VALIDATION OF THE MULCH-II CODE FOR THERMAL-HYDRAULIC SAFETY ANALYSIS OF THE MIT RESEARCH REACTOR CONVERSION TO LEU

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ABSTRACT

An in-house thermal hydraulics code was developed for the steady-state and loss of primary flow analysis of the MIT Research Reactor (MITR). This code is designated as MULti-CHannel-II or MULCH-II. The MULCH-II code is being used for the MITR LEU conversion design study. Features of the MULCH-II code include a multi-channel analysis, the capability to model the transition from forced to natural convection during a loss of primary flow transient, and the ability to calculate safety limits and limiting safety system settings for licensing applications. This paper describes the validation of the code against PLTEMP/ANL 3.0 for steady-state analysis, and against RELAP5-3D for loss of primary coolant transient analysis. Coolant temperature measurements obtained from loss of primary flow transients as part of the MITR-II startup testing were also used for validating this code. The agreement between MULCH-II and the other computer codes is satisfactory.

1. Introduction

An in-house thermal hydraulics code, MULti-CHannel-II or MULCH-II, was developed for the steady-state and loss of primary flow analysis of the MIT Research Reactor (MITR) [1,2,3]. The MULCH-II code features the multi-channel analysis, natural circulation and anti-siphon valve models, fin effectiveness model and correlations for low pressure systems. In addition, the MULCH-II code is

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capable of modeling forced to natural convection during a loss of primary flow transient and calculating the safety limits and limiting safety system settings for licensing applications.

This paper presents the benchmark results of the MULCH-II code for the MITR low enrichment uranium (LEU) conversion study. The PLTEMP/ANL (version 3.0) [4] and RELAP5-3D (version 2.3.6) [5] are chosen to benchmark MULCH-II for steady state analysis and loss of primary flow transient, respectively. Furthermore, coolant temperature measurements obtained from loss of primary flow transients as part of the MITR-II startup testing were also used for the benchmark of the MULCH-II.

2. Description of the MIT Research Reactor

Figure 1 is an isometric view of the MIT Research Reactor (MITR). The MITR is a 5 MW nuclear research reactor that is owned and operated by the Massachusetts Institute of Technology to further its educational and research missions. It is currently being relicensed for 6 MW operation. The reactor uses finned plate-type fuel with aluminum clad and is cooled and moderated by light water. The longitudinal fins are 10 mils by 10 mils which doubles the heat transfer surface area. Currently the MITR uses highly enriched uranium (HEU) fuel in the form of UAl_x cermet. The fuel elements are rhomboid in shape and each contains fifteen plates. The reactor core can hold up to twenty- seven of these elements. The normal core configuration is twenty-four fuel elements with three positions available for in-core experiments.[6]

