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Loss-of-Offsite-Power Simulations for the Conversion of RHF to Low Enriched Uranium Fuel

J.R. Licht and B. Dionne
GTRI Convert Program, Nuclear Engineering Division,
Argonne National Laboratory, IL 60439 – USA

F. Thomas
RHF Reactor Department
Institut Laue-Langevin (ILL), Grenoble – France

ABSTRACT

The code RELAP5/Mod 3.3 was used to simulate a loss-of-offsite-power accident in the RHF research reactor for highly-enriched and low enriched uranium fuels (HEU and LEU fuels, respectively). The steady-state nominal condition results (initial conditions) were in agreement with the known temperature, pressure and flow distributions. Qualitatively the transient behavior of the reactor was found to reasonably agree with previous simulations performed with the CATHARE code. Good agreement was obtained for the magnitude in peak fuel cladding temperature but its evolution differed due to modeling choices in discretizing the core coolant volumes. The magnitude in natural circulation flow for RELAP5 was comparatively lower due to the specified minor loss coefficients at tee junctions but their justification could be inferred from the pump coast down measurements. These preliminary simulations of the RHF reactor show that the fuel type had little impact on the loss-of-offsite-power accident scenario.

1. Introduction

In support of converting the Institut Laue-Langevin (ILL) High Flux Reactor (RHF) from High to Low Enriched Uranium fuel (HEU and LEU, respectively), the code RELAP5/Mod 3.3 [1] was used to simulate a Loss-of-Offsite-Power (LOOP) accident. RHF, located in Grenoble France, is a 58.3 MWt tank-in-pool type research reactor dedicated to fundamental science (Figure 1). The core is located inside a heavy water filled tank at the curved plates welded in bottom of a light water pool. It consists of a single fuel element comprised of 280 involute between two concentric aluminum tubes. Reactor control is provided by a centrally located control rod. The coolant inlet temperature is ~30^{o}C with a flow rate of ~735 kg/s; this flow

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splits to separately cool the fuel element (primary loop) and control rod (CRAB loop). Each loop has its own set of heat exchangers and pumps. The mid-plane elevation of the heavy water tank is maintained at 4 bar due to pressurization pumps which draw coolant from an expansion vase at near atmospheric conditions. For a LOOP type accident, the reactor depressurizes and valves in three natural circulations lines open to aide long term cooling of the core.

