LEU-HEU Mixed Core Conversion Thermal-hydraulic Analysis and Coolant System Upgrade Assessment for the MIT Research Reactor

by

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Abstract

The MIT Research Reactor (MITR) is in the process of converting from the current 93%-enriched U-235 highly-enriched uranium (HEU) fuel to the low enriched uranium (LEU, <20%-enriched U-235) fuel, as part of the global non-proliferation initiatives. A high-density, monolithic uranium-molybdenum (U-10Mo) fuel matrix is chosen. The fuel element design is changed from 15-plate finned HEU fuel to 19-plate unfinned LEU fuel with the same geometry. The reactor power increases from 6.0 MW to 7.0 MW thermal, and primary coolant flow rate increases from 2000 gpm to 2400 gpm. Detailed analyses were completed for initial LEU core with 22 fuel elements, and demonstrated both neutronic and thermal hydraulic safety requirements are met throughout equilibrium cycles. An alternative conversion strategy is proposed which involves a gradual transition from an all-HEU core to an all-LEU core by replacing 3 HEU fuel elements with fresh LEU fuel elements during each fuel cycle. The objectives of this study are to demonstrate that the primary coolant system can be safely modified for 2400 gpm operation, and to perform steady-state and loss-of-flow (LOF) transient thermal-hydraulic analyses for the MITR HEU-LEU transitional mixed cores to evaluate this alternative conversion strategy.

The primary technical challenge for the 20% increase in primary flow rate with existing piping system is flow-induced vibration. Several experiments were performed to measure and quantify vibration acceleration and velocity on three main hydraulic components to determine if higher flowrates cause excessive vibration. The test results show that the maximum vibration velocity is 9.70 mm/s, the maximum vibration acceleration is 0.98 G at the current flow rate 2000 gpm and no significant spectral change in the vibration profile at 2550 gpm. Therefore, it can be concluded that the existing piping system can safely support 2400 gpm primary flow operation.

Thermal hydraulics analysis was performed using RELAP5 MOD3.3 code and STAT7 code. The MITR transitional mixed core input models were constructed to simulate the reactor primary system. Two scenarios, steady-state and loss-of-flow transient were simulated at power level of 6 MW. RELAP5 results show that during steady state, there is significant safety margin (> 10 °C) to onset of nucleate boiling for both HEU and LEU fuel. The maximum core temperature occurs at HEU fuel in Mix-core 3, the maximum wall temperature reached was 89 °C. During the LOF transient case, the result shows that The HEU fuel element is more limiting than the LEU in transitional cores. Nucleate boiling is predicted to occur only in the HEU hot channel during the first 50 seconds after the pump coastdown. The peak cladding temperatures are much lower than the fuel temperature safety limit of UAl_x fuel plates, which is 450 °C. From the STAT7 calculation results, the operational limiting power at which onset of nucleate boiling (ONB) occurs in all cases show significant margins from the Limiting System Safety Setting (LSSS) over-power level. The lowest margin for LEU element during the mixed core transition is at Mix-7, 11.43 MW with a 4.03 MW power margin. For the HEU element, the lowest margin during the transition is at Mix-2, 8.51 MW with a 1.11 MW power margin. The location at which ONB is always expected to occur is F-Plate Stripe 1 and 4 for the LEU fuel element; side plate for the HEU fuel element with the HEU element is always more limiting.

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It’s not easy to be a graduate student at MIT from year 2020 to 2022, pandemic has changed the world and challenged everyone who lives in it, myself included. But the light at the end of the tunnel is most brilliant, I made it, we made it.

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1 Core Conversion Strategy

1.1 MITR

The Massachusetts Institute of Technology Research Reactor (MITR) is one of five High-performance research reactors in the U.S; the other four are the University of Missouri Research Reactor (MURR), the National Institute of Standards and Technology Reactor (NBSR), the Advanced Test Reactor (ATR) at Idaho National Laboratory, and the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory [1]. The original MITR, MITR-I reached criticality in 1958 and operated at power levels of up to 5 MW. The MITR is the fourth-oldest operating reactor in the country, the original MITR-I core was both heavy-water moderated and cooled with an open array of plays-type fuel elements. In 1975, the original MITR was transformed into current core design MITR-II after a major upgrade was completed. It uses light water to cool and moderate a close-packed array of finned, plate-type fuel elements, and a heavy water reflector was installed to maximum the thermal neutron flux in the reflector region [2].

The current MITR-II is a light water cooled and moderated reactor with 6 MW thermal power that employs finned-plates with Highly Enriched Uranium (HEU) UAl_x cermet fuel meat and Al 6061 alloy cladding. The reactor core is typically filled with 24 rhomboidal shaped fuel elements and 3 positions available for in-core experiments. Each HEU fuel element consists of 15 fuel plates [3]. The MITR core map is shown below in Figure 1-1.

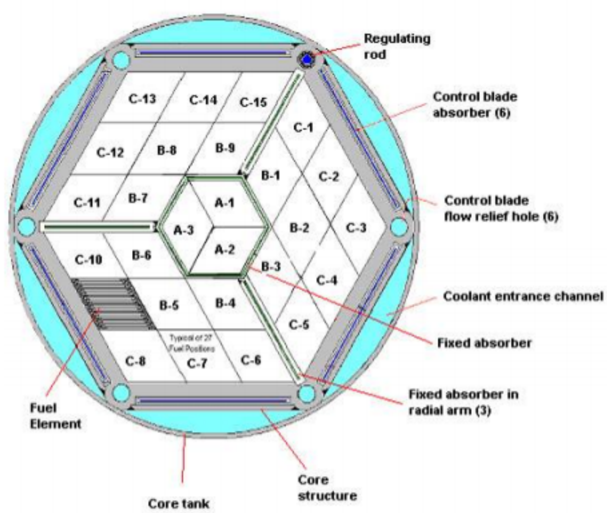

Figure 1-1: Horizontal cross-section of the MITR core [3]

The light water primary coolant has temperature around 51.7 °C at inlet and 55°C at outlet, operating under atmospheric pressure and nominal flow rate of 125 kg/s (2000 gpm). The fission power produced in the core is removed via the primary heat exchanger HE-1 to secondary coolant which transfers the heat to the forced draft cooling towers outside the reactor building and dissipates the heat into the ambient air. The primary loop diagram is shown in Figure 1-2. Few devices have been installed to measure the flow rates and pressure at specific points, where MM-1/1A are primary pumps, MF-1A is a flow meter, MF-1B is a flow rate meter, MP-3 is a static pressure sensor at the inlet of HE-01, MP-4 is a static pressure sensor at the outlet of HE-01, MP-6/MP-6A are static pressure sensors at the bottom of the core tank.

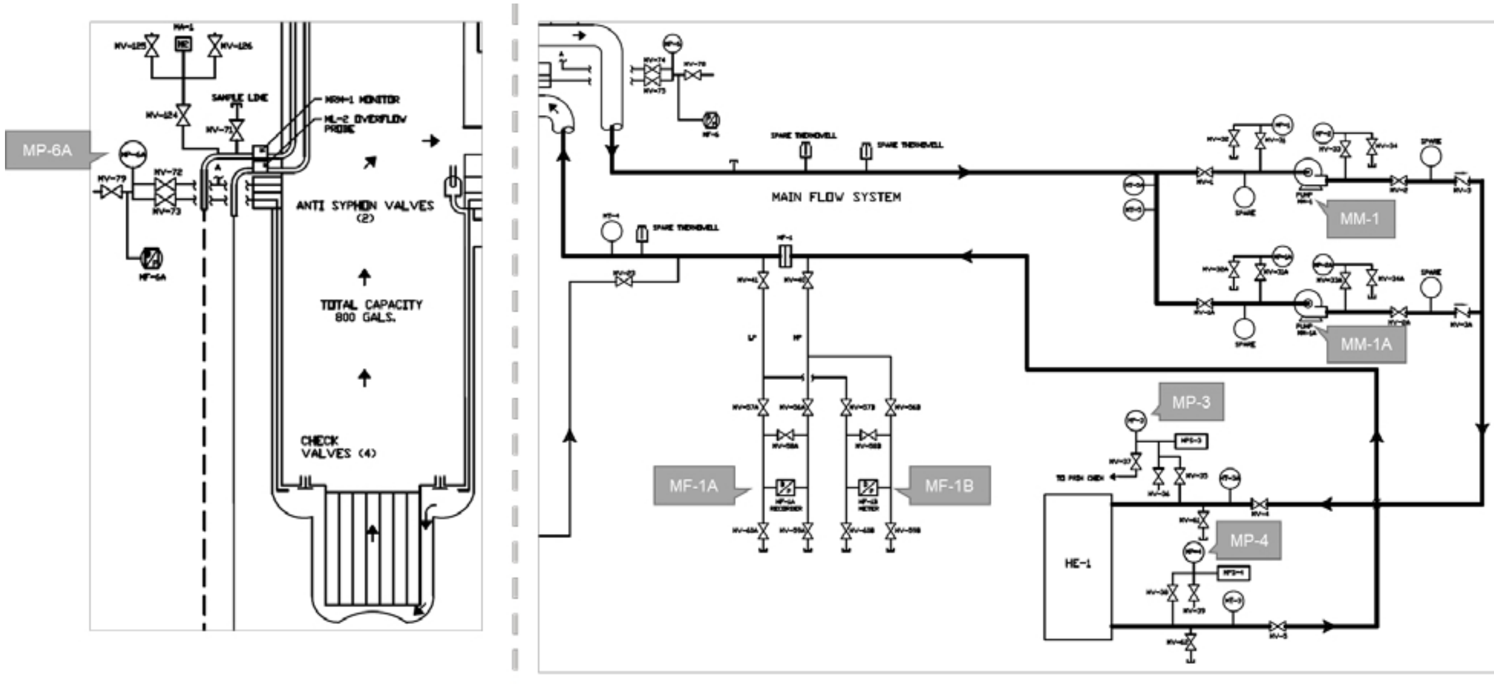

Figure 1-2: Schematic of the primary coolant system [4]

1.2 LEU Fuel Conversion Program

The Reduced Enrichment for Research and Test Reactor (RERTR) was initiated by the U.S Department of Energy in 1978, this program helps developing the technology that converts the civilian-use facilities from using high-enrichment uranium (HEU) fuel to low-enrichment fuel (LEU) fuel. HEU is defined as nuclear fuel that has a 20% or higher concentration of U-235, while LEU has a lower than 20% concentration of U-235. In 2004, U.S. DOE's National Nuclear Security Administration (NNSA) established the Global Threat Reduction Initiative (GTRI), the overall objectives of which are the conversion, removal or protection of vulnerable radiological and fissile material [5]. As an important part of GTRI, the conversion program of civilian-use reactors is put on the agenda and accelerated. During the past 70 years, more than 70 research reactors have been converted from HEU to LEU fuels [5]. MITR, along with the other four USHPRRs is continuing the work of RERTR. There are six important steps that facilities have to take in the process of conversion, they are [6]:

1. Determine feasibility of conversion.
2. Develop conversion plan.
3. Begin irradiation of prototype element.
4. Order LEU elements for conversion.
5. Load first LEU elements in the core.
6. Unload last HEU elements from the core.

Previous studies has shown that high-density uranium-molybdenum (U-10Mo), a fuel that has a uranium composition enriched to 19.75 wt% U-235 with a uranium density of 15.5 g/cm^3, is proven to be a feasible fuel for the conversion of the MITR and is undergoing irradiation test in Idaho National Laboratory [3], the specification of U-10Mo will be discussed in the following sections.

1.3 HEU and LEU Fuel Design Comparison

The current MITR core uses 15-plate finned HEU fuel element design, held by the supporting plats on both sides, each element has 14 full coolant channels and 2 side coolant channels. Each plate contains a fuel core of approximately 93% enriched uranium in the form of UAl_x cermet, each plate contains 33.7 grams of U-235, each fuel element contains 506 grams of U-235. The core housing has 27 fuel element positions and typical core configuration contains 24 fuel elements. [2]. The specification of the HEU and cross-section view are shown in Table 0-1 and Figure 1-3.