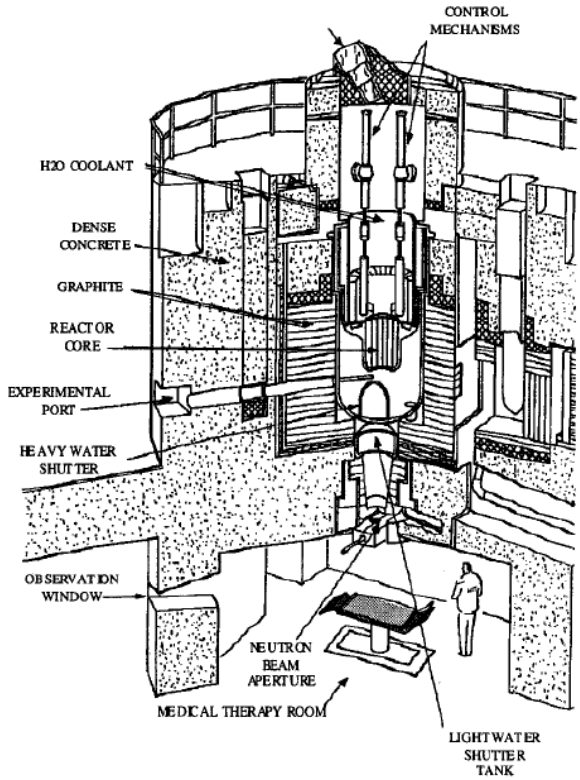

Figure 1. Isometric View of the MIT Research Reactor

Reactor control is provided by six boron-impregnated stainless-steel shim blades and one cadmium regulating rod. The core is contained in a tank of light-water and this tank is in turn surrounded by first a heavy-water and then a graphite reflector. Forced flow removes heat from the primary, heavy water, and graphite region with all heat loads being deposited in a common secondary cooling system. There are two anti-siphon valves located in the upper core tank to prevent complete drainage because of a siphon effect in the event of a break in the inlet primary piping. Four natural convection valves, that are located next to the flow guide, provide a natural circulation flow path for decay heat removal. The pressure in the system is practically atmospheric, and coolant temperature is approximately 50 °C (120 F).

3. MULCH-II benchmark study for steady-state analysis using PLTEMP/ANL

PLTEMP/ANL is developed and maintained by ANL and has been used for other conversion studies [7]. Benchmark analyses are based on a steady-state reactor power of 6 MW for the existing high enrichment uranium (HEU) core. For simplicity, in the following paragraph the terms “MULCH” and “PLTEMP” will be used instead of “MULCH-II” and “PLTEMP/ANL” code.

The fin effectiveness of the MULCH code is a multiplication factor used in conjunction with the coolant heat transfer coefficient to account for the heat transfer augmentation due to the longitudinal fins on the clad surface. Since PLTEMP v3.0 cannot include the fin effectiveness as in the case of MULCH, the plate width was increased to account for the larger heat transfer area. Regarding the heat transfer correlation, PLTEMP uses Dittus-Boelter to calculate single phase and Bergles-Rohsenow to calculate two-phase heat transfer coefficient. MULCH uses the Chen correlation to calculate both single and two-phase heat transfer coefficient.

Figure 2 is the comparison of coolant temperature. Average and hot channel temperature are both plotted in the figure. Coolant temperature is determined by energy conservation equation which is a function of power (integrated heat flux) and coolant inlet temperature. Since these parameters are the same in MULCH and PLTEMP as input parameters, as shown in Fig.2, the calculated coolant temperatures are about the same. Figure 3 is the comparison of cladding temperature. As shown in Fig. 3, the cladding temperature curves are very close between these two codes. PLTEMP predicts slightly lower cladding temperature than MULCH which is consistent with the coolant temperature difference.

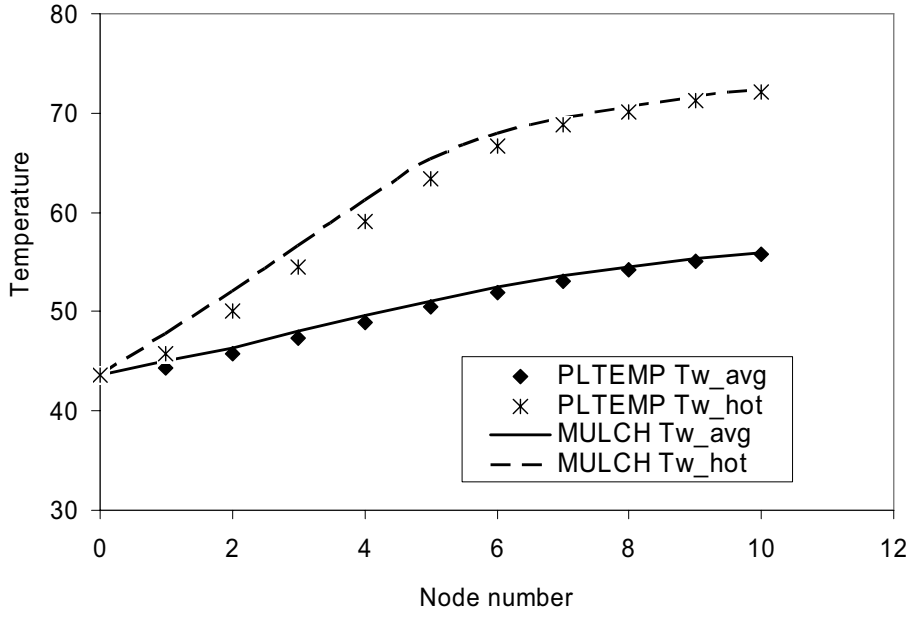

Figure 2. Comparison of coolant temperature (MULCH VS PLTEMP, steady state)

