation 3}$$

3.3 PARET/ANL

PARET/ANL is a transient, two-phase thermal-hydraulics and point-kinetics code. For this work, it models the BR2 reactor with two coolant channels, including a local hot stripe of the limiting BR2 fuel element and the remainder of all the fuel elements of the BR2 core (Fig 4). The fuel elements are modelled in a symmetric slab geometry such that only a half plate and half coolant channel make up each of the two channels. Note that PARET/ANL allows only one input for the plate width (PW) and fuel width (FW), and since these are equal in the hot stripe, the coolant channel thickness of the average channel must be increased by a constant factor (1.13 as in Fig 4) to maintain the proper coolant volume. The impact of this modification is negligible since PARET/ANL is used at BR2 mainly for reactivity insertion transients to investigate the hot stripe cooling conditions. The inlet and outlet plenums of the two channels must be considered separately in PARET/ANL. Therefore, each channel is represented by five distinct axial regions: inlet and outlet plenums, upper and lower unfueled portions of the fuel plates, and the fueled region.

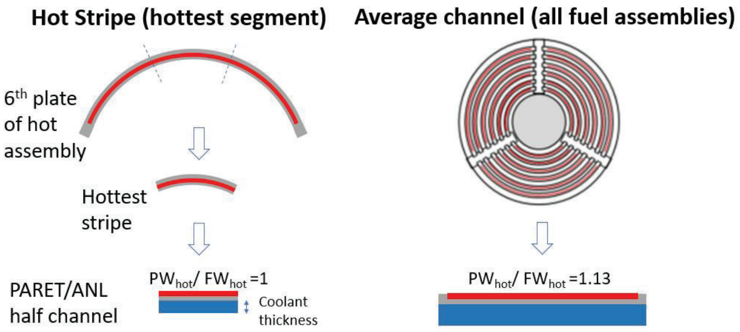


Fig 4. BR2 model discretization in the PARET/ANL analyses

PARET/ANL can be set up to calculate in flow-driven or pressure-driven mode. In pressure-driven mode, the user supplies the pressure boundary conditions at the inlet and outlet plenums. Flow distribution is determined iteratively from the calculated flow resistance. Similar to PLTEMP/ANL, a flow-driven calculation is applied to BR2 safety analyses to match the correct boundary conditions. In flow-driven mode, PARET/ANL requires the user to specify either an inlet or outlet plenum pressure and the channel mass flux values. Note that PARET/ANL applies the user-defined plenum pressure to all nodes of the channel in flow-driven mode, which is different from both PLTEMP/ANL and RELAP5-3D.

3.4 General comparison of the friction factor correlations

To investigate the consistency between the friction factors from the two codes, the friction factors in PLTEMP/ANL (Tab 2) and RELAP5-3D (Tab 3) are compared in Fig 5 for both smooth and rough walls, as a function of Reynolds number. PARET/ANL is not included in this comparison since the pressure distribution is not utilized in flow-driven mode and we seek only to evaluate the friction modelling in RELAP5-3D to develop the independent models. The BR2 fuel elements are estimated to have a surface roughness value of 1.6 μm. Here, it is assumed that this roughness is characteristic of a root mean square (RMS) measurement, in which case the wall sand-grain roughness is 4.96 μm (3.1 times the RMS value) [9]. The user-defined constants of shape factors in RELAP5-3D have been set to match that of the PLTEMP/ANL formulations; therefore, the models produce identical results in the laminar region. In the turbulent region, the friction factors show good agreement at large flow rates. The largest differences occur in the turbulent region as the flow is reduced to near the transition region (2,200 <Re <3,000). The differences between PLTEMP/ANL and RELAP5-3D are very minimal (less than 0.5% for a smooth wall and less than 0.4 % for a rough wall).