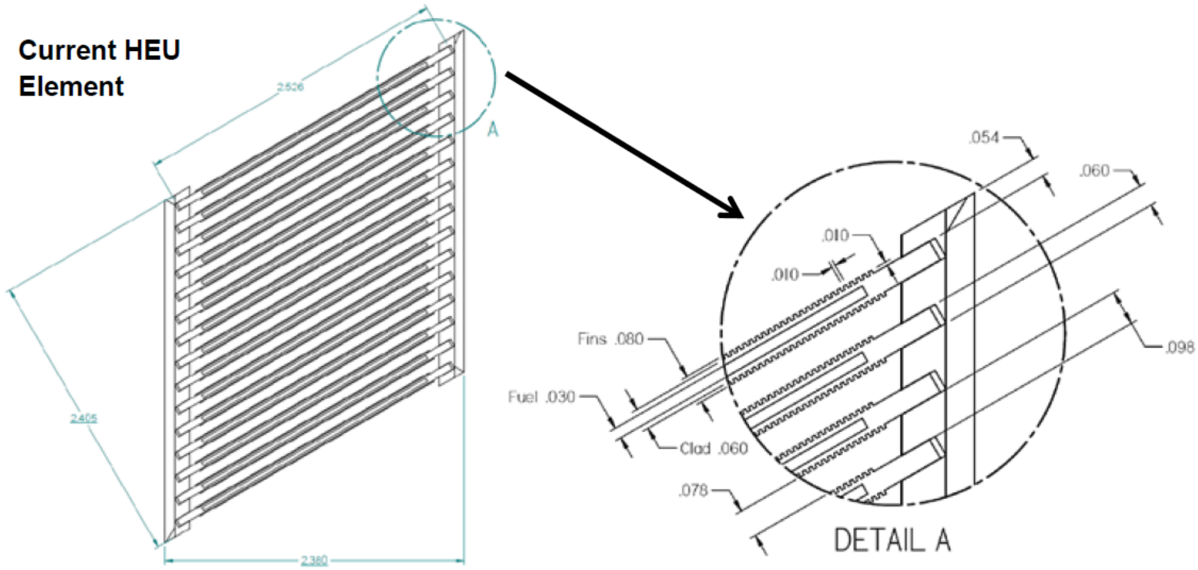

Figure 1-3: Current HEU fuel element (dimensions in inch) [7]

A high-density, monolithic uranium-molybdenum (U-10Mo) fuel matrix is chosen for MITR's LEU fuel conversion. The new MITR LEU fuel is unfinned, plate-type, aluminum-clad fuel that has a uranium composition enriched to 19.75 wt% U-235. Each fuel element consists of 19 fuel plates and 18 full coolant channels. 968 grams of U-235 is contained in each LEU fuel element, unlike HEU fuel, the amount of U-235 is not evenly distributed among each fuel plate. Three types of fuel plate with different fuel meat thickness present in each fuel element. Two T-Plates (Plate No. 1 and 19) have a fuel meat thickness of 0.013 inch. Four Y-Plates (Plate No. 2, 3, 17, and 18) have 0.017 inch. Thirteen F-Plates (Plate No. 4-16) have 0.025 inch thick fuel core. The cladding thickness for each type of fuel plate varies and the total thickness of each plate is the same. There is a zirconium interlayer (0.001 inch in thickness) between the fuel and clad, and the LEU cladding is unfinned. The cross-section view and specification of LEU fuel are shown below in Figure 1-4

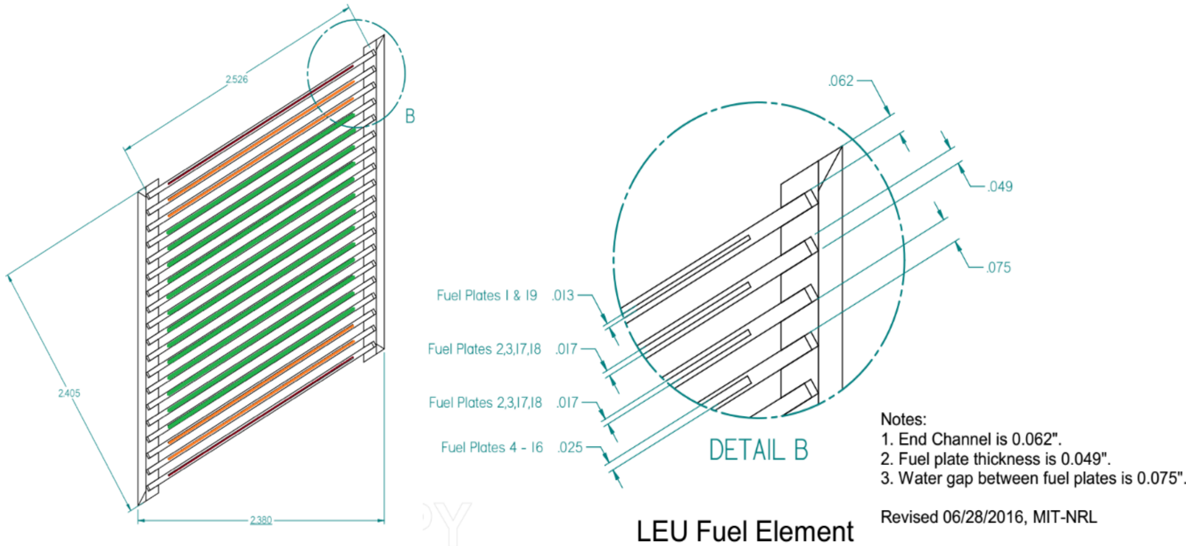

Figure 1-4: LEU Fuel Element (dimensions in inch) [1] Fuel plate colored in Brown are the two end plates, the ones in pink are the four middle plates, the ones in green are the thirteen full plates.

The design changes to enable the transition from HEU to LEU include the fuel element design, a power uprate from 6 MW to 7 MW, and consequently, an increase in coolant flow rate from 2000 gpm to 2400 gpm in the primary system. With a 20% increase in the coolant flow rate, several hydraulic components (i.e. pumps and heat exchanger) need to be upgraded. The overall side-by-side comparison of the major design parameters of the MITR HEU and LEU fuel is tabulated in Table 1-1, and LEU core primary coolant system operation parameter is tabulated in Table 0-2.

Table 0-1: The Major Reactor Parameters of the MITR HEU and LEU Core [8]

Parameter	HEU Core	LEU Core
Operating Power	6.0 MW	7.0 MW
Primary Coolant Flow rate	2000 gpm	2400 gpm
Limiting Safety System Setting a) Power b) Flow c) Temperature	a) 7.40 MW (Maximum) b) 1800 gpm (Minimum) c) 60 °C (Maximum)	a) 8.68 MW (Maximum) b) 2200 gpm (Minimum) c) 60 °C (Maximum)
Fuel Meat thickness	0.076 cm	0.033 cm for T-plate (2) 0.043 cm for Y-plate (4) 0.064 cm for F-plate (13)
Interlayer	N/A	0.0025 cm Zirconium
Clad thickness	0.038 cm	0.045 cm for T-plate (2) 0.038 cm for Y-plate (4) 0.028 cm for F-plate (13)
Fin Depth	0.025 cm	N/A

Table 0-2: Primary Coolant System Operation Parameters [8]

Parameter	Specification
Material Coolant Piping	Light Water 6061 Aluminum and Stainless Steel
Flow Rate Minimum Nominal	2200 gpm 2400 gpm
Temperature ΔT at 2200 gpm ΔT at 2400 gpm	11 °C 10 °C
Pressure Pump Discharge Top of Core Outlet Plenum	17 psig 14.7 psig

1.4 Full-Core Fuel Conversion

To convert from HEU core to LEU core, a previous transition core strategy proposed by K. Sun et al [9] was evaluated by A. Dave et al. [10] to determine the thermal-hydraulic safety margins of each transition cycle at each of its states. This conversion strategy planned to convert MITR from 22 fresh LEU elements (i.e., beginning-of-life) gradually to a 24-element equilibrium core configuration. The transition core plan starts cycle 1 with 22 fresh fuel elements and 5 dummy elements. In the second cycle, one B-ring dummy element (at B-6 position) will be replaced with another fresh fuel element. In the third cycle, the same replacement will occur at B-9 position. From the third to the seventh cycle, there will be constantly three fresh elements being inserted and three partially depleted elements being taken out. The first seven cycles are considered as a transition period, during the transition period, 39 fresh elements will be involved, and 15 partially depleted ones will be stored as backup fuel. From the eighth cycle to the fourteenth cycle, fully depleted fuel elements will be discharged at the beginning of each cycle. Throughout the transition plan, the reactor run at a power level of 7 MW. Figure 1-5 summarizes the element-by-element path towards equilibrium fuel cycle.

Cycle	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Weeks	10 + 3	10 + 3	10 + 3	10 + 3	10 + 3	10 + 3	10 + 3	10 + 3	10 + 3	10 + 3	10 + 3	10 + 3	10 + 3	10 + 3
ML-101	A2	A2	f: C3	C3	C3	r: C3	C3	DIS	DIS	DIS	DIS	DIS	DIS	DIS
ML-102	B1	B1	B1	f: C1	C1	C1	r: C1	C1	DIS	DIS	DIS	DIS	DIS	DIS
ML-103	B2	B2	A2	A2	f: C4	C4	C4	r: C4	C4	DIS	DIS	DIS	DIS	DIS
ML-104	B4	B4	f: C8	C8	C8	r: C8	C8	DIS	DIS	DIS	DIS	DIS	DIS	DIS
ML-105	B5	B5	B5	f: C6	C6	C6	r: C6	C6	DIS	DIS	DIS	DIS	DIS	DIS
ML-106	B7	B7	f: C13	C13	C13	r: C13	C13	DIS	DIS	DIS	DIS	DIS	DIS	DIS
ML-107	B8	B8	B8	f: C11	C11	C11	r: C11	C11	DIS	DIS	DIS	DIS	DIS	DIS
ML-108	C1	r: C1	C1	WS	WS	WS	WS	WS	WS	WS	WS	WS	WS	WS
ML-109	C2	C2	C2	r: C2	C2	WS	WS	WS	WS	WS	WS	WS	WS	WS
ML-110	C3	C3	WS	WS	WS	WS	WS	WS	WS	WS	WS	WS	WS	WS
ML-111	C4	C4	r: C4	C4	WS	WS	WS	WS	WS	WS	WS	WS	WS	WS
ML-112	C5	C5	C5	C5	r: C5	C5	WS	WS	WS	WS	WS	WS	WS	WS
ML-113	C6	r1: C6	C6	WS	WS	WS	WS	WS	WS	WS	WS	WS	WS	WS
ML-114	C7	C7	C7	r: C7	C7	WS	WS	WS	WS	WS	WS	WS	WS	WS
ML-115	C8	C8	WS	WS	WS	WS	WS	WS	WS	WS	WS	WS	WS	WS
ML-116	C9	C9	r: C9	C9	WS	WS	WS	WS	WS	WS	WS	WS	WS	WS
ML-117	C10	C10	C10	C10	r: C10	C10	WS	WS	WS	WS	WS	WS	WS	WS
ML-118	C11	r1: C11	C11	WS	WS	WS	WS	WS	WS	WS	WS	WS	WS	WS
ML-119	C12	C12	C12	r: C12	C12	WS	WS	WS	WS	WS	WS	WS	WS	WS
ML-120	C13	C13	WS	WS	WS	WS	WS	WS	WS	WS	WS	WS	WS	WS
ML-121	C14	C14	r: C14	C14	WS	WS	WS	WS	WS	WS	WS	WS	WS	WS
ML-122	C15	C15	C15	C15	r: C15	C15	WS	WS	WS	WS	WS	WS	WS	WS
ML-123	-	B6	B6	B6	f: C9	C9	C9	r: C9	C9	DIS	DIS	DIS	DIS	DIS
ML-124	-	-	B9	B9	f: C14	C14	C14	r: C14	C14	DIS	DIS	DIS	DIS	DIS
ML-125	-	-	B2	B2	B2	f: C2	C2	C2	r: C2	C2	DIS	DIS	DIS	DIS
ML-126	-	-	B4	B4	B4	f: C7	C7	C7	r: C7	C7	DIS	DIS	DIS	DIS
ML-127	-	-	B7	B7	B7	f: C12	C12	C12	r: C12	C12	DIS	DIS	DIS	DIS
ML-128	-	-	-	B1	A2	A2	f: C5	C5	C5	r: C5	C5	DIS	DIS	DIS
ML-129	-	-	-	B5	B5	B5	f: C10	C10	C10	r: C10	C10	DIS	DIS	DIS
ML-130	-	-	-	B8	B8	B8	f: C15	C15	C15	r: C15	C15	DIS	DIS	DIS
ML-131	-	-	-	-	B1	B1	B1	f: C3	C3	C3	r: C3	C3	DIS	DIS
ML-132	-	-	-	-	B6	B6	B6	f: C8	C8	C8	r: C8	C8	DIS	DIS
ML-133	-	-	-	-	B9	B9	B9	f: C13	C13	C13	r: C13	C13	DIS	DIS
ML-134	-	-	-	-	-	B2	A2	A2	f: C1	C1	C1	r: C1	C1	DIS
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ML-136	-	-	-	-	-	B7	B7	B7	f: C11	C11	C11	r: C11	C11	DIS
ML-137	-	-	-	-	-	-	B2	B2	B2	f: C4	C4	C4	r: C4	C4
ML-138	-	-	-	-	-	-	B5	B5	B5	f: C9	C9	C9	r: C9	C9
ML-139	-	-	-	-	-	-	B8	B8	B8	f: C14	C14	C14	r: C14	C14
ML-140	-	-	-	-	-	-	-	B1	A2	A2	f: C2	C2	C2	r: C2
ML-141	-	-	-	-	-	-	-	B6	B6	B6	f: C7	C7	C7	r: C7
ML-142	-	-	-	-	-	-	-	B9	B9	B9	f: C12	C12	C12	r: C12
ML-143	-	-	-	-	-	-	-	-	B1	B1	B1	f: C5	C5	C5
ML-144	-	-	-	-	-	-	-	-	B4	B4	B4	f: C10	C10	C10
ML-145	-	-	-	-	-	-	-	-	B7	B7	B7	f: C15	C15	C15
ML-146	-	-	-	-	-	-	-	-	-	B2	A2	A2	f: C3	C3
ML-147	-	-	-	-	-	-	-	-	-	B5	B5	B5	f: C8	C8
ML-148	-	-	-	-	-	-	-	-	-	B8	B8	B8	f: C13	C13
ML-149	-	-	-	-	-	-	-	-	-	-	B2	B2	B2	f: C1
ML-150	-	-	-	-	-	-	-	-	-	-	B6	B6	B6	f: C6
ML-151	-	-	-	-	-	-	-	-	-	-	B9	B9	B9	f: C11
ML-152	-	-	-	-	-	-	-	-	-	-	-	B1	A2	A2
ML-153	-	-	-	-	-	-	-	-	-	-	-	B4	B4	B4
ML-154	-	-	-	-	-	-	-	-	-	-	-	B7	B7	B7
ML-155	-	-	-	-	-	-	-	-	-	-	-	-	B1	B1
ML-156	-	-	-	-	-	-	-	-	-	-	-	-	B5	B5
ML-157	-	-	-	-	-	-	-	-	-	-	-	-	B8	B8
ML-158	-	-	-	-	-	-	-	-	-	-	-	-	-	B2
ML-159	-	-	-	-	-	-	-	-	-	-	-	-	-	B6
ML-160	-	-	-	-	-	-	-	-	-	-	-	-	-	B9

Figure 1-5: Element-by-element path towards equilibrium fuel cycle of the MITR LEU core ML: MIT-LEU Fuel Docket Number, f: Flip, r: Rotate, WS: Wet Storage, DIS: Discharge [9]

The STAT7 code was used for the evaluation during steady-state operation. The limiting power level (P_{ONB}) for each cycle-state was determined. The results indicated that the proposed Limiting System Safety Setting (LSSS) of 8.4 MW is conservative and has a 0.8 MW margin to the minimum P_{ONB}. The loss-of-flow (LOF) transient was simulated using RELAP5. The transient results shows that the maximum centerline fuel temperature did not exceed 100 °C and was significantly lower than the blistering temperature limit of 350 °C. The cladding wall temperatures did not exceed saturation temperature, and no nucleate boiling is expected during LOF.