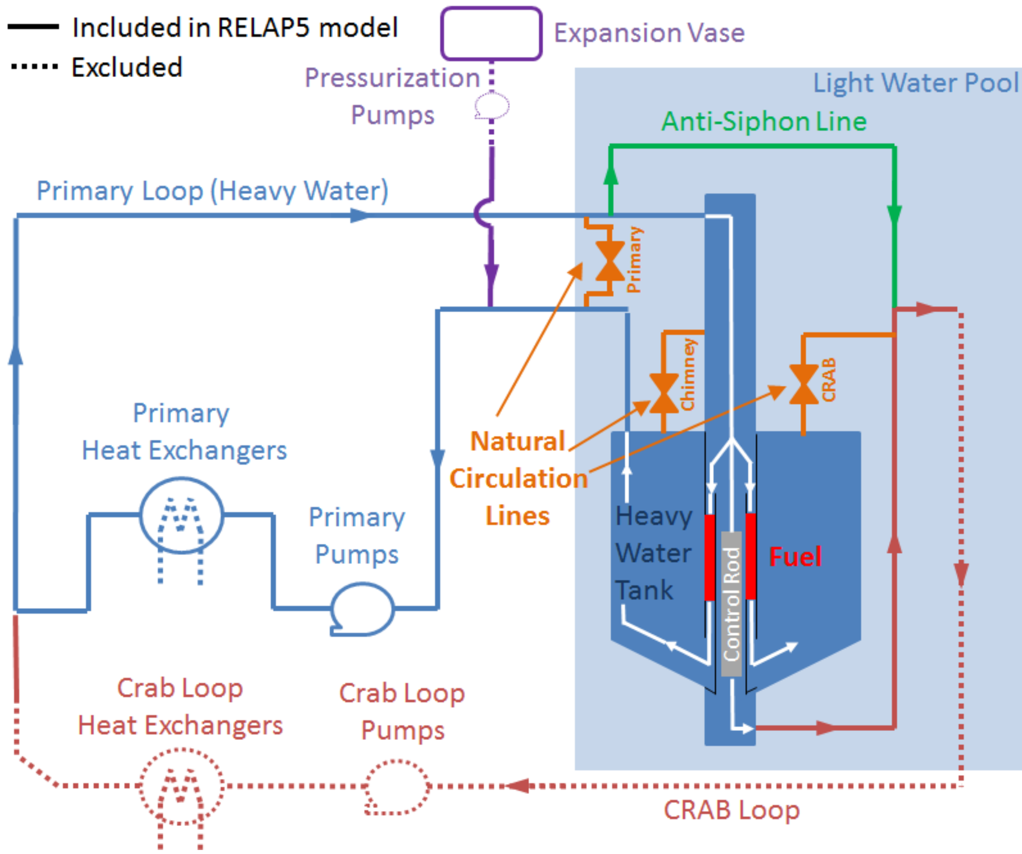

Figure 1. Conceptual drawing of RHF.

2. RHF Model

Figure 1 illustrates the piping components included in the RELAP5 model. A majority of the CRAB loop was not included in the model since the information was not readily available; however, experiments have shown that its flow rate decreases rapidly to zero following a loss of power, within ~7s, and therefor does not significantly contribute to these simulations. The portions of the CRAB loop that have been excluded (Figure 1) have been replaced with time dependent mass flow rate boundary conditions.

The pressurizer, consisting of the pressurization pumps, expansion vase and various other components, is a rather complicated system which has been simulated with a time dependent pressure boundary condition. The pump flow rate has been neglected since it contributes less than 1% of the primary loop flow rate.

Piping outside the pool utilized a constant temperature (20^{o}C) and heat transfer coefficient (10 W/m^{2}-K) boundary condition to approximate the surrounding atmospheric conditions. Piping and components within the pool were connected to a constant temperature volume (30^{o}C) where the heat transfer coefficient was determined from a natural convection correlation.

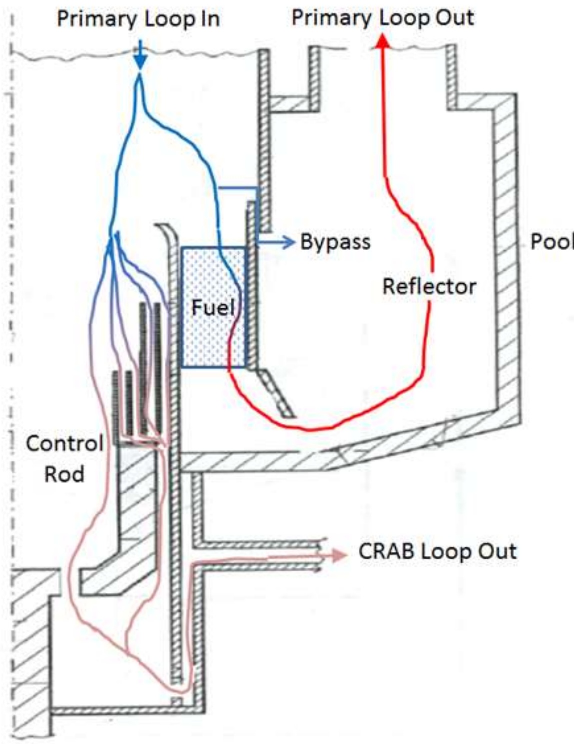

Figure 2. Axisymmetric drawing of the heavy water tank.

Figure 2 illustrates the heavy water tank, its internal components and the coolant flow paths modeled in RELAP5. At nominal conditions, the primary loop coolant enters the heavy water tank at 735.5 kg/s, 30^{o}C and 12.4 bar[1]. A portion of the flow, 24.9 kg/s, passes through the centrally located control rod which consists for four annular tubes. The coolant collects in the bottom of the tank and is discharged into the CRAB loop. Another small portion of flow, 12.8 kg/s, bypasses the fuel element and enters the reflector region directly. The remaining coolant passes through the fuel element and then into the reflector region, which discharges into the primary loop at the top of the tank. Heat generation obtained from MCNP calculations was applied to the fuel, the tank walls, the control rod, the control rod coolant, and the coolant in the reflector region.