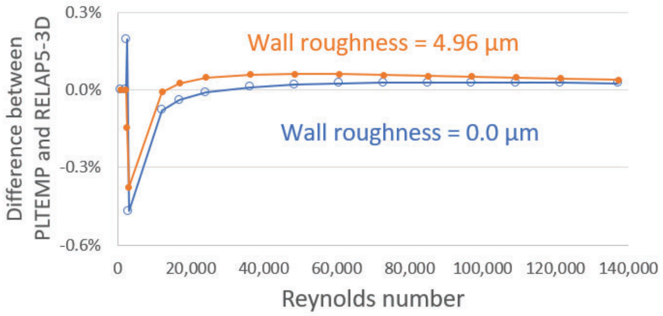


Fig 5. Comparison of friction factors in PLTEMP/ANL and RELAP5-3D

4. Independent hydraulic models

This section describes the results of independent hydraulic models of the BR2 standard and COBRA fuel elements that were developed using EXCEL spreadsheets and its built-in solver to perform iterations for obtaining velocities and pressure distributions. First, channel velocity data from a standard fuel element (Tab 1) is used to verify the independent 7-channel coolant model (referred to as a multi-channel model and equivalent to one sector of a BR2 fuel element). A COBRA fuel element is also analyzed to evaluate the expected changes in the velocity distribution. Second, due to different geometric modelling requirements in the safety analysis codes, other independent models are developed, including a single-channel and two subchannel models (as shown in Fig 3 for RELAP5-3D and Fig 4 for PARET/ANL). All of these models are validated against the measured flow versus pressure drop data to demonstrate consistency of the various fuel element discretizations used in the different safety analysis codes. The independent models are based on the equations used in RELAP5-3D. They consider the effects of the contraction and expansion losses described in Equation 3, pressure head, recoverable pressure losses, and frictional losses described in Tab 3.

When comparing the standard fuel flow distribution of independent model with measured data, using the sand-grain roughness value of 4.96 µm for all surfaces, it was found that there is reasonable agreement within the six inner channels of the fuel element. However, the calculated velocity between the fuel element and Be channel was much larger than experimentally measured (11.33 m/s vs 10.49 m/s). Several options were considered as the cause for this discrepancy. The experimental data indicated that the higher outer channel coolant velocity was not associated with the mispositioning of the fuel element within the channel, as the measurement data across all three outer channels consistently produced similar results. A more likely explanation is the difference between the wall roughness of the experiment pipe surface and the fuel element. Using a roughness value characteristic of the reactors' Be channel (sand-grain roughness = 9.3 µm) gave results similar enough to the measurements (10.78 m/s vs 10.49 m/s) and is a reasonable assumption for a potentially rough pipe wall in the experiment. This approach using a Be roughness value in the outer channel can also extend the analyses from the standard fuel element to the COBRA fuel element.

In Fig 6, the model produces a velocity distribution that is consistent with the measurements and does not overpredict the velocity in the 7th channel. The measured pressure drop is used as an input to the calculations and produces a total flow rate that is -0.9% different from the measurement (35.085 kg/s calculated vs 35.395 kg/s measured) and average velocity 10.32 m/s, which is quite consistent with the SAR value of 10.4 m/s (or more specifically 10.36 m/s). Fig 6 also shows the predicted velocity distribution of the COBRA geometry using the same assumptions. The velocity distribution in the COBRA fuel element is nearly identical to the standard fuel element for the six internal channels (as expected). The reduced velocity in channel seven due to the reduced flow area in COBRA fuel (9.59 m/s vs 10.49 m/s). The overall calculated mass flow rate of the COBRA fuel is reduced to 32.491 kg/s, or -6.42%.