While this strategy is proven to have significant thermal-hydraulic margins, both during steady-state operation and LOF transient, it will require a complete removal of all current HEU elements from the MITR core and a restart with a freshly loaded LEU core. This will expose MITR to few potential risks such as the excess reactivity of fresh LEU core and unexpected fabrication and performance issues because MITR will be the first research reactor to use a U-10Mo LEU fuel element.

2 Core Conversion Strategy

As part of the conversion planning from current all-HEU core to the targeted all-LEU core, a proper conversion strategy needs to be evaluated and selected. Two conversion strategies have been proposed, the first one entails a complete removal of all HEU elements from the MITR core and restart with a freshly loaded LEU core. An alternative strategy is a gradual transition from an all-HEU core to an all-LEU core. It was proposed that 3 burned HEU fuel elements are replaced with fresh LEU fuel elements during each refueling outage. There are 7 transitional core configurations that are assumed, denoted as MIX-1 to MIX- 7, and where MIX-0 denotes the current state of the MITR with an all-HEU core. TC-10 is the final transitional core that only contains LEU fuel elements. All seven transitional cores and two full cores configurations are tabulated in Table 2-1. In order to reduce power peaking in the fresh LEU elements, the fuel management strategy is such that the fresh elements will be inserted in the B-ring (see Figure 2-2-1) which has the lowest neutron flux. In each transitional cycle, 3 HEU fuel elements will be replaced with fresh LEU fuel in the B-ring, after all 8 positions are filled with LEU fuel elements, 3 slightly depleted LEU fuel elements will be moved to the C-ring, and 3 fresh LEU fuel elements will be inserted in the B-ring. The planned transition of inserting fresh LEU fuel elements in core locations can be seen in Figure 1. Each core configuration is planned to be operated at 6 MW for a typical fuel cycle of 10 weeks. [11] This transitional core conversion strategy offers several operational benefits. MITR is expected to be the first research reactor to use U-10Mo LEU fuel elements, transitional conversion from HEU core to LEU core enables the opportunity to monitor the performance of such newly designed fuel and allow reversion to the original HEU core if any unexpected fabrication and performance issues are identified. Such strategy also mitigates the risk of excess reactivity in a fresh LEU core.

Previous work by Y. Wang [12] has evaluated this transitional mixed core conversion strategy with different proposed LEU fuel that contains 18 plates per element with fin structures, compared to the current proposed LEU design of 19 plate per element without fin structure. The study was performed with limited neutronics analysis data although it demonstrated that mixed core conversion strategy is a viable option for the MITR LEU conversion, and LEU fuel elements have higher ONB margins than HEU fuel elements in all mixed core configuration.

Table 2-1: The Number of LEU and HEU Fuel in Each Configuration

	N_{LEU}	N_{HEU}
MX-0	0	24
MX-1	3	21
MX-2	6	18
MX-3	9	15
MX-4	12	12
MX-5	15	9
MX-6	18	6
MX-7	21	3
TC-10	24	0

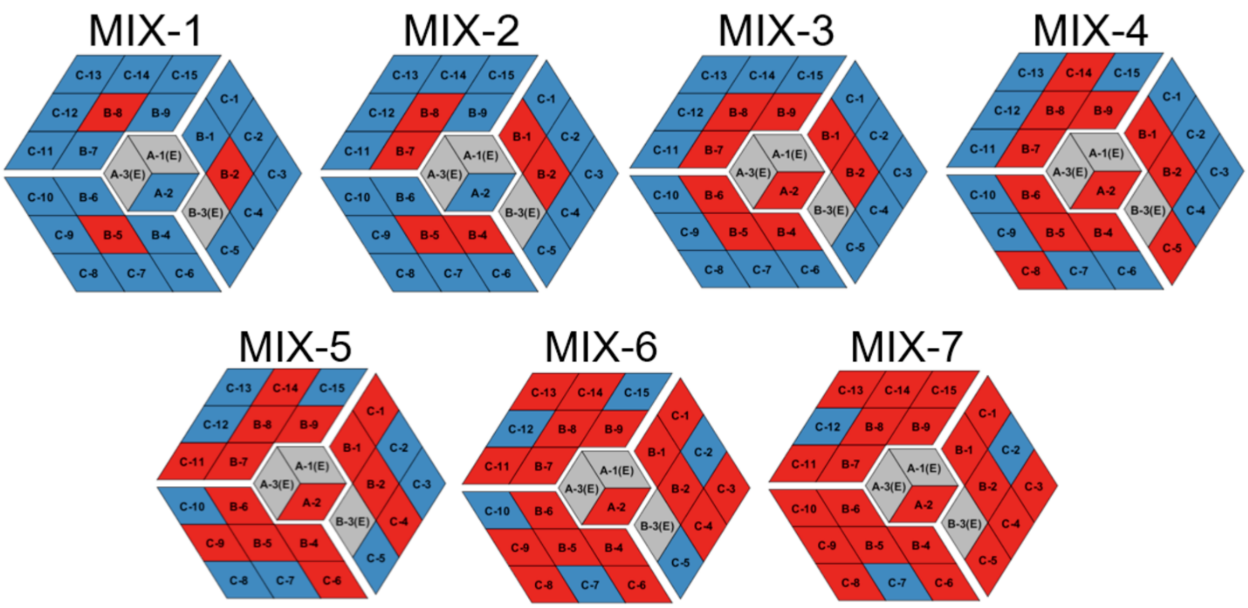


Figure 2-2-1: Step by Step In-core HEU and LEU fuel elements distribution, red blocks represent LEU fuel elements, blue blocks represent HEU fuel, gray blocks represent in-core experiment positions. [11]

3 Research Objectives

The objective of this study is to (1) perform steady-state and Loss-of-flow transient thermal-hydraulic analyses for the MITR HEU-LEU transitional Mixed core using RELAP5 MOD3.3 code and STAT7 code, and (2) perform experimental assessment of flow induced vibration in the primary coolant circuit.

A transitional MIX-Core is a core that consists of both HEU and LEU elements. There are seven transitional mixed core configurations containing different numbers of HEU and LEU elements between the current homogeneous HEU core to the final homogeneous LEU cores. The first objective of this study is to use RELAP5 MOD3.3 and STAT7 code to determine the thermal hydraulic safety margins of the hot plate in each transitional core during both steady-state and Loss-of-flow transient cases with steady-state power of 6 MW. The safety margins pertain ONB power, coolant outlet temperature, cladding surface temperature, and fuel centerline temperature.

The conversion of MITR fuel from HEU to LEU requires a power uprate from 6.0 to 7.0 MW and, subsequently, a primary coolant flow rate increase from 2000 to 2400 gpm is necessary. There is a concern that the 20% increase in flow rate may cause mechanical issues, specifically flow-induced vibration at pipes and hydraulic components. The second objective of this study is to conduct vibration test on the three main hydraulic components and quantify the vibration acceleration and velocity to determine if increasing flowrates exacerbates observed vibration. If so, we would require further evaluation.

4 Neutronics Analysis

In this study, two computational codes, STAT7 and RELAP5 are used to evaluate thermal-hydraulic safety margin of each mixed core. Detailed power distributions are incorporated for both computer codes to each heat structure so the amount of fission energy deposited in the coolant and other structural materials can be calculated as well as the temperature rise.

4.1 MCODE

MCODE (MCNP-ORIGEN Depletion Program) is a code developed at MIT that links MCNP5 (Monte Carlo N-Particle code) with ORIGEN-2.2 (an isotope generation and depletion code) in a user-friendly manner. MCNP is used to extract cross-sections and flux values, and then the output is parsed into ORIGEN for depletion calculations. MCODE is an efficient code that can reduce the probability of human error.

4.2 Power profile

Previous neutronics analysis by K. Sun et al. [13] utilized MCODE to generate fission power distribution of each mixed core state, seven sets of power distribution represent seven stage of the conversion plan from all-HEU core to all-LEU core, and each power distribution is composed of power profiles for HEU element and LEU element in accordance with the conversion strategy. The power profiles were then parsed into the RELAP5 model and STAT7 model. Fission power of all LEU elements in the mixed cores is tallied with nodalization of 16-axial, 19-plate, and 4-stripe, fission power of all HEU elements in the mixed cores is tallied with nodalization of 16-axial, 15-plate, and 1-stripe. The RELAP5 and STAT7 input deck are consistent with this nodalization method. An example power profile for mixed core configuration Mix-1 is shown in Figure 4-1.

In order to determine the hot plate and hot stripe for HEU fuel element and LEU fuel element respectively, an identification method which was proposed in previous work by A. Dave et al. [14]

is used. This method identified the location where ONB occurs most frequently using STAT7. The fuel plates and fuel stripes where ONB occurs most frequently in each mixed core are identified as hot fuel plates and hot fuel stripes for HEU and LEU fuel element, respectively. The hot plate/stripe locations are tabulated in Table 4-1, and the hot plate/strip power profile was created by taking the corresponding power profile at corresponding locations. An example axial power profile of hot plate/stripe for HEU and LEU for mixed core configuration Mix-1 is shown in Figure 4-2.

The power profiles for hot plates or hot stripes are normalized and parsed into the heat structure section of RELAP5 input deck in form of percentage of 6 MW total core power. An example normalized axial power profile input of hot plate/stripe for mixed core configuration Mix-1 is shown in

Table *4-2*.

The power profiles for all other transitional mixed core are attached in Appendix.

Number	101	102	103	104	105	106	107	108	109	110	111	112	113	114
Position	A-1	A-2	A-3	B-1	B-2	B-3	B-4	B-5	B-6	B-7	B-8	B-9	C-1	C-2
1 (Top)	0.00E+00	1.62E+04	0.00E+00	1.24E+04	1.44E+04	0.00E+00	1.23E+04	1.44E+04	1.28E+04	1.31E+04	1.45E+04	1.27E+04	7.07E+03	6.31E+03
2	0.00E+00	1.42E+04	0.00E+00	1.11E+04	1.29E+04	0.00E+00	1.11E+04	1.28E+04	1.15E+04	1.17E+04	1.28E+04	1.14E+04	6.66E+03	5.87E+03
3	0.00E+00	1.59E+04	0.00E+00	1.29E+04	1.50E+04	0.00E+00	1.30E+04	1.53E+04	1.35E+04	1.36E+04	1.53E+04	1.33E+04	7.99E+03	6.88E+03
4	0.00E+00	1.79E+04	0.00E+00	1.47E+04	1.73E+04	0.00E+00	1.49E+04	1.77E+04	1.54E+04	1.56E+04	1.77E+04	1.52E+04	9.29E+03	7.88E+03
5	0.00E+00	1.98E+04	0.00E+00	1.65E+04	1.94E+04	0.00E+00	1.67E+04	1.99E+04	1.72E+04	1.75E+04	2.00E+04	1.70E+04	1.05E+04	8.80E+03
6	0.00E+00	2.14E+04	0.00E+00	1.80E+04	2.14E+04	0.00E+00	1.83E+04	2.20E+04	1.88E+04	1.92E+04	2.20E+04	1.86E+04	1.16E+04	9.66E+03
7	0.00E+00	2.26E+04	0.00E+00	1.92E+04	2.30E+04	0.00E+00	1.96E+04	2.37E+04	2.01E+04	2.05E+04	2.38E+04	1.99E+04	1.26E+04	1.05E+04
8	0.00E+00	2.28E+04	0.00E+00	1.98E+04	2.43E+04	0.00E+00	2.01E+04	2.51E+04	2.06E+04	2.11E+04	2.52E+04	2.04E+04	1.38E+04	1.15E+04
9	0.00E+00	2.27E+04	0.00E+00	2.01E+04	2.52E+04	0.00E+00	2.05E+04	2.61E+04	2.08E+04	2.15E+04	2.62E+04	2.07E+04	1.55E+04	1.32E+04
10	0.00E+00	2.28E+04	0.00E+00	2.04E+04	2.57E+04	0.00E+00	2.08E+04	2.67E+04	2.11E+04	2.17E+04	2.68E+04	2.10E+04	1.71E+04	1.52E+04
11	0.00E+00	2.27E+04	0.00E+00	2.04E+04	2.57E+04	0.00E+00	2.08E+04	2.67E+04	2.11E+04	2.17E+04	2.68E+04	2.10E+04	1.79E+04	1.62E+04
12	0.00E+00	2.22E+04	0.00E+00	2.01E+04	2.52E+04	0.00E+00	2.03E+04	2.61E+04	2.07E+04	2.13E+04	2.61E+04	2.07E+04	1.82E+04	1.64E+04
13	0.00E+00	2.13E+04	0.00E+00	1.97E+04	2.39E+04	0.00E+00	1.97E+04	2.47E+04	2.03E+04	2.08E+04	2.47E+04	2.02E+04	1.80E+04	1.60E+04
14	0.00E+00	2.01E+04	0.00E+00	1.87E+04	2.21E+04	0.00E+00	1.85E+04	2.25E+04	1.92E+04	1.96E+04	2.26E+04	1.92E+04	1.72E+04	1.52E+04
15	0.00E+00	1.92E+04	0.00E+00	1.72E+04	2.00E+04	0.00E+00	1.69E+04	2.01E+04	1.77E+04	1.81E+04	2.02E+04	1.77E+04	1.60E+04	1.41E+04
16 (Bottom)	0.00E+00	2.31E+04	0.00E+00	2.06E+04	2.38E+04	0.00E+00	2.01E+04	2.38E+04	2.09E+04	2.14E+04	2.41E+04	2.12E+04	1.82E+04	1.63E+04

