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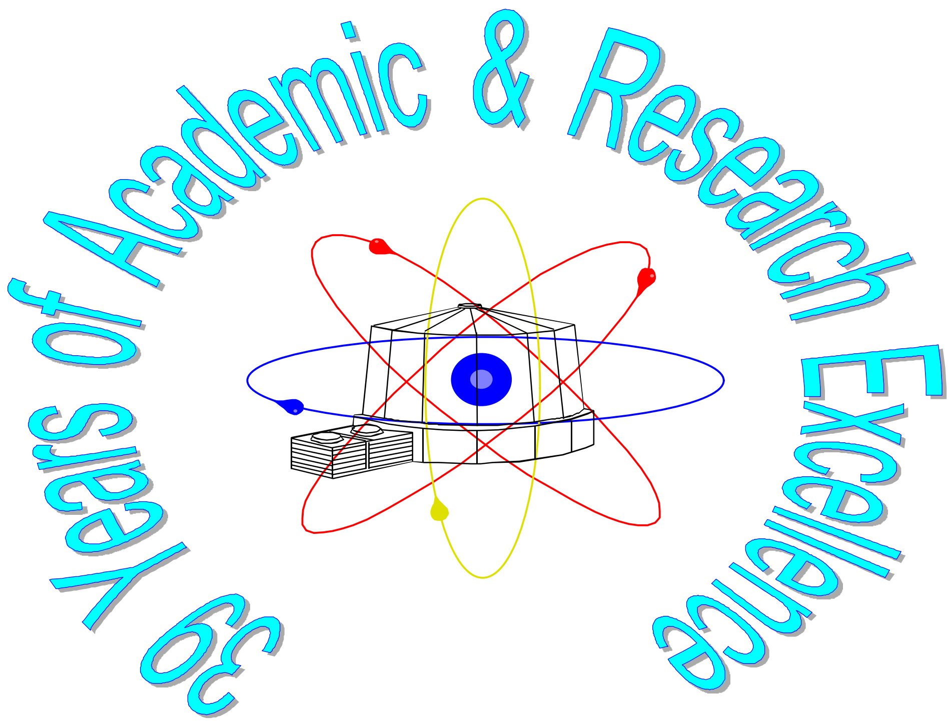
CATHENA Simulation of the MNR CORE with LEU Fuel Assemblies



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1. Introduction

It is planned to use low-enriched uranium (LEU) fuel in the MNR core. To support such a proposal, this report addresses the thermalhydraulics ramifications of the use of LEU plate assemblies of a design identical to the 18 plate HEU fuel currently used in the MNR core.

2. Model Setup

The core (48c) is modelled as the reference case. The core layout and associated flow assignments are depicted in figure 1. To provide a direct comparison, four high power (125 kW) assemblies are modelled:

- 10 plate PTR, node HPTR = central flow channels, node HPTROUT = outermost inner channel with full flow on both sides, node HPTRBYP = outside channel with reduced flow on one side
- 18 plate HEU, node MNR18HOT
- 18 plate LEU (225 grams of uranium per assembly), node HLEU225
- 18 plate LEU (285 grams of uranium per assembly), node HLEU284.

The rest of the core is modeled as 16 average 18 plate assemblies (node MNR18), 10 average 10 plate PTR assemblies (nodes APTR and APTRBYP), 6 control assemblies (nodes SHIM, SHIMBYP and SHIMABS) and 10 irradiation sites (node SAMPLES) for a total of 46 sites that involve coolant flow. The core bypass flow through the small grid holes are modeled by the COREBYP node and by the above nodes denoted by the label BYP.

From [TR98-05] the 225 gram LEU fuel meat is 32.25 % by volume U_3Si_2 in an Al matrix while the 285 gram LEU fuel meat is 41.0 % by volume U_3Si_2 in an Al matrix. The only difference in the 18 plate assemblies listed above that would impact on thermalhydraulic performance is the different heat capacity and thermal conductivity of the fuel meat caused by the different uranium loadings.