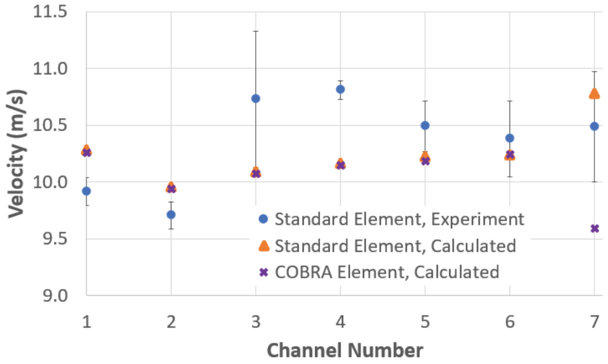
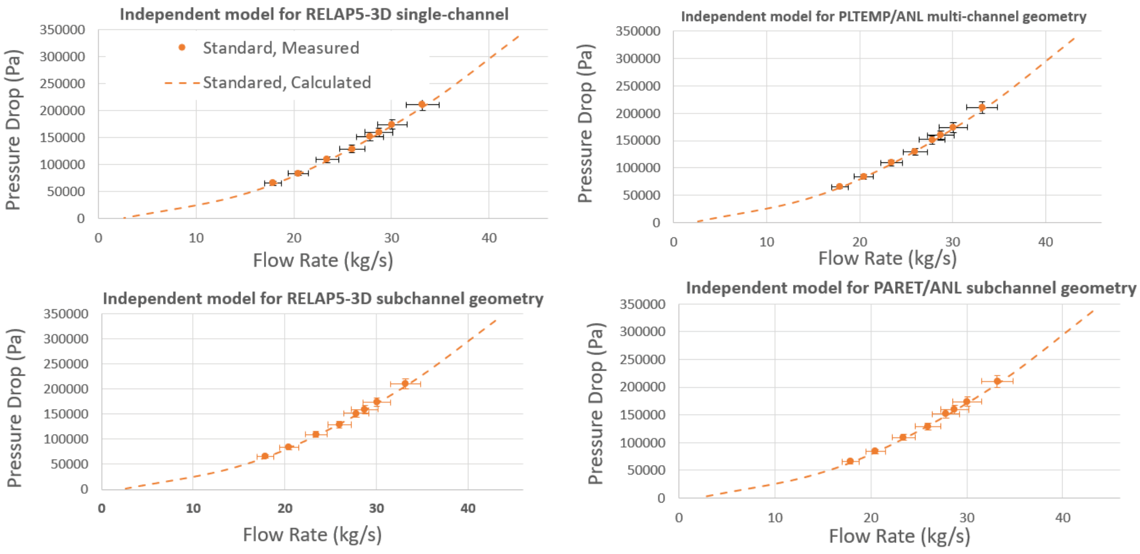


Fig 6. Comparison of the measured and calculated velocity distribution in BR2 fuel elements.

The validation of multi-channel and single-channel models against more recent measurements for both the standard and COBRA geometries are now discussed. These independent models have the same geometric modelling schemes used for safety analyses. PLTEMP/ANL modelling includes all seven channels of one fuel element sector, denoted here as the multi-channel model. RELAP5-3D modelling uses a set of subchannels to model the limiting fuel elements. RELAP5-3D modelling also uses a single-channel model that lumps the remaining fuel elements together for a single flow area for modelling other non-limiting fuels. Subchannel modelling is also used in PARET/ANL, where one channel represents a 10-degree stripe of the seventh channel and the other a single-channel model for the whole core.

The multi-channel model for the standard fuel element was shown in Fig 6 to align well with the historical measured data. Fig 7 further demonstrates that this model also matches well the more recent flow rate vs. pressure drop measurements, as well as for other geometries of independent models. This well validates the modelling approach and extends to the COBRA fuel element geometries as shown in Fig 8. Both Fig 7 and Fig 8 show that the various independent models of the fuel element match the flow pressure drop data extremely well and within an assumed experiment uncertainty of 5% across all flow rates. Based on these results, confidence is achieved that the independent models and different ways in which the fuel elements are discretized in the various safety analysis codes is consistent with the expected flow rate and pressure drop behavior.