The fuel element consists of 280 involute plates; an example of the fuel plate is shown in Figure 3. The plate thickness is 1.27 mm with a fuel meat thickness of 0.51 mm and the coolant gap between the plates is 1.8 mm. The fuel plates are welded to concentric tubes radially bounding the coolant between 0.1369 m and 0.1988 m. These concentric tubes separate the coolant within the fuel element from the control rod and reflector regions. In the RELAP5 model, the fuel plates and coolant channels are consolidated into an equivalent single coolant channel and fuel plate. The heat structures describing the fuel plate were discretized as shown in Figure 3. Two 'hot stripes' were defined at the outer edge of the fuel plate (heat structures 410 and 420) and another at the inner edge (heat structure 430). The remainder of the heated fuel plate was lumped into heat structure 400. The non-heated portion of the fuel plate was

[1] The pressure 12.4 bar is calculated from the measured value of 13.7 bar in the primary loop taking into account the pressure drop and elevation change.

designated as heat structure 401. This discretization was based on the radial power density profile shown in Figure 4. Briefly, heat structure 410 is considered to contain the peak cladding temperature for BOC conditions. Heat structure 420 and 430 are place holders for cases in which the peak clad temperature is suspected to occur inside of heat structure 410 or at the inner edge of the fuel (e.g. EOC conditions). The axial discretization of the fuel was 26 even spaced nodes of which first and last were unheated. This axial discretization was also used for the coolant. Two different models were setup for the coolant radial discretization. In one model, all of the heat structures were linked to a single coolant volume. The second model utilized a separate coolant volume for each of the “hot stripes” and the remainder of the fuel (four coolant volumes). For reference, separate simulations performed with the CATHARE code [2] used the discretization shown in Figure 3 where the coolant and heat structure where separated into regions A, B and C. The coolant associated with the unfueled section was not included in the CATHARE model.

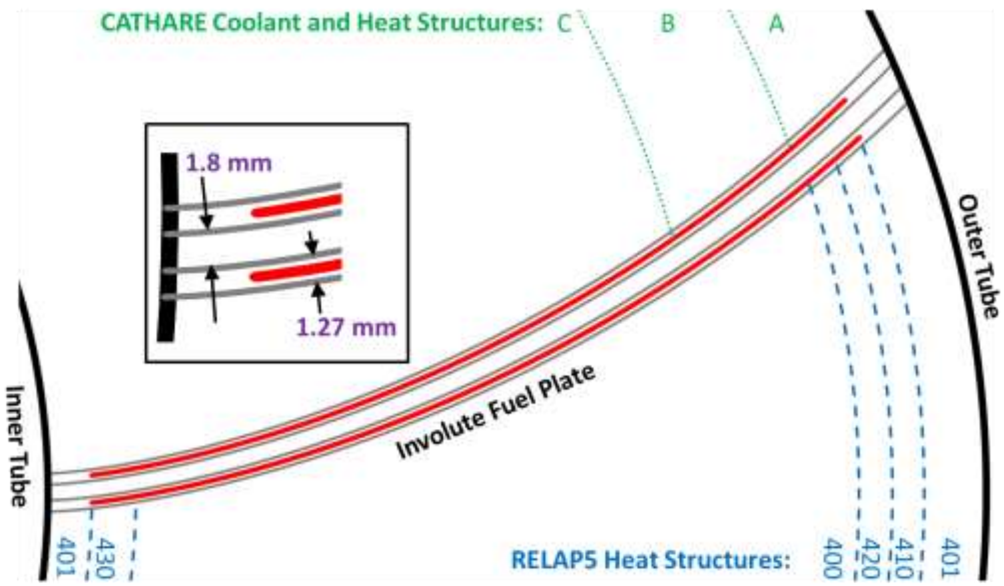

Figure 3. Conceptual drawing of the involute fuel plates (only 2 of 280 shown) and the CATHARE and RELAP5 discretization.