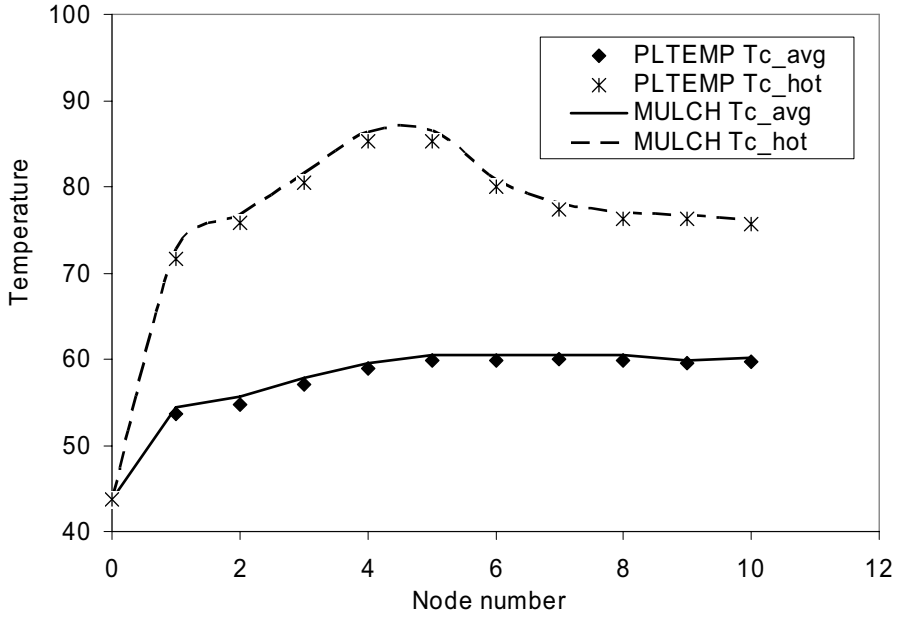

Figure 3. Comparison of cladding temperature (MULCH VS PLTEMP, steady state)

Table 1. Comparison of hot channel heat flux, temperature difference* and heat transfer coefficient (MULCH VS PLTEMP, steady state)

	Heat Flux q" (W/m^2)		Temperature Difference Tc – Tw (ºC)		Heat Transfer Coefficient h (W/m^2 ºC)	
Node	MULCH	PLTEMP	MULCH	PLTEMP	MULCH	PLTEMP
1	4.21E+05	4.21E+05	24.9	25.96	1.69E+04	1.62E+04
2	4.33E+05	4.33E+05	24.7	25.775	1.75E+04	1.68E+04
3	4.52E+05	4.52E+05	24.9	25.995	1.82E+04	1.74E+04
4	4.70E+05	4.70E+05	25.1	26.163	1.87E+04	1.80E+04
5	4.06E+05	4.05E+05	21.1	21.914	1.92E+04	1.85E+04
6	2.51E+05	2.51E+05	12.8	13.25	1.96E+04	1.89E+04
7	1.65E+05	1.65E+05	8.7	8.586	1.89E+04	1.92E+04
8	1.17E+05	1.17E+05	6.3	6.068	1.86E+04	1.93E+04
9	9.77E+04	9.77E+04	5.1	5.023	1.92E+04	1.94E+04
10	6.95E+04	6.95E+04	3.7	3.554	1.88E+04	1.95E+04

*Temperature Difference = cladding temperature (Tc) – coolant temperature (Tw)

Table 1 summarizes the comparison of hot channel heat flux and heat transfer coefficient. It shows that the heat flux is exactly the same in the two codes. Since the simulation case is steady state, i.e., no boiling occurs, MULCH and PLTEMP use the same correlation for single phase heat transfer (Chen's correlation reduces to standard Dittus-Boelter during single phase flow). Therefore the values of heat transfer coefficient should be roughly the same. It should be noted that the discrepancy in cladding-coolant temperature difference is less than 4% and is consistent with that of heat transfer coefficients.