Number	115	116	117	118	119	120	121	122	123	124	125	126	127
Position	C-3	C-4	C-5	C-6	C-7	C-8	C-9	C-10	C-11	C-12	C-13	C-14	C-15
1 (Top)	6.13E+03	6.82E+03	7.27E+03	6.70E+03	7.34E+03	5.99E+03	7.31E+03	7.45E+03	7.60E+03	6.89E+03	6.35E+03	6.85E+03	6.84E+03
2	5.91E+03	6.31E+03	7.11E+03	6.49E+03	6.61E+03	5.90E+03	6.72E+03	7.21E+03	7.25E+03	6.37E+03	6.17E+03	6.31E+03	6.57E+03
3	7.03E+03	7.30E+03	8.32E+03	7.65E+03	7.82E+03	7.05E+03	7.96E+03	8.70E+03	8.67E+03	7.51E+03	7.35E+03	7.45E+03	7.92E+03
4	8.20E+03	8.36E+03	9.59E+03	8.80E+03	9.03E+03	8.19E+03	9.23E+03	1.01E+04	1.01E+04	8.65E+03	8.55E+03	8.65E+03	9.20E+03
5	9.31E+03	9.32E+03	1.08E+04	9.85E+03	1.02E+04	9.30E+03	1.04E+04	1.13E+04	1.13E+04	9.72E+03	9.68E+03	9.77E+03	1.03E+04
6	1.03E+04	1.02E+04	1.19E+04	1.08E+04	1.12E+04	1.04E+04	1.14E+04	1.25E+04	1.25E+04	1.08E+04	1.08E+04	1.08E+04	1.15E+04
7	1.16E+04	1.10E+04	1.30E+04	1.18E+04	1.23E+04	1.17E+04	1.24E+04	1.37E+04	1.36E+04	1.17E+04	1.20E+04	1.18E+04	1.25E+04
8	1.34E+04	1.19E+04	1.43E+04	1.31E+04	1.35E+04	1.36E+04	1.35E+04	1.51E+04	1.50E+04	1.28E+04	1.39E+04	1.31E+04	1.37E+04
9	1.58E+04	1.36E+04	1.59E+04	1.48E+04	1.53E+04	1.61E+04	1.55E+04	1.70E+04	1.68E+04	1.47E+04	1.64E+04	1.49E+04	1.54E+04
10	1.76E+04	1.56E+04	1.74E+04	1.63E+04	1.74E+04	1.80E+04	1.77E+04	1.87E+04	1.84E+04	1.69E+04	1.82E+04	1.69E+04	1.71E+04
11	1.83E+04	1.64E+04	1.81E+04	1.71E+04	1.82E+04	1.89E+04	1.85E+04	1.93E+04	1.89E+04	1.78E+04	1.89E+04	1.79E+04	1.80E+04
12	1.82E+04	1.65E+04	1.82E+04	1.73E+04	1.80E+04	1.90E+04	1.84E+04	1.92E+04	1.89E+04	1.78E+04	1.88E+04	1.81E+04	1.82E+04
13	1.75E+04	1.61E+04	1.82E+04	1.72E+04	1.73E+04	1.85E+04	1.76E+04	1.89E+04	1.86E+04	1.73E+04	1.82E+04	1.75E+04	1.81E+04
14	1.65E+04	1.51E+04	1.76E+04	1.66E+04	1.60E+04	1.74E+04	1.64E+04	1.80E+04	1.76E+04	1.62E+04	1.71E+04	1.64E+04	1.73E+04
15	1.53E+04	1.41E+04	1.66E+04	1.55E+04	1.47E+04	1.62E+04	1.50E+04	1.66E+04	1.63E+04	1.49E+04	1.59E+04	1.51E+04	1.60E+04
16 (Bottom)	1.71E+04	1.60E+04	1.88E+04	1.75E+04	1.68E+04	1.82E+04	1.70E+04	1.85E+04	1.82E+04	1.70E+04	1.77E+04	1.75E+04	1.81E+04

Position	B-2	B-5	B-8
1 (Top)	1.44E+04	1.44E+04	1.45E+04
2	1.29E+04	1.28E+04	1.28E+04
3	1.50E+04	1.53E+04	1.53E+04
4	1.73E+04	1.77E+04	1.77E+04
5	1.94E+04	1.99E+04	2.00E+04
6	2.14E+04	2.20E+04	2.20E+04
7	2.30E+04	2.37E+04	2.38E+04
8	2.43E+04	2.51E+04	2.52E+04
9	2.52E+04	2.61E+04	2.62E+04
10	2.57E+04	2.67E+04	2.68E+04
11	2.57E+04	2.67E+04	2.68E+04
12	2.52E+04	2.61E+04	2.61E+04
13	2.39E+04	2.47E+04	2.47E+04
14	2.21E+04	2.25E+04	2.26E+04
15	2.00E+04	2.01E+04	2.02E+04
16 (Bottom)	2.38E+04	2.38E+04	2.41E+04

Figure 4-1: Mix-1 full core power profile element-wise in W per node volume. Top: Mix-1 HEU fuel element power profile. Bottom: Mix-1 LEU fuel element power profile.

Stripe 1	Plate 16
Axial 1	290
Axial 2	261
Axial 3	298
Axial 4	337
Axial 5	379
Axial 6	418
Axial 7	443
Axial 8	457
Axial 9	465
Axial 10	477
Axial 11	470
Axial 12	458
Axial 13	436
Axial 14	407
Axial 15	381
Axial 16	446

	plate 15
Axial 1	1.26E+03
Axial 2	1.15E+03
Axial 3	1.24E+03
Axial 4	1.42E+03
Axial 5	1.57E+03
Axial 6	1.70E+03
Axial 7	1.80E+03
Axial 8	1.73E+03
Axial 9	1.70E+03
Axial 10	1.71E+03
Axial 11	1.66E+03
Axial 12	1.69E+03
Axial 13	1.63E+03
Axial 14	1.57E+03
Axial 15	1.56E+03
Axial 16	1.87E+03

Figure 4-2: Mix-1 hot plate/stripe power profile in W per node volume. Left: Mix-1 LEU hot stripe power profile. Right: Mix-1 HEU hot plate power profile.

Table 4-1: The fuel position, stripe and plate of individual elements at the location where ONB occurs most frequently.

	Location (Element, Stripe, Plate)				
	LEU			HEU	
Cycle	Loc	Stripe	Plate	Loc	Plate
Mix 1	B8	1	16	B9	15
Mix 2	B7	1	4	A2	1
Mix 3	A2	4	16	C13	1
Mix 4	B7	1	4	C13	1
Mix 5	C9	4	4	C8	15
Mix 6	A2	4	16	C12	15
Mix 7	A2	4	16	C12	15

Table 4-2: Normalized axial power profile input of hot plate/stripe for mixed core configuration Mix-1

LEU		HEU	
Node	Normalized factor	Node	Normalized factor
1	0.0000484	1	0.000210
2	0.0000435	2	0.000191
3	0.0000497	3	0.000207
4	0.0000561	4	0.000237
5	0.0000632	5	0.000261
6	0.0000696	6	0.000283
7	0.0000738	7	0.000301
8	0.0000761	8	0.000288
9	0.0000774	9	0.000283
10	0.0000795	10	0.000285
11	0.0000784	11	0.000277
12	0.0000763	12	0.000281
13	0.0000726	13	0.000271
14	0.0000678	14	0.000262
15	0.0000635	15	0.000261
16	0.0000743	16	0.000312

5 Primary Cooling System Upgrade

Part of the MITR LEU conversion project is the coolant system upgrade. Primary, secondary and shield coolant systems including pumps, electrical controls and heat exchangers need to be modified to enable higher flows and heat removal capacity. One of the important tasks of the coolant system upgrade is the flow-induced vibration testing. Flow-induced vibration are caused by pulsations induced by flow past orifices, dead legs, or other devices that interfere with the flow of the fluid in the pipeline. When the flow passes through these devices, the vortices are created at certain frequency, when such frequency reaches one of the modes of the natural frequency of the pipe, the flow-induced pulsations (FIP) are created in the piping system and result in forces that cause vibrations of the wall of the pipe [15], which, when severe enough, can lead to vibration-induced fatigue failure in piping system. In the nuclear reactors, any damage to the coolant piping system can have catastrophic consequences such as loss of coolant accident (LOCA). In the MITR fuel conversion project, the coolant flow rate will be increased by 20%, from 2000 gpm to 2400 gpm with existing coolant pipes. In MITR primary piping system, the primary coolant reaches the highest velocity in the vertical pipe chases between the core tank and the pipe tunnel, which is made of 6061 T6 aluminum with 7.5 inch inner diameter and a 0.25 inch wall thickness [16] Therefore, it is important to ensure increase flow velocity will not lead to excessive flow vibration that may pose safety concerns.

5.1 Flow Induced Vibration Experiments

The Flow-induced vibration at three main components were investigated using accelerometer: both inlet and outlet of the primary coolant pump, both inlet and outlet of the pipe tunnel, and both inlet and outlet of the heat exchanger. Figure 5-1 shows the primary coolant system and accelerometer install positions. Figure 5-2 shows the actual pictures taken in the mechanical room at three main components with accelerometers strapped. Vibration tests are conducted under eight different flow rate conditions, ranging from 1000 to 2550 gpm. The testing cases are tabulated in Table 5-1.

The accelerometers used in this study for vibration measurement are ADXL354/ADXL355 3-Axis MEMS Accelerometers from Analog Devices Inc. These accelerometers have very low measurement range which makes them sensitive to even smallest vibrations and can measure vibrations along all three axes. The specifications of the accelerometers are tabulated in Table 5-2.

The data analysis includes calculating the steady state standard deviation for all measured data from 0 s to 300 s, the maximum velocity and acceleration of vibrations. Fourier transform analysis will also be performed using MATLAB. Fourier transform converts the vibration signals from time domain to a representation in the frequency domain. The discrete Fourier transform (DFT) is obtained by decomposing the vibration signals into components of different frequencies to observe if there are any major modes of vibration at specific frequency that appear at higher flow rate.

Table 5-1: Flow Induced Vibration testing matrix

	Inlet/outlet at Pump	Inlet/outlet at Pipe tunnel	Inlet/outlet at Heat exchanger
1000 gpm	✓	✓	✓
1500 gpm	✓	✓	✓
1900 gpm	✓	✓	✓
2000 gpm	✓	✓	✓
2200 gpm	✓	✓	✓
2300 gpm	✓	✓	✓
2400 gpm	✓	✓	✓
2550 gpm	✓	✓	✓

Table 5-2: Specifications of accelerometer

Parameters	Values
Measurement Range	+/- 2G
Data Acquisition Rate	2k Hz
Frequency Range	50 Hz → 2k Hz
Non-Linearity	+/- 0.1%
Sensitivity	400 mV/G
Temperature Range	-40 ℃ → 125 ℃