According to [ANL87], the volumetric heat capacity (which is the required input to CATHENA) is given as:

$$C_P(U_3Si_2-Al) = 0.0122\ V_F\ C_P(U_3Si_2) + 0.0027\ (1-V_F-V_P)\ C_P(Al)\ \mathrm{MJ/m^3\,°K}.$$

U_3Si_2 has a porosity fraction, V_P, for a fuel volume fraction, V_F, given by:

$$V_P = 0.072\ V_F^2 + 1.32\ V_F^3$$

and the heat capacities are:

$$C_p(U_3Si_2) = 199 + 0.104T \text{ J/kg}^\circ\text{K}.$$

$$C_p(Al) = 892 + 0.46T \text{ J/kg}^\circ\text{K}.$$

In the temperature range of interest (25°C to 600°C) the derived volumetric heat capacities for both loadings of LEU fuel are as given in the following table:

	Cp U_3Si_2 J/kg °K	
Temp	**225 gm**	**285 gm**
25	2.35104	2.26651
50	2.38110	2.29552
100	2.44122	2.35356
200	2.56145	2.46964
300	2.68169	2.58571
400	2.80192	2.70179
500	2.92215	2.81786
600	3.04239	2.93393

The thermal conductivities as determined from figure 6 of [ANL87] are:

k = 95 W/m°K for 225 gm fuel
k = 65 W/m°K for 285 gm fuel.

For previously reported CATHENA simulations of MNR, the fuel clad material used was alumina, whose properties are built-in to CATHENA. For any of the 18 plate assemblies at a high power position in a 2 MW core, this gives a fuel centerline temperature about 2 °C above the sheath temperature, hardly a significant temperature rise. When the actual aluminum properties are used, there is no discernible temperature rise in the fuel plate at all. In this report and henceforth, the sheath is modeled as aluminum unless otherwise stated.

Apart from the above minor differences, the thermalhydraulic model is as described in [TR97-04].

3. Simulation Results

Table 1 summarizes the flows and temperatures of the various core regions. The hottest fuel plates for this base case are the outer plates of the high power 10 plate PTR fuel assembly (HPTRBYP) at 67°C, compared to a maximum of 61°C for the high power 18 plate assembly (MNR18HOT, HLEU225 and HLEU284). As noted above, the temperature rise through the fuel plate is negligible when aluminum is used as the clad material. A core inlet temperature of 30°C is assumed throughout this report. The coolant velocity in the PTR assembly is calculated to be

0.96 m/s, compared to a velocity of 0.69 m/s in the 18 plate assemblies. The higher power per plate accounts for the higher temperatures in the PTR fuel in spite of the higher coolant velocities. These 10 plate PTR assemblies are of lower hydraulic resistance that the 18 plate assemblies and steal some flow from the 18 plate assemblies. It is thus worth noting that by switching to LEU fuel, the PTR fuel will eventually be displaced, resulting in additional cooling to the remaining 18 plate HEU and LEU assemblies, thereby increasing the safety margins.

There is no discernible difference within roundoff in the thermalhydraulic response as a function of LEU fuel loadings (225 grams vs 284 grams).

As seen in table 2, even at 6 times overpower (12 MW), the performance of the LEU plate fuel is virtually identical to that of HEU plate fuel. At this power, the coolant outlet temperature for the high power 18 plate assemblies is nearing saturation and a heat transfer crisis. The heat transfer crisis will occur at the coolant-sheath interface, not within the fuel plate, since the plate conductivity is so high, even with the use of alumina rather than aluminum for the sheath, as in this run.

Tables 3 and 4 show the results of MNR at 5 MW and 125% overpower of the 5 MW case. The core flow is raised to a nominal 138 kg/s (2200 USGPM), up from the 2 MW nominal flow of 101 kg/s (1600 USGPM). Again the 18 plate LEU assemblies behave like the 18 plate HEU assemblies. Note that the 10 plate PTR fuel has a sheath temperature at saturation for the overpower case, suggesting that a heat transfer crisis is imminent. This is consistent with the current license limitation that the reactor not be run above 2 MW with PTR fuel in the core.