4. MULCH-II benchmark study for loss of primary flow transient using RELAP5-3D

The RELAP5-3D input model for the MITR 6 MW power uprate was assembled. Analyses are based on a steady-state reactor power of 6 MW with an initial flow rate at 2000 gpm for the existing HEU core. For simplicity, the term "RELAP5" will be used instead of "RELAP5-3D" in the following description.

Figure 4 is a comparison of the simplified primary loop control volumes of MITR for MULCH and RELAP5 code for the LOF transient simulations. Anti-siphon valves (ASVs) and natural convection valves (NCVs) are also shown in the figures. Both ASV and NCV are very important components for establishing natural circulation during the loss of primary flow transients. As shown in Fig. 4, it can be found that RELAP5 divides the primary loop into more control volumes. In the RELAP5 MITR model,

mixing area is split into three sub-regions and the average channel, hot channel and bypass flow are separate control volumes.

Convection heat transfer correlations are different in the MULCH and RELAP5 codes. MULCH uses Chen's correlation for both single and two-phase transfer. For RELAP5, single phase heat transfer correlations are calculated relying on evaluating forced turbulent convection, forced laminar convection, and natural convection and selecting the maximum of these three. The correlations are by Dittus-Boelter, Kays, and Churchill-Chu, respectively. Two-phase heat transfer correlations are calculated by Chen's correlation for nucleate boiling and transition boiling; by Bromley correlation for film boiling.

When a pump coast down accident occurs, the reactor will shut down automatically upon receiving a low primary coolant flow scram signal. In the loss of primary flow simulation, MULCH assumes the reactor will shut down after 2.3 seconds (one second of instrument delay time and 1.3 seconds for shim blade insertion) by a step reactivity insertion after the low flow scram setpoint is reached. For RELAP5, it is assumed that the reactor will scram by a ramp reactivity insertion with a reactivity insertion of -7.5 beta (corresponding to MITR shim bank height of 10") within one second after the scram is initiated.