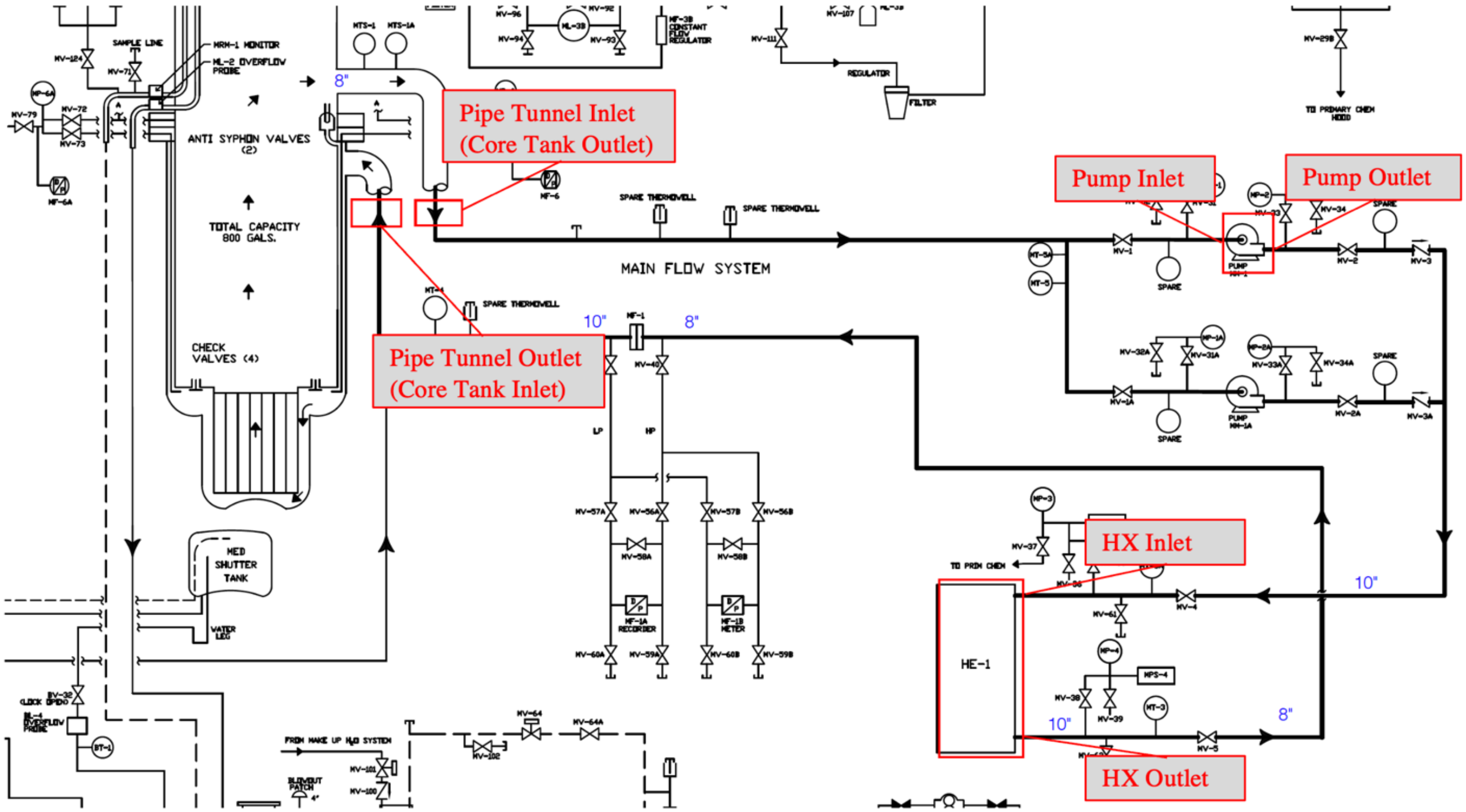
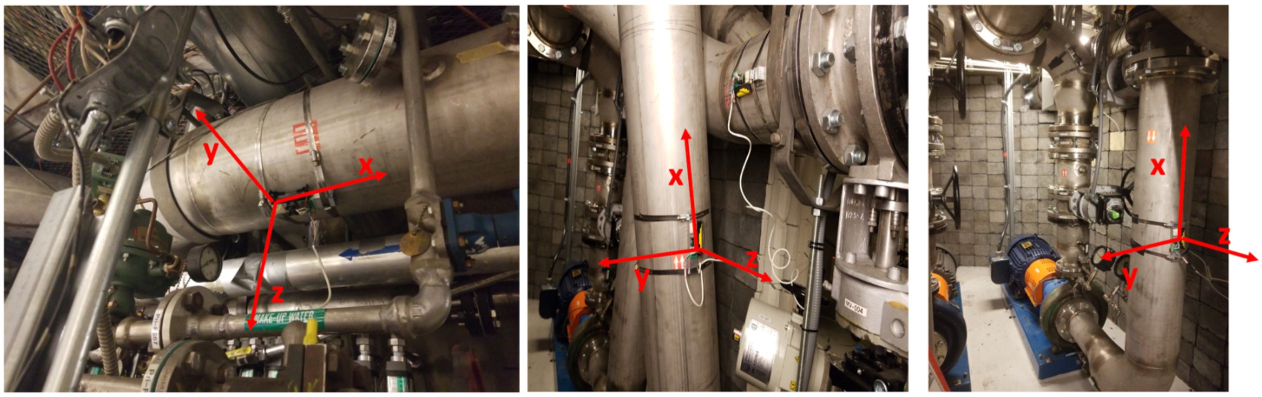


Figure 5-1: Primary coolant circuit and accelerometer positions



Pipe Tunnel Heat Exchanger Pump

Figure 5-2 Accelerometers Positions and 3 axes of measurement

5.2 Vibration testing results

The raw data taken from the accelerometers are the acceleration along all 3 axes against time. Figure 5-3 shows a sample raw vibration profile at pipe tunnel inlet with flow rate of 2000, 2400 and 2550 gpm. The standard deviation is also calculated as well as another parameter σ/σ_{avg}, it can help to compare the results with all other locations. σ_{avg} is calculated using following equations,

$$\sigma_{avg} = \frac{\Sigma\,\sigma}{Number\ of\ data\ sets} = \frac{\sigma_{1000\ gpm,\ pipe\ tunnel\ inlet} + \sigma_{1500\ gpm,\ pipe\ tunnel\ inlet} + \cdots}{48} \tag{5-1}$$

Data shows that the three locations where the largest vibration occurred are pipe tunnel outlet, heat exchanger inlet and outlet. The maximum vibration velocity and acceleration at these three locations are tabulated in

Table *5-3*. Results shows that pipe tunnel outlet is the location where the vibration occurs the most. The maximum vibration velocity is 9.70 mm/s, the maximum vibration acceleration is 0.98 G when the flow rate is set at 2000 gpm.

Fourier transform analysis was performed at pipe tunnel outlet to observe if there is any significant spectral shift. The power spectral density (PSD) of vibration profile at pipe tunnel outlet at all testing flow rates is shown in Figure 5-4 and Figure 5-5. The peak occurs at around frequency of 150 Hz, and no significant spectral shift is observed.

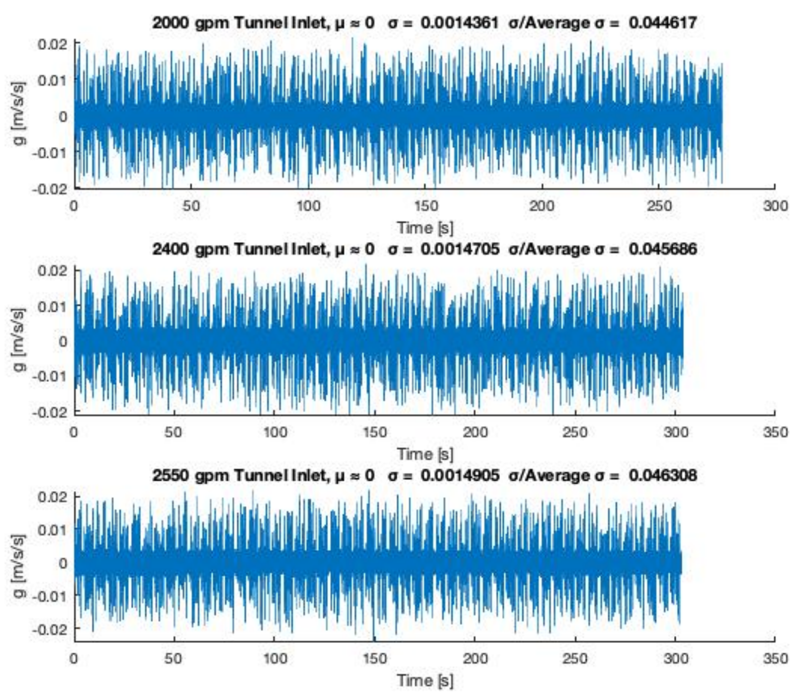


Figure 5-3 Raw data sample at pipe tunnel inlet, G vs. time

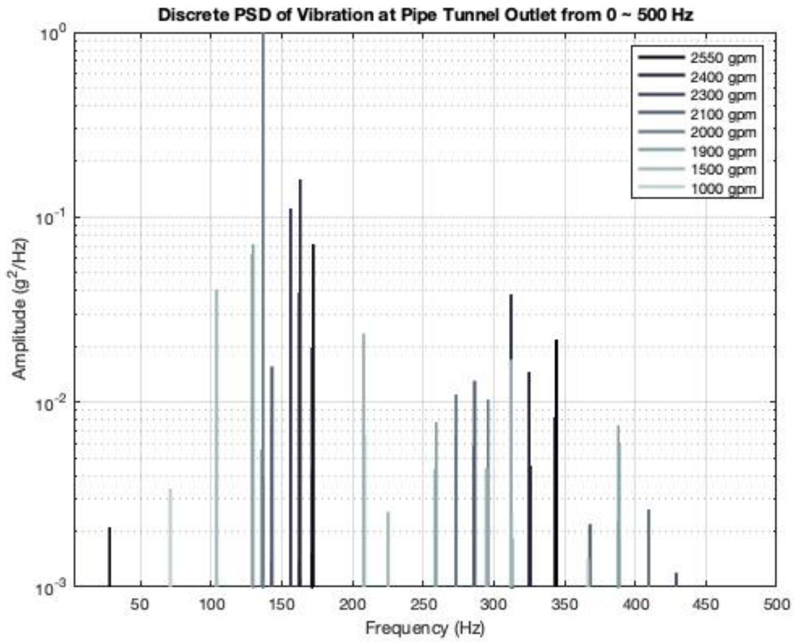


Figure 5-4. Discrete PSD of vibration at Pipe Tunnel Outlet at all flow rates

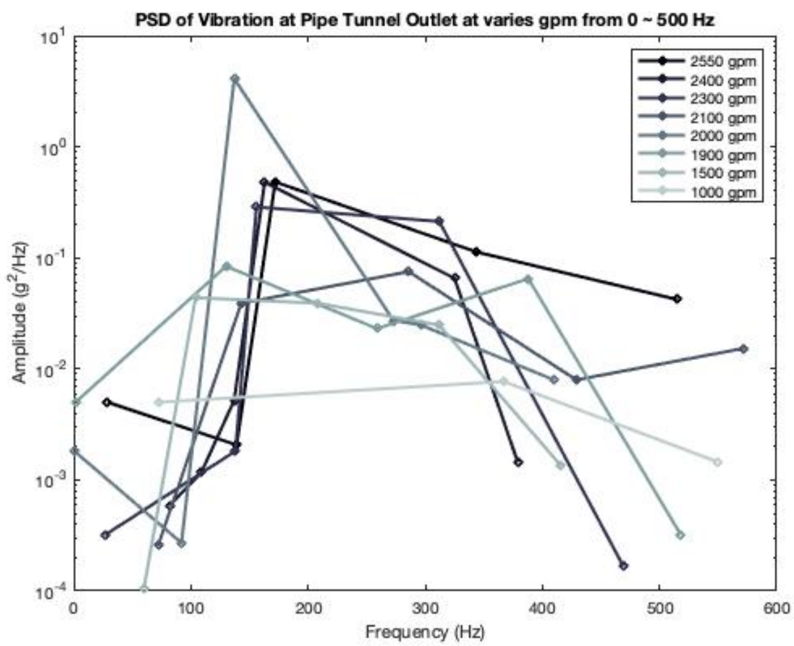


Figure 5-5. Integrated PSD of vibration at Pipe Tunnel Outlet at all flow rates (The darker the line, the higher gpm it represents)

Table 5-3. Maximum vibration velocity and acceleration at heat exchanger inlet and outlet and pipe tunnel outlet

Location: HE-01 Outlet Riser		Velocity (mm/s)				Acceleration (G)		
MF-1 Rec Flow (gpm)		X Axis	Y Axis	Z Axis		X Axis	Y Axis	Z Axis
2550		2.30	2.00	1.00		0.13	0.11	0.06
2400		1.70	2.20	1.00		0.05	0.10	0.07
2000		1.70	1.20	0.80		0.04	0.03	0.05
Location: HE-01 Inlet Offset Ell								
MF-1 Rec Flow (gpm)		X Axis	Y Axis	Z Axis		X Axis	Y Axis	Z Axis
2550		4.50	4.20	3.90		0.46	0.55	0.40
2400		5.00	5.70	6.20		0.49	0.76	0.56
2000		4.30	2.00	3.10		0.17	0.21	0.28
Location: Pipe Tunnel Outlet								
MF-1 Rec Flow (gpm)		X Axis	Y Axis	Z Axis		X Axis	Y Axis	Z Axis
2550		4.90	6.70	3.20		0.38	0.76	0.43
2400		2.20	5.70	2.00		0.39	1.35	0.30
2000		1.90	9.70	9.00		0.18	0.98	0.87

5.3 Conclusion

Results shows that pipe tunnel outlet is the location where the vibration occurs the most. Measurements for primary flow rates from 1000 to 2550 gpm show that the maximum vibration velocity is 9.70 mm/s, the maximum vibration acceleration is 0.98 G obtained for 2000 gpm. An NRC technical report, NUREG-1016 [17] suggests that the threshold vibration velocity for triggering more detailed stress investigations is 25 mm/s and the threshold vibration velocity for any serious concern is 12 mm/s. The worst-case vibration velocity of the coolant system is well below the suggested value. The Fourier transform analysis shows there was no significant spectral change in the vibration profile. Therefore, it can be concluded that pipe vibration up to 2550 gpm should not be a concern.

6 RELAP5 Mixed Core Steady-State Simulation

As discussed in the Conversion Strategy section in section 2, the conversion process of the MITR will be completed by implementing transitional mix-cores. A transitional MIX-Core is a core that consists of both HEU and LEU elements. The seven MIX-Core configurations account for the seven different core compositions during a gradual transition between the current homogeneous all HEU core to the final homogeneous all LEU cores. In this chapter, RELAP5 Mod3.3 is used to determine the thermal hydraulic safety margins of each transitional core during steady state. Initial evaluation of the all-HEU and all-LEU cores was performed by Ko et al. [18] using the RELAP5-3D code at a reactor power of 6 MW.

Under steady-state conditions, the MITR operates at a steady-state thermal power level of 6.0 MW with a primary coolant flow rate of 2400 gpm (151.42kg/s). The MITR's thermal hydraulic design basis is that, under conditions of forced convection, the primary coolant system can remove the 6 MW power produced routinely and transfer it to the secondary coolant system without the onset of nucleate boiling. This chapter explores the thermal hydraulic feasibility of the transitional mix-core strategy during steady-state by examining the temperature at fuel centerline, cladding, and coolant outlet.

Two RELAP5 models were developed and run in this study. The major difference between these two models is the treatment of the hot LEU fuel plate (fuel plate with the highest power generated) and hot flow channel. In the first model, hot LEU fuel plates/channel, same as the hot HEU fuel plates/channel, is treated as a whole plate/channel. Lateral coolant mixing between stripes is ignored, also lateral conduction between stripes in the fuel and clad is ignored. This model is the most basic model that can simulate the transitional core conversion strategy. Previous study [19] found that the lateral conduction significantly decreased peak cladding temperatures and determined that the 4-stripe geometry are conservative for a multi-stripe steady state calculation with no lateral conduction. Therefore, in the second model, the hot LEU fuel plate is modeled by

4 lateral stripes (quarter-element slices) and is referred as "LEU hot stripe" model. Note that in both models, HEU fuel elements are modeled with 1 stripe.