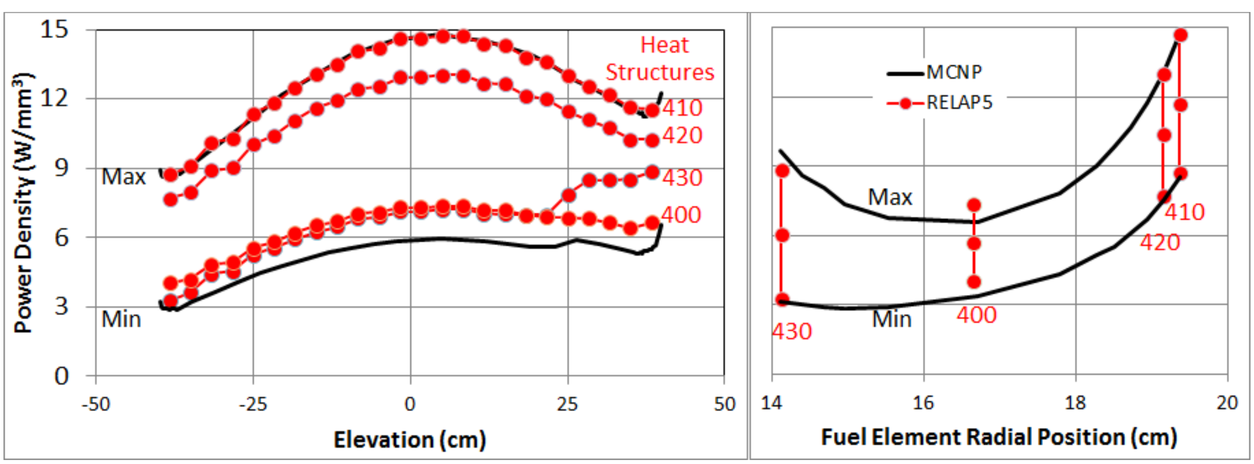

Figure 4. Axial and radial power density distribution at BOC (HEU fuel).

2. Steady-State Nominal Condition Simulations at Zero Power

A set of reference reactor conditions was provided in [2,3,4] and is summarized here in Table 1. The pressurizer boundary condition was set to maintain a primary outlet pressure of 4 bar. The total flow rate was controlled by setting the pumps velocity ratio to 0.9482. The CRAB loop flow rate (inlet and outlet) was set to 24.9 kg/s using the mass flow rate boundary conditions. These user controlled variables have been set to bold font in Table 1. The remaining non-bold values were RELAP5 calculated values. Results indicate that the RELAP5 model matches the target values quite well. The fact that the primary inlet and outlet pressure are correct but the pump outlet pressure, and hence the pump pressure differential, are low indicates that the pressure losses between the pump and inlet pressure measurement location are slightly underestimated. This difference could be due to the pipe tees and elbows that were not accounted for when simplifying the parallel piping in the primary loop by replacing it with an equivalent single pipe. The anti-syphon flow rate is also shown to be under predicted. However, it is not clear how this value was determined as there is no flow measurement made in this section of piping. It should be noted that removal of the minor loss coefficients applied to the anti-syphon pipe tees results in a flow rate very similar to reference value.

Table 1. RELAP5 model results compared to RHF parameters at nominal conditions.

	Ref. [2,3]	RELAP5		Ref. [2,3]	RELAP5
Mass Flow Rate	kg/s	kg/s	Absolute Pressure	bar	bar
Primary Pump	735.5	**735.4**	Pump inlet	4.2	4.2
CRAB pump	24.9	**24.9**	Pump outlet	16	15.6
Control rod	23.7	2.1	Primary inlet	13.7	13.7
Anti-syphon	1.2	0.8	Primary outlet	4	**4.0**
Fuel	722.6	722.4			
Fuel bypass	12.8	13.0			
	Ref. [2,3]	RELAP5		Ref. [4]	RELAP5
Pressure Differential	bar	bar	Absolute Pressure	bar	bar
Δp fuel plate	8	7.8	Core inlet	10.91	10.48
Δp pump	12	11.4	Core outlet	3.1	2.67
Δp heat exchanger	1.5	1.42			

Further comparisons can be made for the core region by comparing the inlet and outlet core pressure to CFD simulations in Ref. [4]. The pressure losses in the core are relatively simple to determine as they only consist of frictional losses for the coolant between the fuel plates and the inlet and outlet abrupt area change losses. Utilizing a flow rate of 735.5 kg/s (722.6 kg/s through the fuel), the calculated pressure drop in the fuel element was 7.81 bar for RELAP5. This value is close to the value specified in Ref. [4] of 7.71 determined from CFD simulations (slightly lower flow rate of 713.8 kg/s. The inlet pressures were 10.48 bar and 10.91 bar for RELAP5 and CFD, respectively; the outlet pressures were 2.67 bar and 3.1 bar. Differences in the magnitudes can be attributed to the difference in the pressure boundary condition.

3. Loss-of-Offsite-Power Simulations

LOOP simulations for both HEU and LEU fuel with a Beginning-of-Cycle (BOC) power distribution were performed with the operating conditions previously specified. After reaching steady-state conditions, the RELAP5 trip model was activated and the LOOP transient was initiated.