Independent model for RELAP5-3D single-channel

Independent model for PLTEMP/ANL multi-channel geometry

Independent model for RELAP5-3D subchannel geometry

Independent model for PARET/ANL subchannel geometry

Fig 7. Comparison of independent models with measurements for standard fuel elements

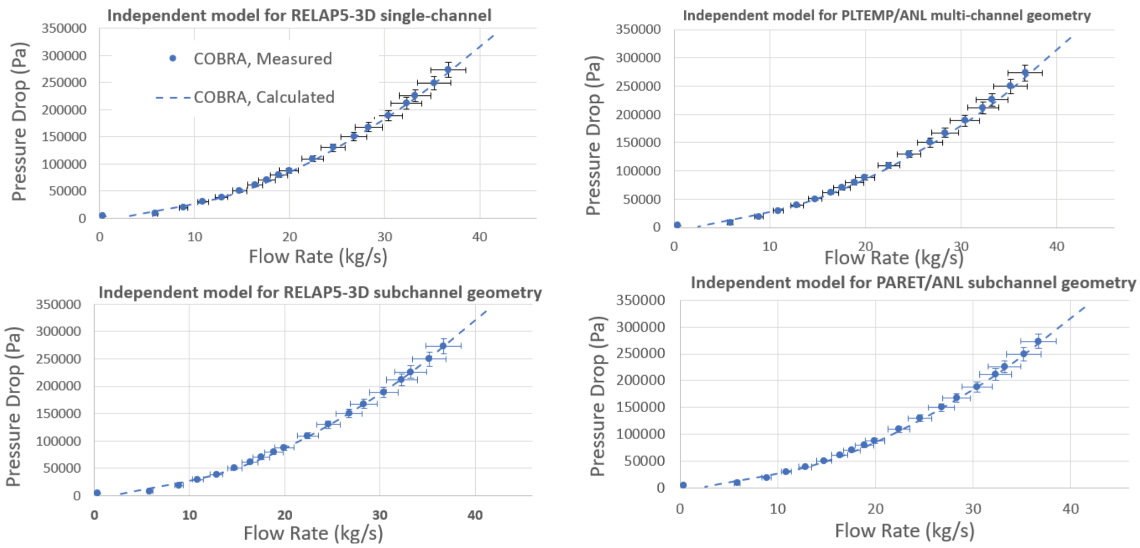


Fig 8. Comparison of independent models with measurements for COBRA fuel elements

5. Hydraulic models for safety analyses

5.1 PLTEMP/ANL and PARET/ANL hydraulic models

For PLTEMP/ANL, it was previously shown in Section 3.1 that the flow-driven mode should be used for a BR2 element, as code limitations prevent the user from implementing either a minor loss coefficient or wall roughness value for different coolant channels. In addition, the user must specify both the required flow and pressure drop across the fueled region. Here, the validated independent multi-channel hydraulic model is used to define the input parameters required in the PLTEMP/ANL safety analyses.

The PLTEMP/ANL input requires the mass flow rate of each channel and requires one pressure drop value. Tab 4 shows a comparison of the pressure distribution computed for the single and multi-channel hydraulic models at the inlet and outlet plenums, as well as the inlet and outlet of the plate and fueled regions. It can be seen that the pressure distribution calculated by the single-channel model is in very good agreement with the multi-channel model for nominal conditions (differences are less than 0.36%). Based on this, the flow and pressure distributions obtained from single-channel and multi-channels models are summarized in Tab 5, which can be used as PLTEMP/ANL input for standard and COBRA BR2 fuel element models in future work and safety analyses.

Tab 4. COBRA BR2 fuel element pressure distribution

		COBRA BR2 Fuel Element Pressure Distribution (Pa)						
		Inlet plenum	**Plate inlet**	**Start of heated section**	**End of heated section**	**Plate outlet**	**Outlet Plenum**	**Pressure Differential**
Single-Channel Model	Channel 1	1240000	1204392	1184726	1040635	1020969	1043507	205940
Multi-Channel Model	Channel 1	1240000	1201229	1181352	1035717	1015841	1043507	205940
	Channel 2		1204956	1185039	1039105	1019187		
	Channel 3		1203432	1183534	1037744	1017846		
	Channel 4		1202561	1182674	1036962	1017075		
	Channel 5		1202050	1182124	1036129	1016203		
	Channel 6		1201602	1181771	1036467	1016636		
	Channel 7		1207917	1187569	1038476	1018127		
Multi-Channel Average =			1203393	1183438	1037229	1017274		
% Difference from Single-Channel Model =			-0.08%	-0.11%	-0.33%	-0.36%		