Because the "LEU hot stripe" model is more conservative at calculating the temperature at cladding surface, this study will primarily focus on the evaluation of the second model.

6.1 Introduction to RELAP5/Mod3.3

RELAP (Reactor Excursion and leak Analysis Program) is a multidimensional thermal-hydraulics and neutron kinetics modeling code designed to simulate the behavior of light water reactor (LWR) system normal operation and postulated accident conditions. The series of RELAP codes began with RELAPSE (Reactor Leak And Power Safety Excursion), which was released in 1966. Subsequent versions of this code are RELAP2 [20], RELAP3 [21], and RELAP4 [22]. All of these codes were based on a homogeneous equilibrium model (HEM) of the two-phase flow process. In 1976, the development of a nonhomogeneous, nonequilibrium model was undertaken for RELAP4. The result of this effort was the beginning of the RELAP5 project [23].

The RELAP5 code was developed by Idaho National Lab (INL) and distributed by Nuclear Regulatory Commission (NRC) for use in rulemaking, licensing audit calculations, evaluation of operator guidelines, and as a basis for a nuclear plant analyzer. The RELAP5 MOD3 version has been developed jointly by the NRC and a consortium consisting of several countries and domestic organizations that were members of the International Code Assessment and Applications Program (ICAP) and its successor organization, Code Applications and Maintenance Program (CAMP). In addition, improvements have been made on behalf of several Department of Energy sponsors. The mission of the RELAP5 MOD3 development program was to develop a code version suitable for the analysis of all transients and postulated accidents in LWR systems, including both large and small-break loss-of-coolant accidents (LOCAs) as well as the full range of operational transients.

The principal new feature of the RELAP5 series was the use of a two-fluid, nonequilibrium, nonhomogeneous, hydrodynamic model for transient simulation of the two-phase system behavior.

MOD3.3 version of the RELAP5 code was used in this study, although MOD3.3 is not the latest version, it is the version that have been repeatedly used in previous study and for which MITR-II input decks had already been benchmarked [24].

6.2 RELAP5 Input Deck for the MITR

The RELAP5 steady-state input deck for the MITR was originally prepared by S. J. Kim [25]. The original input deck was intended for current MITR full HEU core. Several major edits were made in the input deck in this study to model the MITR transitional cores.

The RELAP5 input deck takes specification for hydrodynamic components (pipes, single volumes, valves, pumps, and time-dependent volumes etc.), initial conditions (pressure, flow rate, temperatures etc.), heat structures (fuel plates), boundary conditions, materials properties (heat transfer coefficients etc.), and power level. Hydrodynamic components interconnected with each other to simulate the primary flow path geometry of MITR's coolant system in the input deck. The coolant system consists of cold leg, coolant pump, downcomer, lower plenum, reactor core, flow shroud, mixing area, and hot leg. Dimensions of the major components are summarized in Table 6-1.

The eight flow channels of the transitional mix cores are simulated using eight pipe components including seven flow channels and one bypass channel. These pipes are axially divided into sixteen nodes. Node 1 is the node at the bottom of the channels and node 16 is the node at the top end. In these four flow channels, the flow channel receiving the highest power in HEU core is defined as the hot channel, and the flow channel receiving the highest power in LEU core is divided into four hot stripe channels. The other two flow channels are defined as average channels (the temperature calculated from this channel shall be the average temperature for remaining channels except for the hot channel) for LEU core and HEU core respectively. Hot coolant channel model is constructed in accordance with the actual dimension of a single flow channel in MITR while other flow channels were lumped into a large single channel simulated as the average channel. The schematic of primary core flow path is shown in Figure 6-1. The schematic nodalization of RELAP5 MOD3.3 input deck for MITR is shown in Figure 6-2. The structures of interest from the nodalization scheme shown in Figure 6-2 are nodes 302 (average HEU channel), 312 (average LEU channel), 402 (hot HEU channel), 412 (hot LEU stripe channel #1), 422 (hot LEU stripe channel #2), 432 (hot LEU stripe channel #3) and 442 (hot LEU stripe channel #4). The input dimensions for these flow channels are tabulated in Table 6-2 and Table 6-3.

Heat structure was attached to the hydrodynamic model to simulate the power generated in fueled region. For each HEU and LEU core, one fuel plate heat structure was attached to the hot flow channel of the hydrodynamic component, and the rest of the HEU and the LEU fuel plates were lumped into HEU average heat structure and LEU average heat structure and attached to the respective average flow channels. The power distribution within the heat structures, both in axial direction and radial direction, was generated from MCNP5 in previous study by K. Sun et al. [13]

The RELAP5 MOD3.3 input takes material properties in table form. Thermal conductivity (k) and volumetric heat capacity (ρC_p) of fuel meat and cladding were entered in RELAP5 MOD3.3 input deck [26] and tabulated in Table 6-4, Table 6-5amd Table 6-6.

Table 6-1 Summary of Primary Coolant Loop Dimension

Region	Flow Area (m^2)	Volume (m^3)	Hydraulic Diameter (m)
Flow shroud	0.130	0.099	0.387
Mixing area	0.923	1.920	1.084
Hot leg	0.032	0.427	0.203
Cold leg	0.032	0.468	0.203
Downcomer 1	0.339	0.413	0.180
Downcomer 2	0.111	0.076	0.063
Downcomer 3	0.1256	0.016	0.22
Downcomer 4	0.029	0.018	0.04
4 NCV	0.029	N/A	N/A
2 ASV	0.007674	N/A	N/A

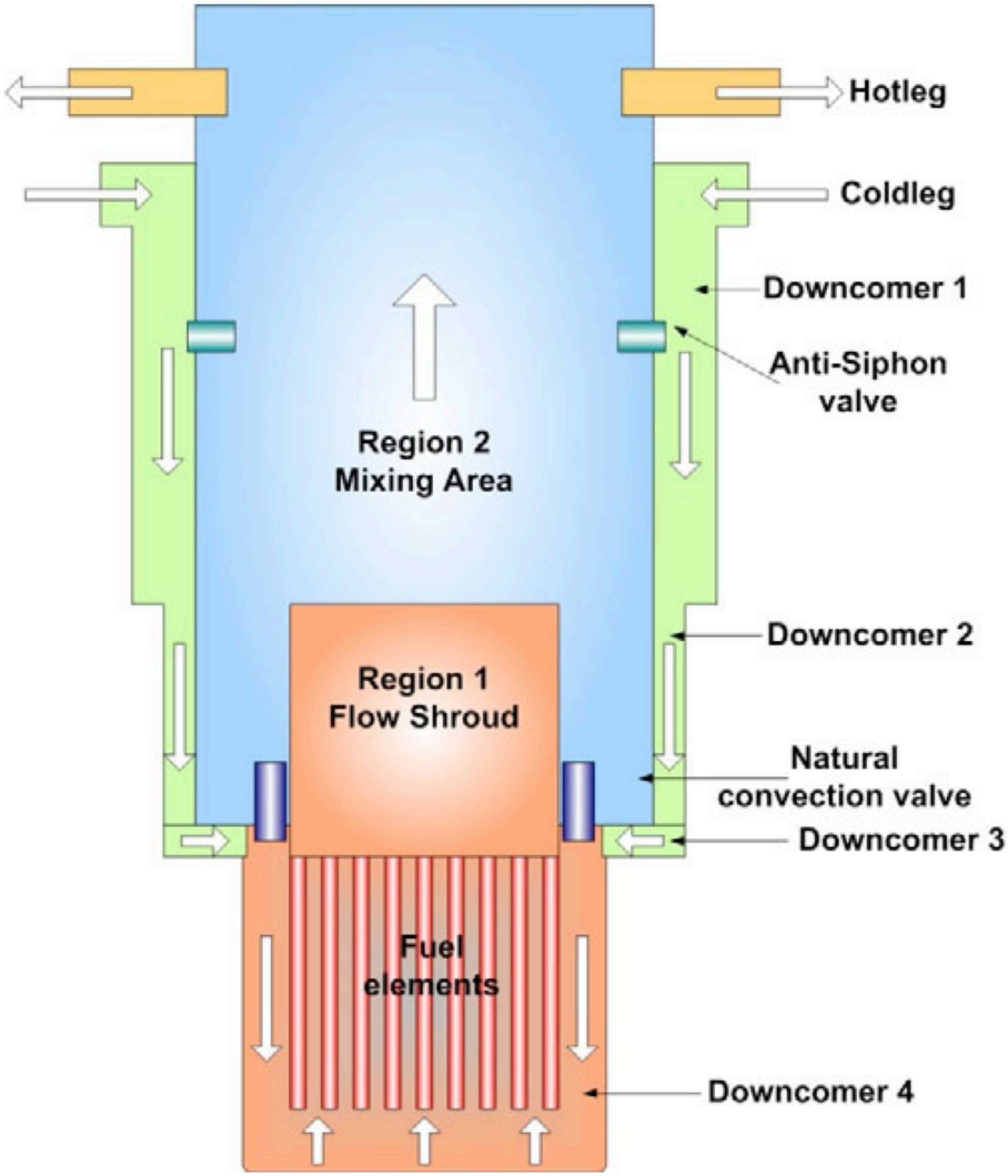


Figure 6-1 Schematic of MITR geometry and primary core flow path [27]

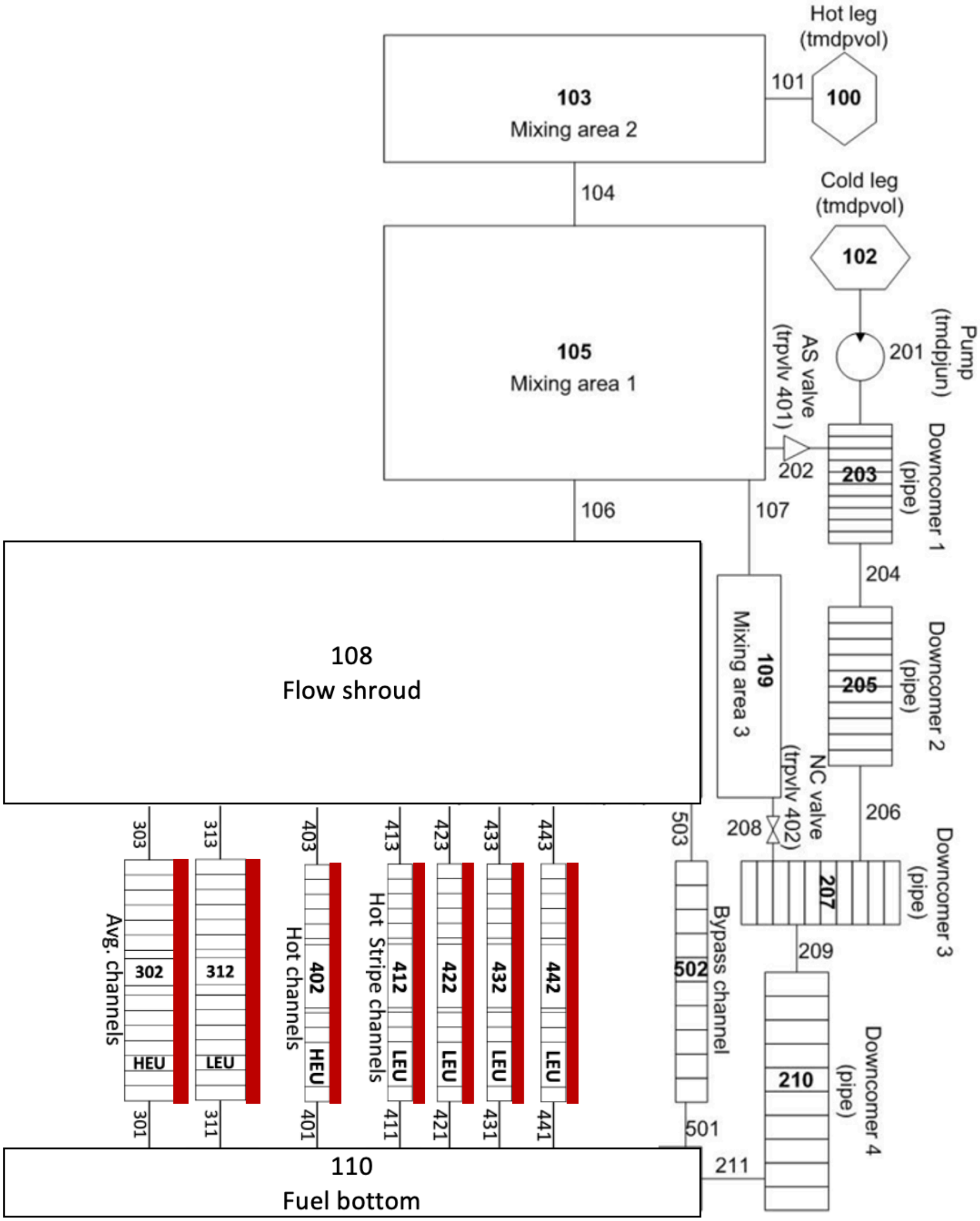


Figure 6-2 RELAP5 nodalization of hydrodynamic components of LEU hot stripe transitional core model.