The decay heat power was obtained from ANSI/ANS-5.1-2005 [5] for thermal fission of 235U at 200 MeV/fission, 24 hours of prior operation, and included neutron capture by fission products. The curve was applied to the steady state power values for each heat structure but does not account for the redistribution of energy following a scram.

The pressurizer boundary condition was based on the 1987 loss-of-flow experiments performed at RHF and resulted in the primary loop outlet pressure decreasing from 4.0 bar down to 2.3 bar in approximately 25 s in the LOOP simulations.

The pump coast down was based on the 1987 loss-of-flow experiments (Figure 5). The torque friction values for RELAP5 pump model were adjusted to match the experimental data such that the flow approached zero at approximately 175 s. The CRAB loop flow rate was also based on these experiments and approached zero at approximately 7 s.

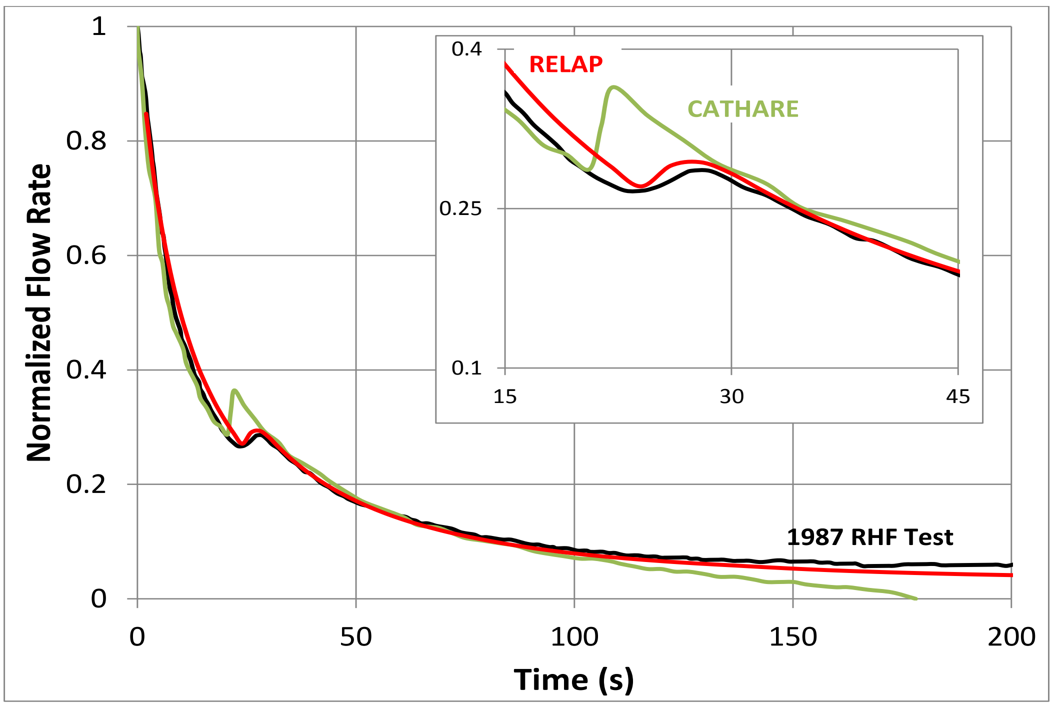

Figure 5. Comparison of the simulated and measured RHF pump coast down.

The natural circulation valves were designed to open when the pressure difference between the valve and the crab loop decreased below a threshold value. The RELAP5 model used the volume adjacent the CRAB loop outlet boundary condition as a reference pressure value and the threshold pressure differential was calibrated to match the opening times in the experiments[2]. Figure 6 shows the normalized mass flow rate calculated by RELAP5 for the natural circulation pipes following the LOOP trip. The natural circulation valves opened 23 s after the trip. As the natural circulation valves open, there was an abrupt drop in the flow through the fuel element. This is consistent with the increase in flow seen in the primary loop shown in pump coast down simulations (Figure 5). In other words, the opening of the natural circulation valves reduces the

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[2] This calibrated pressure differential threshold was very similar to the design values specified for the valves. Differences were attributed to the elevation where the reference pressure was obtained.

hydraulic resistance across the heavy water tank since coolant can bypass the fuel, resulting in a temporary increase in flow through the primary loop and decrease in flow through the fuel. RELAP5 simulations predict a lower flow rate in the primary and chimney natural circulation piping, for both peak and long term cooling, compared to the results predicted by CATHARE (Table 2). The differences are primarily due to the loss coefficients applied to the tees and elbows in the piping associated with the natural circulation lines. Removal of these coefficients from the RELAP5 model produces results that are more similar to the CATHARE results. While no experimental flow measurements in the natural circulation piping are available from the RHF facility, the magnitude of the flow can be estimated from the magnitude in change of the mass flow rate measured in the primary piping. The increase in mass flow rate resulting from opening the natural circulation valves shown in the inset of Figure 5 indicates that the minor loss coefficients for the tee junctions and elbows in RELAP5 are required to better simulate the measured flow rate through the primary loop due to the opening of the natural circulation piping. Also of note is that flow reversal in the fuel element occurs at ~165 s.