CATHENA simulation input and output files are stored in archive directory (AECL-SP): herzberg:u94/garlandw/cathena/development/mod7-leu and in hard copy form at McMaster University.

4. Verification

Verification includes:

- CATHENA model verification as part of the ongoing model development under the guidance of AECL.

5. Conclusion

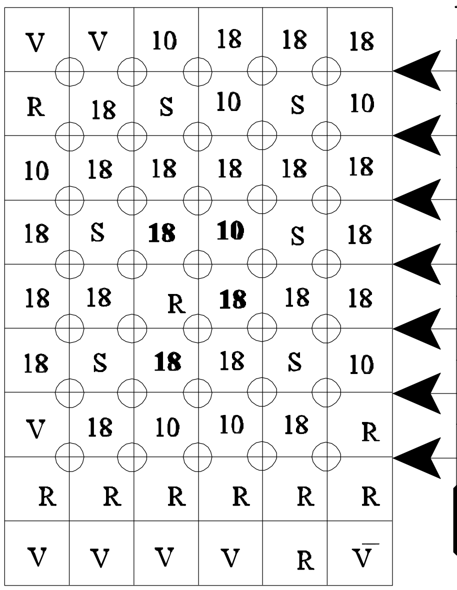
From the thermalhydraulic perspective, there is no reason to restrict the use of the 18 plate LEU plate type assemblies for up to 5 MW operation since the LEU thermalhydraulic performance is essentially identical to that of HEU. By displacing 10 plate assemblies over time, thermalhydraulic safety margins are improved.

6. References

ANL-87 J. L. Snelgrove, R.F. Domagala, G.L. Hofman, T.C. Wiencek, G.L. Copemand, R.W. Hobbs, and R.L. Senn, “The Use of U3Si2 Dispersed in Aluminum in Plate-type Fuel Elements for Research and Test Reactors, Argonne National Laboratory, ANL/RERTR/TM-11, October 1987.

TR97-04 Wm. J. Garland, "Thermalhydraulic Modelling of MNR", McMaster University Nuclear Reactor, Technical Report MNR-TR 97-04, April 28, 1997.

TR98-05 Hassan Basha, “Reactor Physics Calculations for Conversion of MNR from HEU to LEU Fuel”, McMaster University Nuclear Reactor, Technical Report MNR-TR 98-05, June 20, 1998.



APTRBYP	HPTRBYP	SHIMBYP	COREBYP	Total
1.5		2	1.5	5
2		2	1	5
0.5		2	1.5	5
	1	2	2	5
0.5	1	2	2.5	5
0.5		2	2.5	5
2			3	5
7	**2**	**12**	**14**	**35**

Figure 1 Bypass flow assignment for the base case (core 48c)

Table 1 Flow and temperature results for the base case (2 MW) - CATHENA run leu4a.

ASSEMBLY GROUP (# of assemblies in the group)	COOLANT VELOCITY (m/s)	TOTAL FLOW (kg/s)	COOLANT OUTLET TEMP (°C)	MAXIMUM SHEATH SURFACE TEMP (°C)	MAX FUEL TEMP (°C)
MNR18 (16 average HEU)	0.69	35.82	35	43	43
MNR18HOT (1 HEU)	0.69	2.25	43	60	60
HLEU225 (1 LEU225)	0.69	2.25	43	60	60
HLEU284 (1 LEU284)	0.69	2.25	43	60	61
APTR (10 average PTR)	0.96	37.33	33	44	44
APTRBYP	0.69	3.63	33	45	46
HPTR (1 hot PTR)	0.96	2.9	37	63	64
HPTROUT	0.96	0.83	38	63	64
HPTRBYP	0.69	0.69	35	67	67
SHIM (6 control assemb.)	0.69	7.1	34	46	46
SHIMBYP	0.69	3.63	36	46	47
COREBYP	0.69	2.72	30	-	-
SAMPLES (10 irrad.)	0.03	0.28	30	-	-
SHIMABS	0.05	0.27	30	-	-

Table 2 Flow and temperature results for the 6 x overpower case(12 MW) - alumina sheath - CATHENA run leu3a.