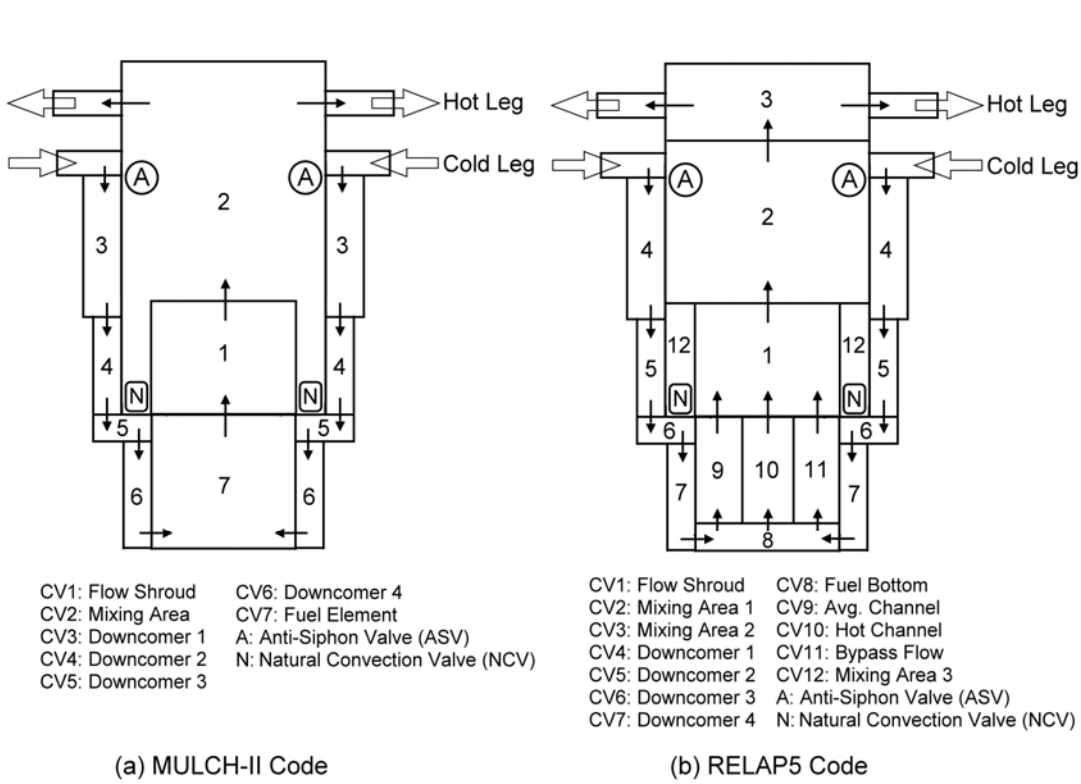

Figure 4. Primary loop control volumes for MIT reactor

There are four natural convection valves (NCVs) and two anti-siphon valves (ASVs) installed in the reactor core tank. During normal operation (forced convection), NCVs and ASVs are closed due to primary coolant pressure head. Determination of the friction loss coefficients of these ball-type check valves is given in Ref [8]. When the pressure reduces (e.g., pump coastdown), NCVs and ASVs will open. Natural convection flow is then established within the core tank because of the buoyancy force of the heated coolant in the core region. In the MULCH simulation cases, it is predicted that the NCV and ASV will open at the same time, about 4.4 seconds after the initiating event. For RELAP5, we use this timing as an assumption to force open the NCVs and ASVs at 4.4 seconds. It is reasonable since RELAP5 adopts the same pump coastdown curve as MULCH.

Figures 5 and 6 are the calculated flow rates of ASV and NCV. In Fig.5 and Fig. 6, positive flow rate means it is an "up-flow" or "bypass flow"; if negative, it is a "down-flow" or "natural convection flow". As show in Fig. 5, the flow passing through ASV is always a down-flow during the transient. Overall, RELAP5 predicts higher ASV flow rate than the prediction of MULCH. Besides, MULCH predicts the steady state ASV flow rate of 1.37 (kg/s), which is slightly less than RELAP5's prediction. of 1.40 (kg/s). Figure 6 shows that at first, the flow passing through NCV is upward during pump coastdown. MULCH predicts flow through the NCV would become downward (natural convection flow) at 18.4 second. RELAP5 predicts the natural convection flow established at time equal to 15.0 second. For RELAP5 and MULCH, the steady-state NCV flow rates are 0.51 (kg/s) and 0.29 (kg/s) respectively.