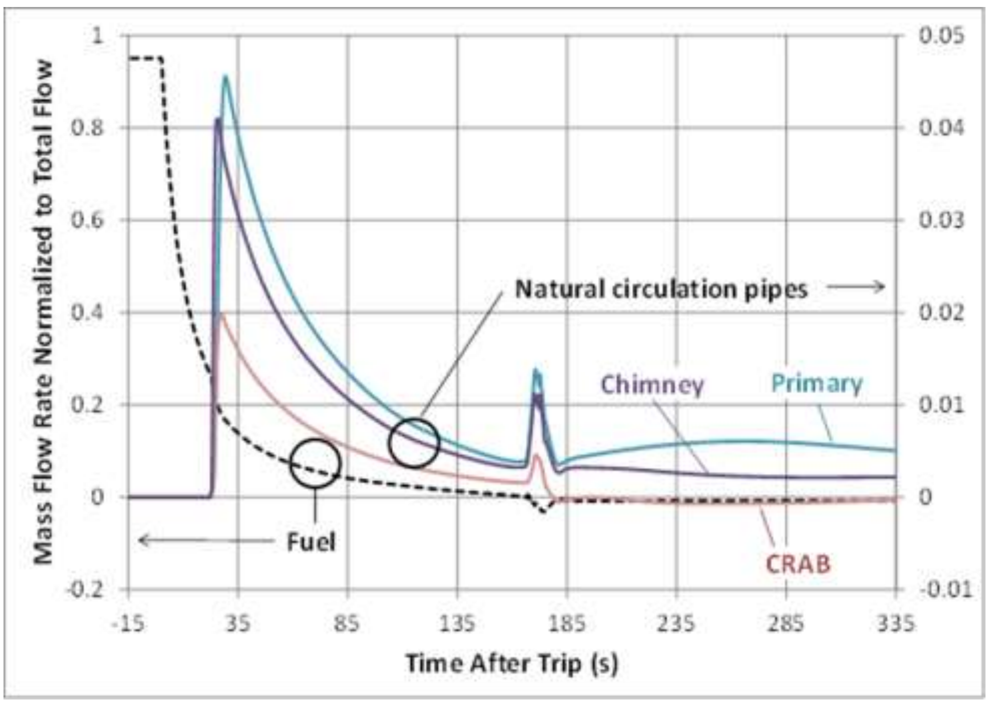

Figure 6. Mass flow rate through fuel and natural circulation pipes calculated by RELAP5 normalized to the total reactor flow rate.

Table 2. Comparison of the natural circulation flow rate calculated by RELAP5 and CATHARE.

Natural Circulation Pipe	Maximum Flow (kg/s)		Long Term Flow, 800 s (kg/s)	
	CATHARE	RELAP5	CATHARE	RELAP5
Primary	60	35	4.3	2.7
Chimney	80	32	2.9	1.8
CRAB	15	15	-1	~0.0

Figure 7 shows the evolution of the cladding temperature of the high heat flux heat structure evaluated at the mid-plane of the fuel element for each of the RELAP5 models with a comparison to results from the CATHARE code. Good agreement is obtained for all three simulations throughout the transient. As expected, the cladding temperature during normal operation (< 0 s) is slightly lower for the case with 1 coolant volume since the 410 heat structure is linked to a relatively lower bulk coolant temperature compared to the model with 4 coolant volumes. Both RELAP5 models indicate an oscillation in cladding temperature near the peak cladding temperature or time of flow reversal and is due to the temporary generation of void in the coolant. For the RELAP5 model with 4 coolant volumes the cladding temperature continues with a regular oscillation that is due to the fact that heat deposited into coolant volume associated with heat structure (410) reaches and stays at saturated conditions. Computational Fluid Dynamic (CFD) simulations have shown that this coolant discretization scheme may be too conservative since there is both lateral conduction in the fuel element and lateral diffusion of heat within the coolant volume under natural convection conditions, neither of which are captured in the RELAP5 model. Each of the RELAP5 models were developed in an attempt to bound the possible range of bulk coolant temperature, which impact peak cladding temperature; however, the results indicate that the boiling process limits the peak cladding temperature and that the results are not sensitive coolant volume discretization scheme for this LOOP analysis.