Table 6-2 Hot LEU Stripe Fuel Plate/Channel Geometry

Geometry	Dimensions
Hot stripe channel flow area	$2.505 \times 10^{-5}\ m^2$
Hot stripe channel perimeter	2.644×10^{-2} m
Hot stripe channel D_h	3.790×10^{-3} m
Heat transfer surface area	$4.696 \times 10^{-4}\ m^2$
U-10Mo fuel meat thickness	6.350×10^{-4} m
Al clad thickness	3.048×10^{-4} m

Table 6-3 Hot HEU Fuel Plate/Channel Geometry

Geometry	Dimensions
Hot channel flow area	$1.182 \times 10^{-4}\ m^2$
Hot channel perimeter	2.250×10^{-1} m
Hot channel D_h	2.101×10^{-3} m
Heat transfer surface area	$1.931 \times 10^{-3}\ m^2$
UAl_x fuel meat thickness	7.620×10^{-4} m
Al clad thickness	3.810×10^{-4} m
Fin height/width/gap	2.540×10^{-4} m

*Note: The fin structures on MITR HEU element are symmetric

Table 6-4: Modeled Volumetric Heat Capacity of HEU UAl_x Fuel. [26]

Temperature (ºC)	Volumetric Heat Capacity (MJ/m^3-K)
20	2.247
260	2.388
537.8	2.560
1648.9	3.250

Table 6-5: Modeled Thermal Conductivity of LEU U-10Mo Alloy Fuel. [26]

Temperature (ºC)	Unirradiated Thermal Conductivity (W/m-K)	Irradiated Thermal Conductivity (W/m-K)
20	10.64	9.30
800	37.36	32.67

Table 6-6: Modeled Volumetric Heat Capacity of LEU U-10Mo Alloy Fuel. [26]

Temperature (ºC)	Volumetric Heat Capacity (MJ/m^3-K)
20	2.362
93.3	2.430
204.4	2.538
315.6	2.655
426.7	2.781

6.3 Nominal Operation Steady-state simulation results

This section introduces the results for the RELAP5 nominal operation (steady-state) simulation. First, the average mass flow rate of each channel for each core configuration is plotted in Figure 6-3. The mass flow rate in each channel is monotonically decreasing from Mix-1 to Mix-7 as more LEU elements are inserted in the core. This is due to the fact that LEU fuel elements have more coolant channels than the HEU elements, more coolant channels in the core will split the coolant flow. HEU channels have lower coolant flow rate than LEU channels, majorly due to higher friction pressure loss brought by the fin structures on the HEU elements.

Figure 6-4 shows the coolant temperature at the outlet for both HEU and LEU hot channels. The coolant outlet temperature at the LEU hot channel monotonically increases because of the decrease of the coolant mass flow rate. On the contrary, the coolant outlet temperature at the HEU hot channel decreases as more HEU fuel elements are shuffled out by LEU fuels because of the gradual depletion of the HEU fuel, it can be observed that there are two sudden drops of the temperature from Mix-2 to Mix-3 and from Mix-5 to Mix-6. The temperature drops from Mix-2 to Mix-3 is because that the A-ring no longer has any HEU fuel elements. The temperature drops from Mix-5 to Mix-6 is because the newly added LEU fuel elements are very closed to the shim blades positions.

Figure 6-5 and Figure 6-6 show the maximum temperature at cladding surface and fuel centerline for both HEU and LEU hot channels at each transitional core cycle. The maximum wall temperature for LEU is around 82 °C which occurs at Mix-7, the maximum wall temperature for HEU element is around 89 °C at Mix-3. There is large safety margin (> 10 °C) to onset of nucleate boiling for both HEU and LEU fuel.

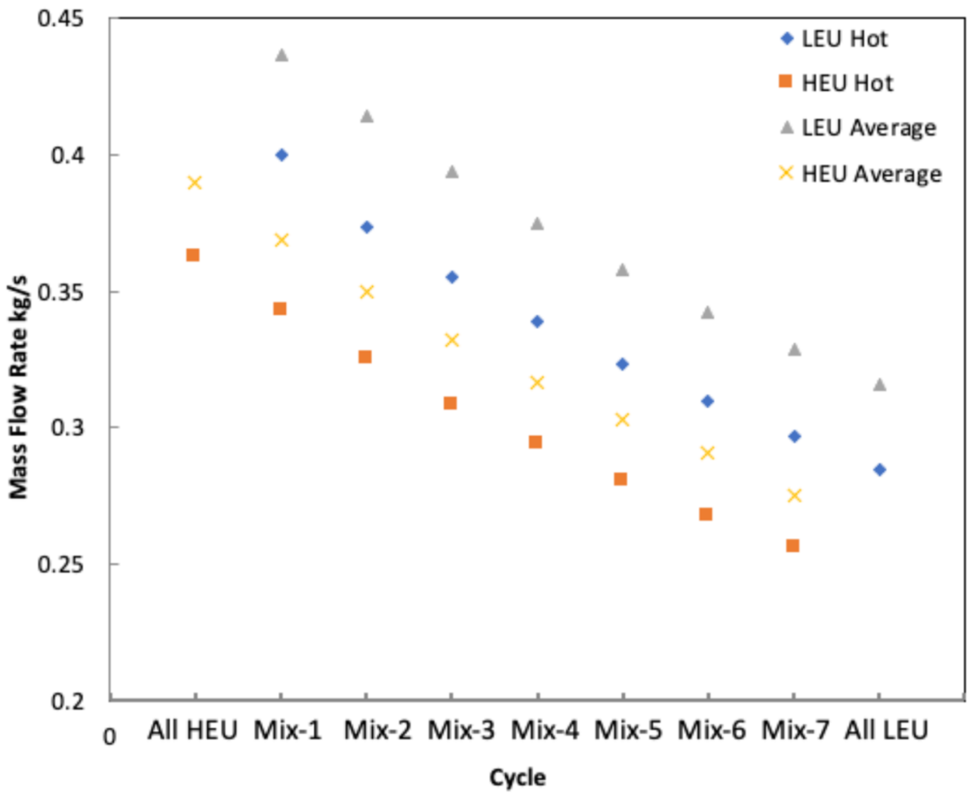


Figure 6-3. Mass flow rate at each channel for all fuel cycles.

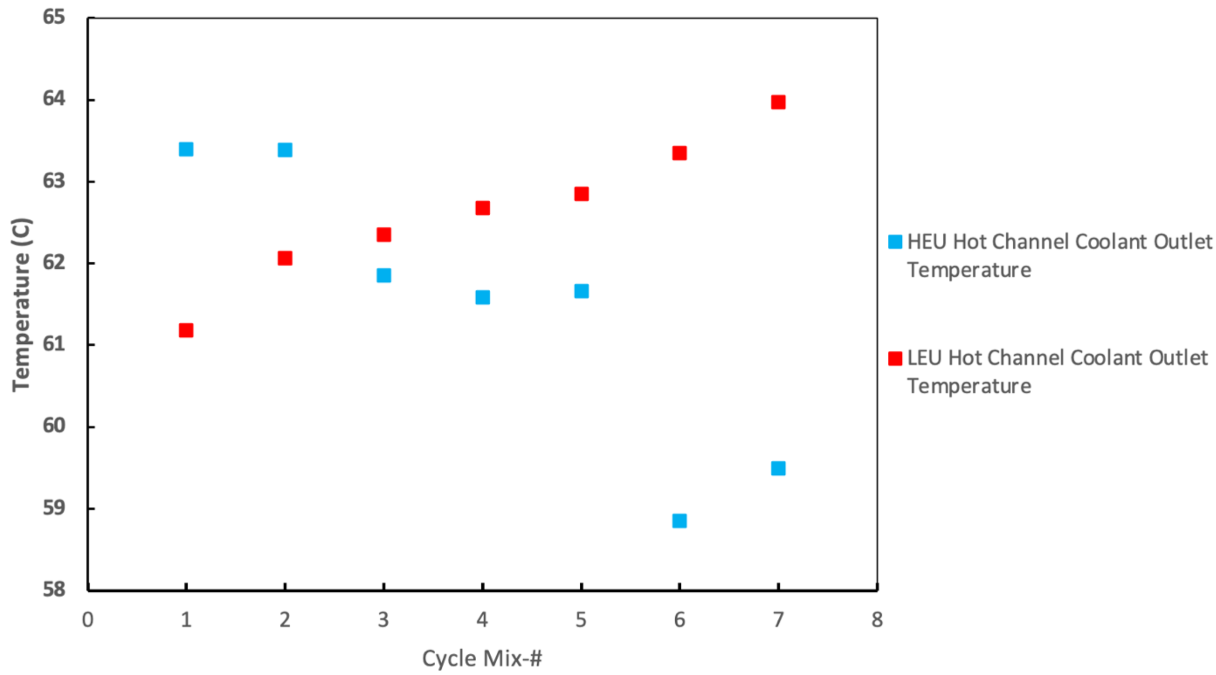


Figure 6-4: Coolant outlet temperature of the hot channels in various mix-core configurations

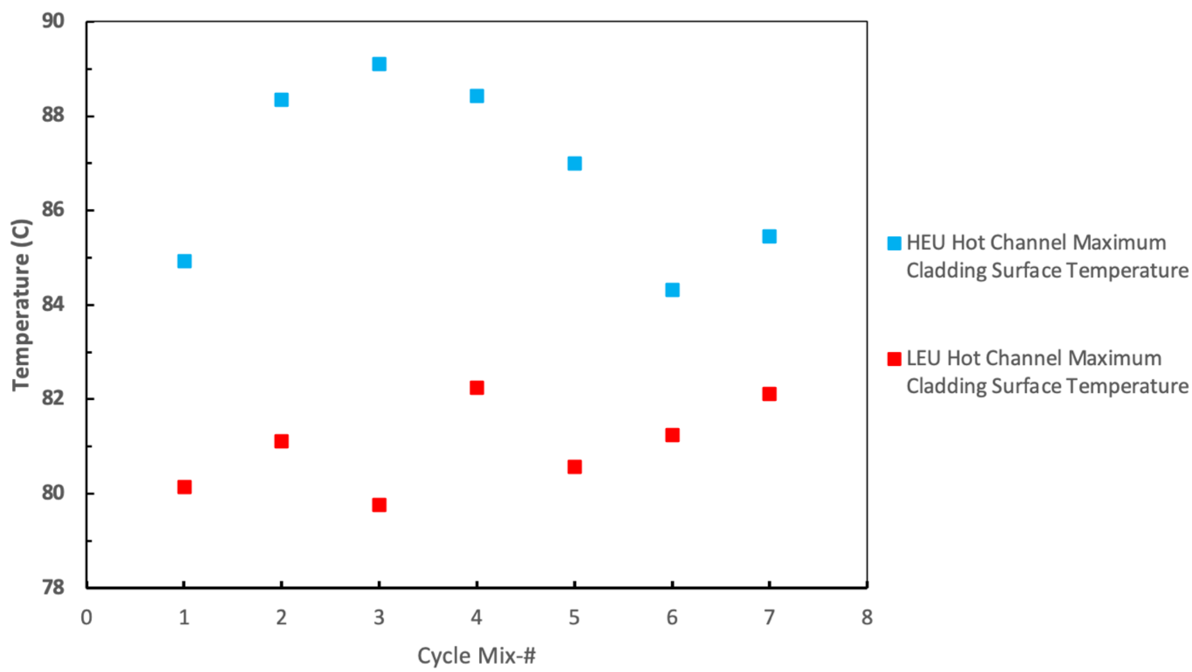


Figure 6-5: Cladding surface temperature of the hot channels in various mix-core configurations

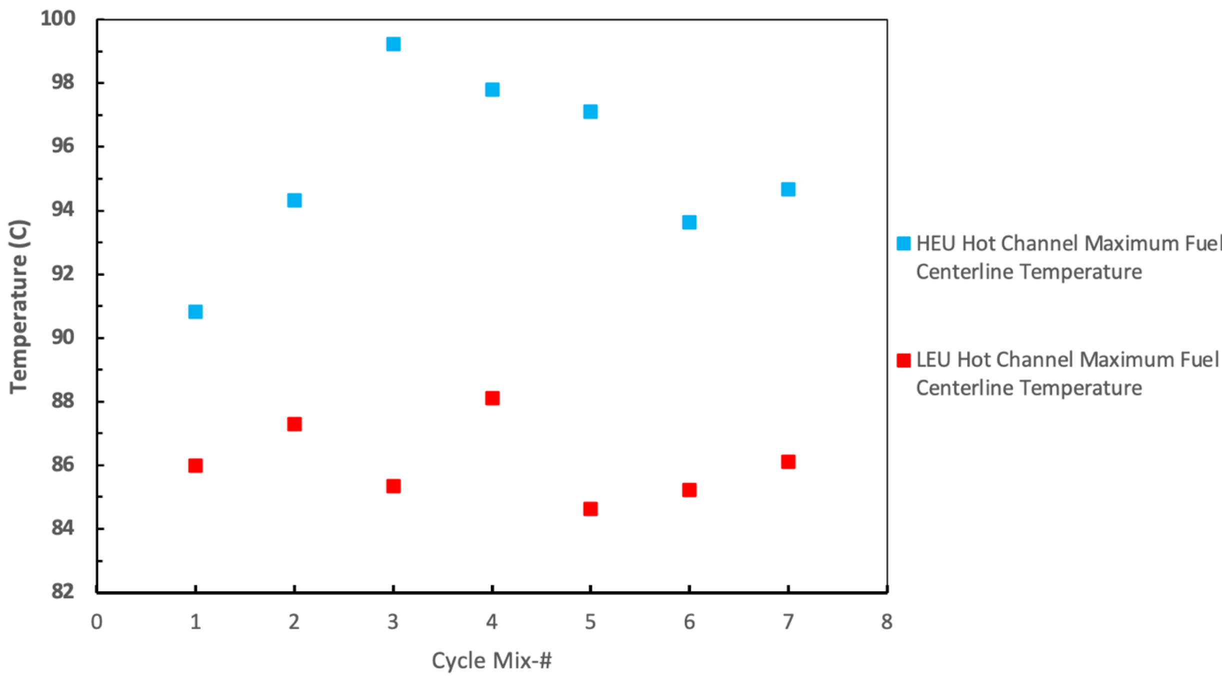


Figure 6-6: Fuel centerline temperature of the hot channels in various mix-core configurations

6.4 Summary of RELAP5 Steady-state simulation Results

During nominal steady-state operation at power level of 6.0 MW with primary coolant flow rate of 2400 gpm, there is significant safety margin (> 10 °C) to onset of nucleate boiling for both HEU and LEU fuel. The maximum core temperature occurs at HEU fuel in Mix-core 7, the maximum wall temperature reached was 89 °C.