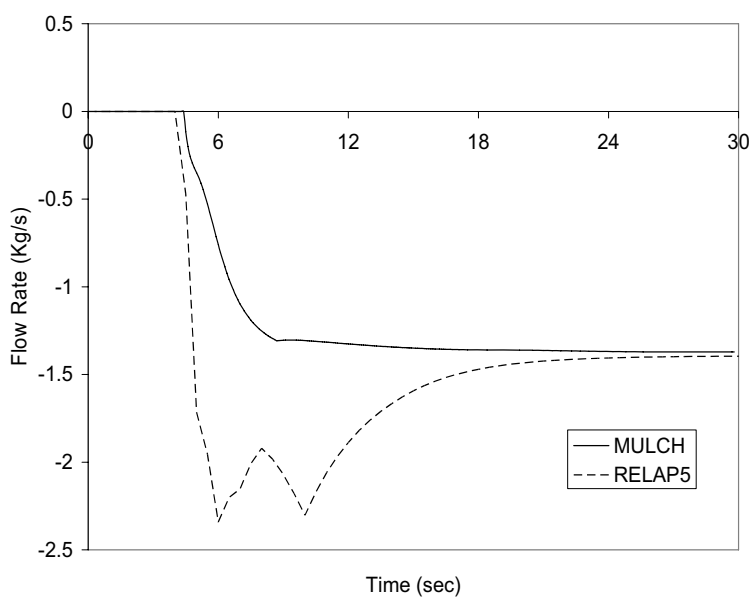

Figure 5. Comparison of ASV flow rate

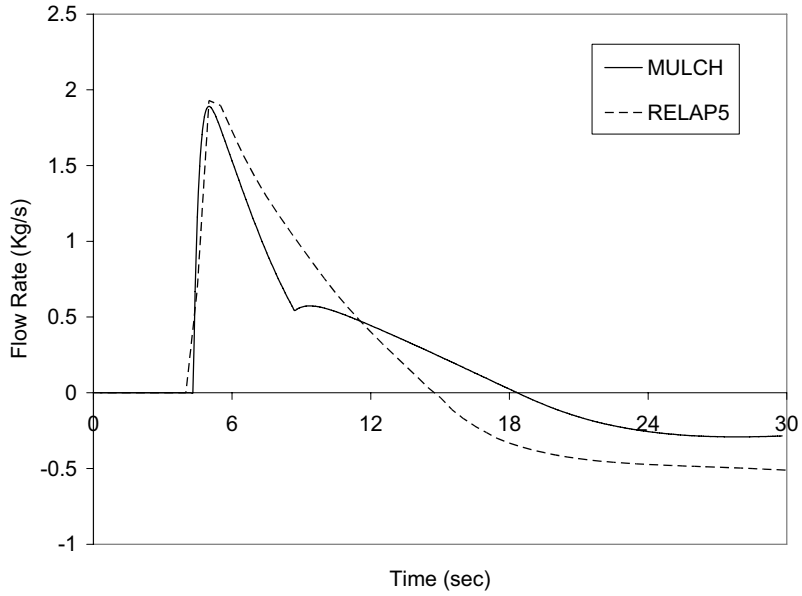

Figure 6. Comparison of NCV flow rate

Table 2. Comparison of primary flow rates through reactor core during LOF transient

Time (sec)	Core flow rate (kg/s)	
	MULCH	RELAP5
0.0	115.1	115.2
1.0	63.2	56.9
2.0	34.2	30.6
3.0	18.6	16.7
4.0	9.96	9.04
4.5	5.80	5.63
5.0	3.46	3.62
6.0	1.74	2.60
7.0	1.08	2.10
8.0	0.77	1.82
9.0	0.68	1.66
10.0	0.69	1.56
20.0	1.35	1.89
30.0	1.52	1.91

Comparison of core flow rate is summarized in Table 2. At the beginning of the transient, MULCH predicts a higher core flow rate than RELAP5. After ASV and NCV open (at 4.4 second), the core flow rate of RELAP5 becomes greater than MULCH. Once the natural convection flow is established, the core flow rate would be steady and equal to the summation of ASV and NCV flow rate. It can be found in Table 2 that RELAP5 predicts a higher steady state core flow rate than MULCH, which is consistent with the results shown in Figs. 5 and 6.

MITR-II startup test are coolant temperature measurements from compared with the predictions by MULCH and RELAP5. The loss of primary flow in MITR-II has been studied in detail by Bamdad [9]. Measured data from thermocouples TC-6, TC-7, and TC-9 are compared with the predicted values of coolant outlet temperature. Notice that the thermocouples are located in different positions. It is expected that the measured temperature would fall between the predicted average and peak temperatures (within experimental error).

Figure 7 shows the comparison of coolant temperature between MULCH and measurements. One can observe that the predicted values lie above and below the measured values. Figure 8 shows the comparison of coolant temperature between RELAP5 and measurements. It can be found that RELAP5 seems to over-predict the peak temperature. However, in general RELAP5 has good performance and the predicted trend and values are closer to the measured values.