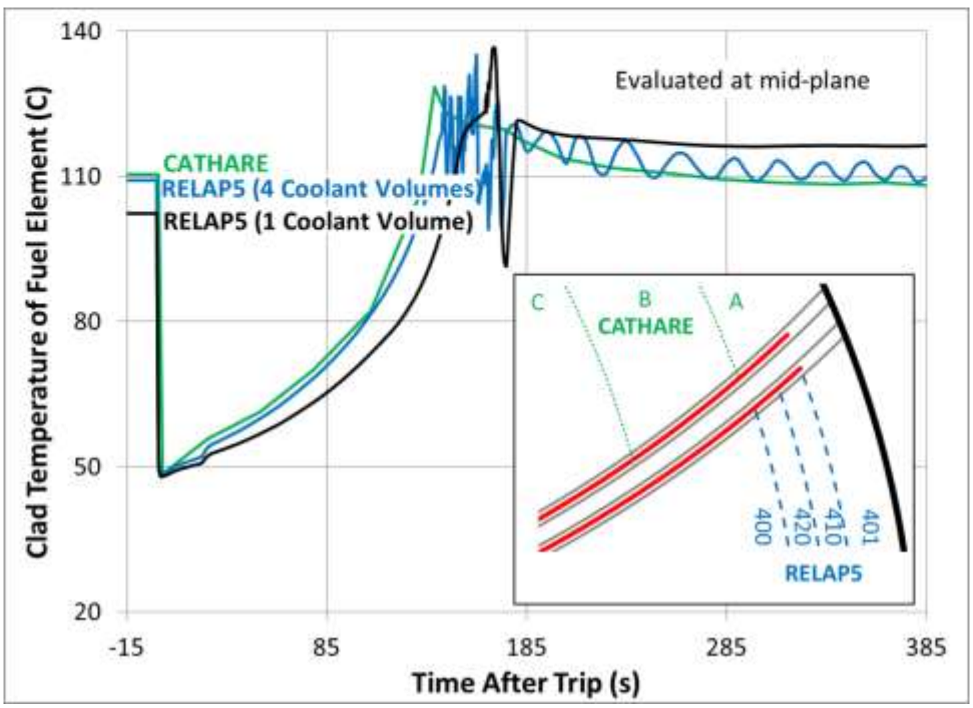

Figure 7. Mid-plane clad temperature at heat structures 410 (RELAP5) and A (CATHARE).

Figure 8 shows a comparison of the RELAP5 calculated axial cladding temperature for heat structure 410 for both HEU and LEU fuel at nominal conditions (model with only one coolant volume in the core). Results are also shown for the peak cladding temperature obtained at each axial location during the LOOP transient. It should be noted that the HEU and LEU fuel meat lengths are 0.8 m and 0.88 m, respectively. The HEU and LEU fuel cladding temperatures are found to be quite similar and indicate that the conversion to LEU fuel does not negatively impact the safety of the RHF research reactor for a LOOP type accident.