ASSEMBLY GROUP (# of assemblies in the group)	COOLANT VELOCITY (m/s)	TOTAL FLOW (kg/s)	COOLANT OUTLET TEMP (°C)	MAXIMUM SHEATH SURFACE TEMP (°C)	MAX FUEL TEMP (°C)
MNR18 (16 average HEU)	0.69	35.84	62	97	102
MNR18HOT (1 HEU)	0.68	2.19	112	135	146
HLEU225 (1 LEU225)	0.68	2.19	112	135	146
HLEU284 (1 LEU284)	0.68	2.19	112	135	147
APTR (10 average PTR)	0.95	37.05	48	107	116
APTRBYP	0.69	3.63	48	116	125
HPTR (1 hot PTR)	0.94	2.84	74	140	166
HPTROUT	0.94	0.81	75	140	165
HPTRBYP	0.69	0.61	60	142	167
SHIM (6 control assemb.)	0.69	7.11	52	116	122
SHIMBYP	0.69	3.63	67	118	124
COREBYP	0.69	2.73			
SAMPLES (10 irrad.)	0.03	0.28			
SHIMABS	0.05	0.27			

Table 3 Flow and temperature results for the 5 MW case - CATHENA run leu7a.

ASSEMBLY GROUP (# of assemblies in the group)	**COOLANT VELOCITY (m/s)**	**TOTAL FLOW (kg/s)**	**COOLANT OUTLET TEMP (°C)**	**MAXIMUM SHEATH SURFACE TEMP (°C)**	**MAX FUEL TEMP (°C)**
MNR18 (16 average HEU)	0.94	48.8	40	53	54
MNR18HOT (1 HEU)	0.95	3.07	54	85	86
HLEU225 (1 LEU225)	0.95	3.07	54	85	86
HLEU284 (1 LEU284)	0.95	3.07	54	85	86
APTR (10 average PTR)	1.28	50.01	35	56	57
APTRBYP	0.94	4.93	36	59	60
HPTR (1 hot PTR)	1.28	3.89	43	94	95
HPTROUT	1.28	1.11	44	94	95
HPTRBYP	0.94	0.82	39	100	102
SHIM (6 control assemb.)	0.94	9.67	37	60	60
SHIMBYP	0.94	4.95	41	61	62
COREBYP	0.94	3.70	30	-	-
SAMPLES (10 irrad.)	0.04	0.37	30	-	-
SHIMABS	0.07	0.36	30	-	-

Table 4 Flow and temperature results for power at 125% of the 5 MW case (6.25 MW) - CATHENA run leu8a.

ASSEMBLY GROUP (# of assemblies in the group)	COOLANT VELOCITY (m/s)	TOTAL FLOW (kg/s)	COOLANT OUTLET TEMP (°C)	MAXIMUM SHEATH SURFACE TEMP (°C)	MAX FUEL TEMP (°C)
MNR18 (16 average HEU)	0.94	48.81	42	59	59
MNR18HOT (1 HEU)	0.95	3.07	60	97	98
HLEU225 (1 LEU225)	0.95	3.07	60	97	99
HLEU284 (1 LEU284)	0.95	3.07	60	97	99
APTR (10 average PTR)	1.28	49.96	37	63	64
APTRBYP	0.94	4.93	37	66	67
HPTR (1 hot PTR)	1.28	3.89	47	108	110
HPTROUT	1.28	1.11	48	108	110
HPTRBYP	0.94	0.82	41	116	118
SHIM (6 control assemb.)	0.94	9.67	38	67	68
SHIMBYP	0.94	4.95	44	68	69
COREBYP	0.94	3.70	30	-	-
SAMPLES (10 irrad.)	0.04	0.37	30	-	-
SHIMABS	0.07	0.36	30	-	-