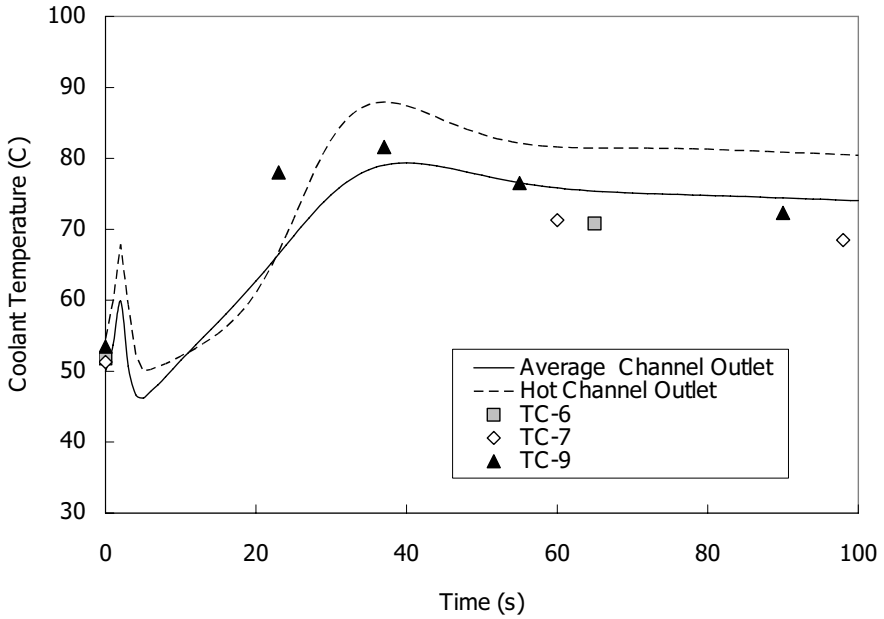

Figure 7. Comparison of coolant temperature between MULCH and measurement

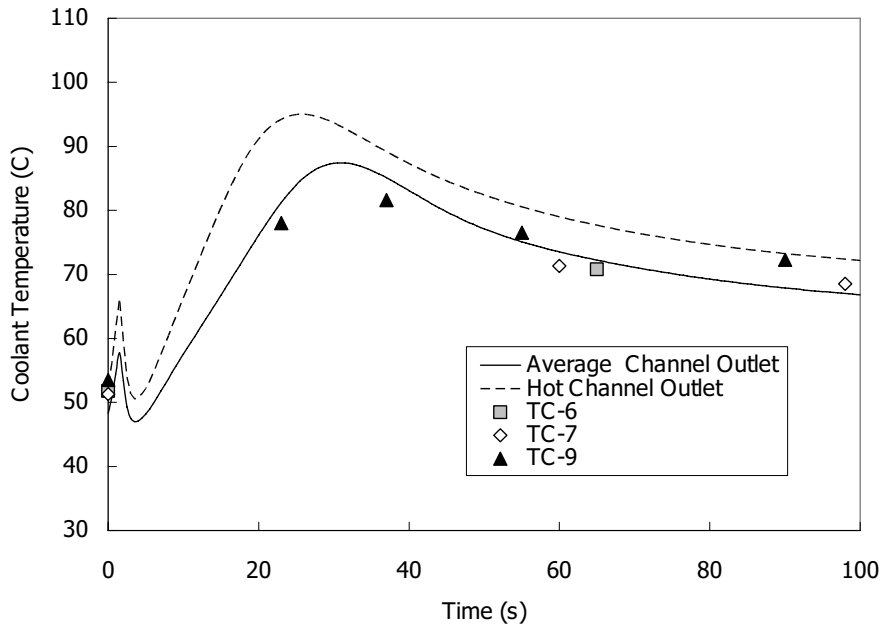

Figure 8. Comparison of coolant temperature between RELAP5 and measurement

5. Conclusions

Steady state analyses are performed by using the MULCH and PLTEMP codes. Comparison of the coolant and cladding temperatures shows that the calculated temperatures by MULCH-II code are in agreement with PLTEMP. Results of loss of primary flow transients show that RELAP5 predicts higher ASV, NCV and core flow when natural convection is established. RELAP5 also predicts that the natural convection flow will establish earlier that the prediction of MULCH.

The calculated outlet coolant temperatures are compared with measurements. Results show that RELAP5 seems to over-predict the peak temperature but the predicted trend and values match the measured values well. MULCH is less conservative than RELAP5; however it can be used for safety analysis since the predicted peak values are always higher than the experimental data.

Based on the benchmark analysis results, the MULCH code is qualified for the LEU core conversion analysis. In the future, a sensitivity study for decay power will be performed. The point kinetics model in MULCH can also be improved. It can be expected that MULCH will predict better results for loss of primary flow transient if the step reactivity insertion is replaced by a ramp reactivity insertion.

References

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