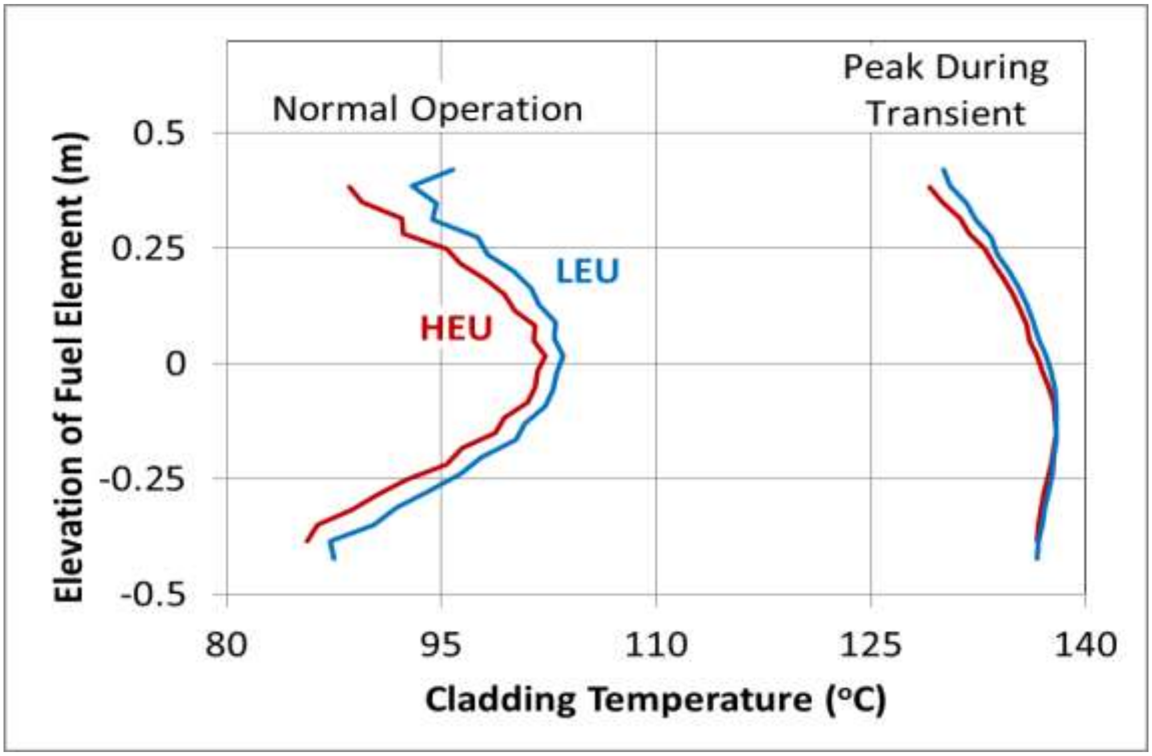

Figure 8. Cladding temperature comparisons for RELAP5 simulations with HEU and LEU fuel for the high heat flux heat structure (410).

4. Summary and Conclusions

The purpose of this work was to develop a RELAP5 model of the RHF research reactor and evaluate the impact of LEU fuel conversion by performing LOOP simulations with the code RELAP5. The model geometry was primarily based on the dimensions used to develop a model for use with the CATHARE code. The RHF safety analysis report, reactor design drawings, and other miscellaneous reports were also used to confirm data or obtain information that was otherwise not available.

Calibration of the model pressures and flow rates were performed using data primarily from loss-of-flow tests performed in 1987 and information provided in the RHF safety analysis report. The RELAP5 model simulation results for steady-state nominal conditions were found to agree very well with the expected nominal conditions for flow rate and pressure distribution.

Simulations of a LOOP accident were performed for HEU fuel with two bounding discretization schemes for the core coolant. Comparison of these simulation results with that from previous CATHARE simulations shows good agreement for the peak cladding temperature magnitude and evolution. The only significant difference between RELAP5 and CATHARE simulation results was the magnitude of the natural circulation flow in the two of the three natural circulation pipes. This difference was mainly due to the minor loss coefficients specified at the Tee junctions and elbows in the RELAP5 model. While data directly measuring the natural circulation flow was not available, comparison of the quantity of flow diverted from the fuel element following the opening of the natural circulation valves supported the use of the minor loss coefficients as well as the magnitude of natural circulation flows calculated by RELAP5.

The RELAP5 LOOP simulation results for LEU fuel were very similar to HEU and indicate that the conversion will not negatively impact safety for a LOOP accident. The peak cladding temperature for these simulations was found to be ~135^{o}C and occurs near the time of flow reversal within the fuel element.

5. References

[1] Information Systems Laboratories Inc., 2003. RELAP5/Mod3.3 patch 03 Code Manual.

[2] E. Pelle, "Note de réalisation du transitoire accidentel < Perte totale des alimentations électriques >," CSSI/312-1/AJ02L050/NRT/LOT4/1.0, 11/04/2003.

[3] "Réacteur à Haut Flux", INB n67, Rapport de Sureté, 2004.

[4] F. Thomas, Y. Calzavara and H. Guyon (ILL); A. Tentner and A. Bergeron (ANL), “Thermo-hydraulique d’une lame RHF,” Rapport RHF n 414, February 29, 2012.

[5] "Etude du refroidissement de l’élément combustible et de la barre de pilotage du Réacteur à Haut Flux, à la suite de la perte totale des alimentations électriques," SPECIFICATION TECHNIQUE Re 3C 53 S 3001 Ind. A.