Tab 5. Standard and COBRA BR2 fuel elements hydraulics for PLTEMP/ANL input files

BR2 fuel element	Mass flow rates for coolant channel (kg/s) (one sector)							Pressure drop (MPa)	Heated Section Inlet Pressure (MPa)	Heated Section Outlet Pressure (MPa)
	#1	#2	#3	#4	#5	#6	#7			
Standard	0.817	0.995	1.280	1.560	1.841	2.110	2.972	0.2059	1.184	1.040
COBRA	0.821	1.003	1.293	1.579	1.856	2.147	2.222	0.2059	1.185	1.041

For the PARET/ANL modelling, these results can be utilized for specifying one of the plenum pressures and the mass flux values for both the 10-degree hot stripe and remainder of the reactor core.

5.2 RELAP5-3D hydraulic models

Section 4 provided the validation of the independent subchannel model through comparison with experimental data. This section shows the comparison of RELAP5-3D subchannel model for the limiting fuel element. Since the independent hydraulic models were based on the RELAP5-3D correlations, it is expected and found that nearly identical results are achieved, as shown in Fig 9. Although not shown here, similar agreement is obtained for the RELAP5-3D single channel model used for modelling the lumping together of the remaining fuel elements in the core.

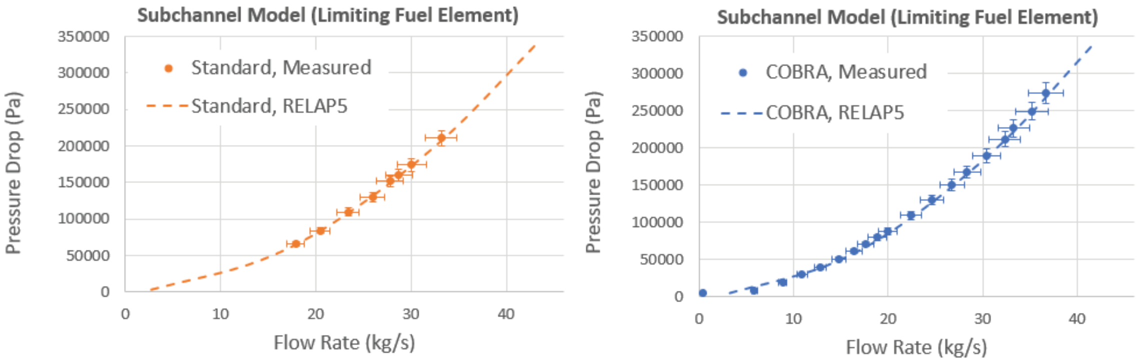


Fig 9. Comparison of the RELAP5-3D limiting fuel element models with measurements.

6. Conclusion

Argonne actively supports SCK CEN in the conversion of the BR2 reactor from HEU to LEU fuel. To accommodate the transition to LEU fuel, the U_3Si_2-Al dispersion fuel required geometric changes, increasing the fuel plate thickness from 1.27 mm to 1.33 mm and reducing the thickness of the outermost coolant channel (channel 7) from 3.52 mm to 2.91 mm. Accurate flow distribution and flow rates are crucial for reactor safety analyses regarding the adequate cooling of the reactor core. Three primary codes, namely PLTEMP/ANL, RELAP5-3D, and PARET/ANL, are utilized for safety analyses for the reactor conversion and the upcoming 2026 periodic safety review.

The models and correlations used by the different software to perform hydraulic calculations were discussed. The friction correlations implemented in the codes were also compared, demonstrating the similarities between the codes. Two experimental data sets were used for validation, one providing the flow distribution of a standard fuel element and the other providing pressure drop vs. flow rates for both standard and COBRA fuel elements. Independent models were developed based on the different discretization schemes used for the fuel elements in different safety analysis codes. These models were denoted the single-channel, multi-channel and subchannel models for standard and COBRA BR2 fuel elements. The models incorporate