7 RELAP5 Mixed Core Loss-of-Flow Simulation

Another condition simulated is loss-of-flow (LOF) transient condition. Transient analysis is important in order to observe the flow behavior during a LOF and the resulting fuel temperatures. There are two initiating events that can cause loss of primary coolant flow accident. The first is a loss of off-site electrical power which will stop the primary pumps, the second is a pump coast down accident that occurs because of primary pump power supply failures or malfunctions of the pump motors. The first event is a more credible scenario.

Under normal conditions, the MITR operates with a primary coolant flow rate of 2400 gpm. If primary coolant flow rate drops below 1900 gpm, a scram signal is automatically actuated. Followed by the initiation of low flow scram signal, the shim blade magnets are de-energized and then all six shim blades drop at the core periphery. As the flow rate decreases, the natural circulation valves (NCVs) and anti-siphon valves (ASVs) open, establishing natural convection within the core tank.

This chapter explores the thermal hydraulic feasibility of the transitional mix-core strategy during LOF transient by examining the temperature at fuel centerline, cladding, and coolant outlet, as well as whether on-site nucleate boiling (ONB) occurs.

The MITR is equipped with natural circulation and anti-siphon valves as passive safety features to promote the removal of decay heat from the core whenever forced convection flow is not sufficient. These valves are particularly important for a loss of flow transient during operation, when natural circulation becomes the primary means of cooling the core. There are four natural circulation valves (NCVs) located at the bottom of the core tank and two anti-siphon valves (ASVs) installed in the core tank at the elevation of the primary inlet pipe. Both the NCVs and ASVs are ball-type check valves. Under forced convection, the valves are shut because the ball is forced to the top of the shaft by the coolant pressure, thereby blocking the top aperture of the valves. When the primary flow is not sufficient to maintain the holding pressure, the ball begins to drop so that the valves will be open.

Figure 7-1 and Figure 7-2 illustrate the forced and natural convection circulation paths in MITR. When a transient or accident causes the pressure drops, for example, pump coast down occurs, NCVs and ASVs will start to open. Natural convection flow is then established within the core tank because of the buoyancy force of the heated coolant in the core region. The hot coolant exiting the core rises within the core tank, mixes with cold coolant in the outlet plenum, reverses direction and flows through the natural convection and/or anti-siphon valves, and then goes back through the core region thereby completing the natural circulation loop.

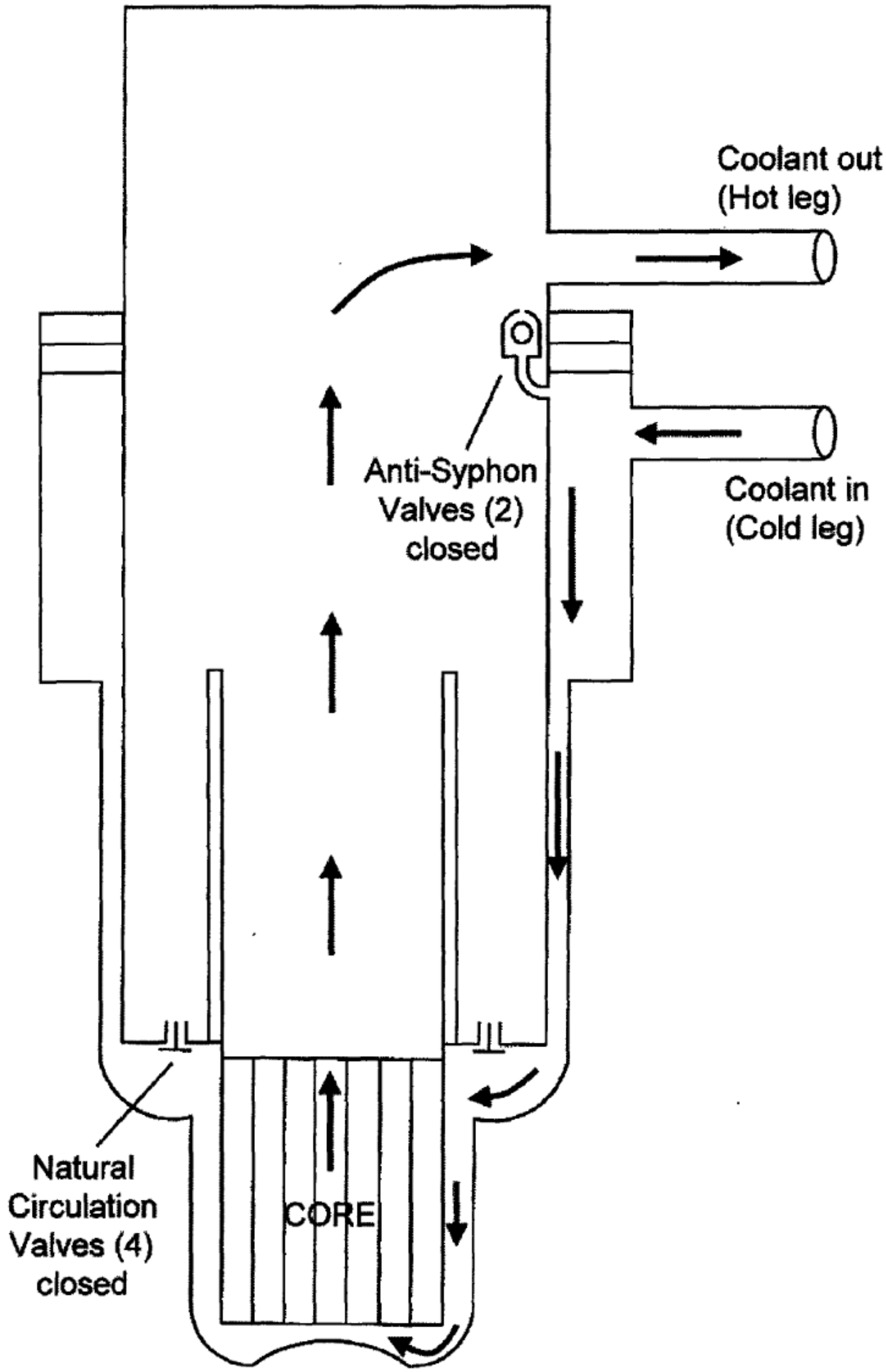


Figure 7-1 Forced convection in MIT reactor *[2]*

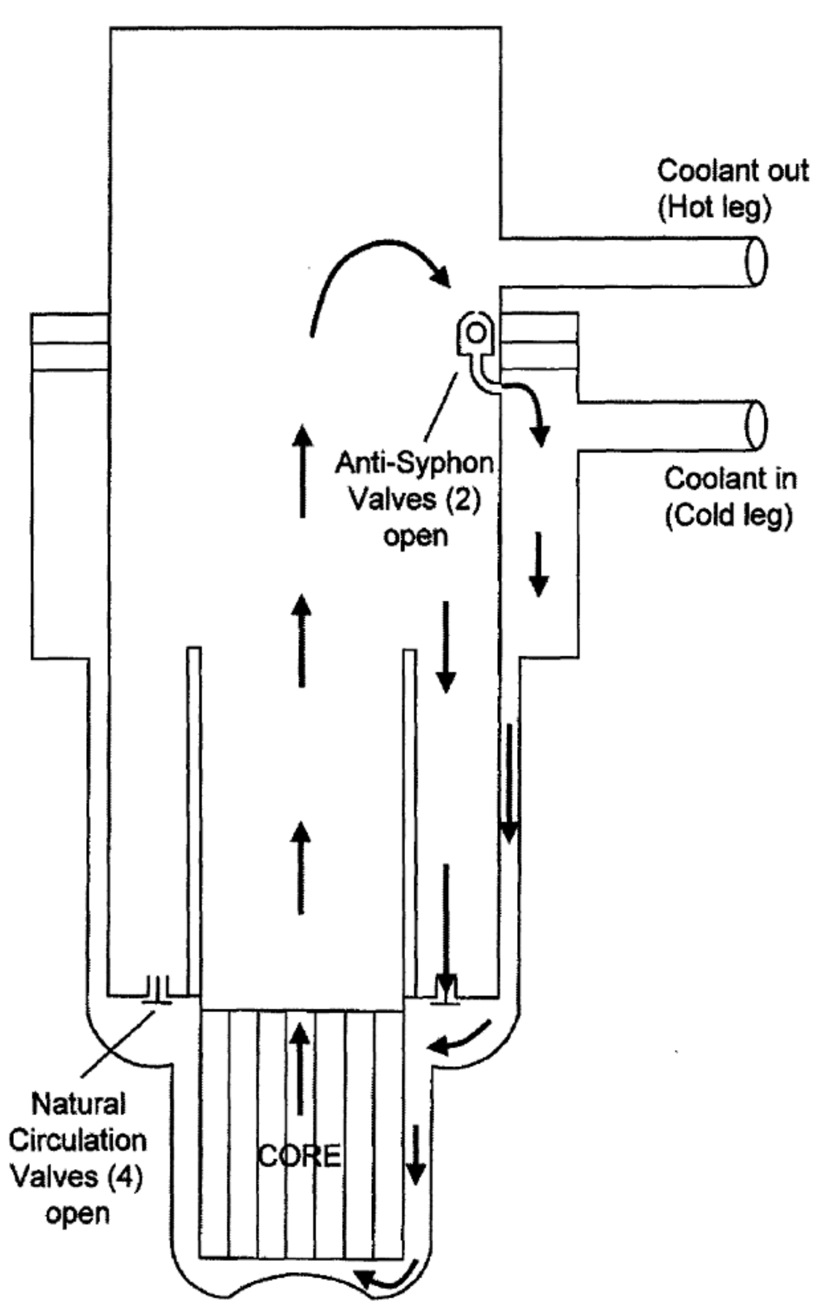


Figure 7-2 Natural convection in MIT reactor *[2]*

7.1 MITR Modeling for LOF Accident

To simulate the scenarios of LOF, relevant trips settings and tabulated data in input deck was constructed. After operating at power level of 6 MW for 300 seconds, at t=300 second, LOF accident occurs, under LOF transient conditions, the MITR loses primary flow via pump coast down. The pump coast down mass flow rate is tabulated in Table *7-1*.

When a LOF accident occurs, the reactor will shut down automatically upon receiving a low primary coolant flow scram signal. In the MITR-II initial startup natural convection tests, a scram delay time of 0.41 seconds [29] is assumed. A conservative value of 0.9 seconds is assumed from the initiation of scram to reach 80% of full insertion of the shim banks. There is also a one-second signal delay to reflect the signal transmission delay in real situation. Ramp reactivity insertion was applied in simulation that -7.5 beta of reactivity was introduced between 1.3 and 2.3 seconds [30] (one second for signal transmission and 1.3 seconds for shim blade insertion) after reactor scram.

Natural circulation is the heat removal mechanism during LOF transients. Four natural circulation valves and two anti-siphon valves are open to enable the natural circulation. In RELAP5 MOD3.3 input deck, these valves were manually set to open on 4.4 seconds after the scram signal.

Table 7-1 Cold leg mass flow rate during transient

Time elapsed after Transient starts [s]	Mass flow rate [kg/s]
0	151.420
0.1	146.204
0.2	152.144
0.3	136.147
0.4	131.303
0.6	121.973
0.8	113.115
1.0	104.714
1.5	85.635
2.0	69.150
2.5	55.071
3.0	43.205
3.5	33.364
4.0	25.354
4.5	18.987
5.0	14.073
6.0	7.837
7.0	5.124
8.0	4.407
10.0	2.868
11.0	0
100000	0

7.2 Loss-of-flow (LOF) transient results

This section introduces the results for the RELAP5 mixed core LOF transient simulation. Figure 7-3 to Figure 7-5 show the temperature at fuel centerline, clad surface, and coolant outlet for HEU hot channel, the coolant saturation temperature is also included. The maximum HEU fuel temperature reached during the transient was around 108 °C, the maximum clad temperature reached was 107 °C.

It can be observed that the coolant temperature reaches the saturation temperature (104.5 °C) around 20.0 s after the pump trips. Temperature fluctuates around the peak due to occurrence of boiling at the very end of the coolant channel in Mix-1 and Mix-2, the duration of the flow fluctuation is around 10.0 s. Figure 7-6 shows the void fraction at node 16 for HEU hot channel in Mix-1 and Mix-2, the peak void fraction reached 0.2. A more detailed view to show the temperature fluctuation is also included in the temperature profile figure. Although ONB does occur during the transient in Mix-1 and Mix-2, the maximum cladding outer surface temperature does not exceed 110 °C and is therefore significantly below the fuel temperature safety limit for the fuels which is 450 °C for UAl_x fuel plates, and 350 °C for U-10Mo fuel plates at the $5x10^{21}$ fissions/cm^3 fission density that will achieve for MITR LEU conversion. [31]

Figure 7-7 to Figure 7-9 show the temperature at fuel centerline, clad surface, and coolant outlet for LEU hot channel, the coolant saturation temperature is also included. The maximum LEU fuel temperature reached during the transient was around 108 °C, the maximum clad temperature reached was 107 °C. The maximum coolant outlet temperature does not exceed 95 °C with approximately 10 °C margin to saturation temperature.

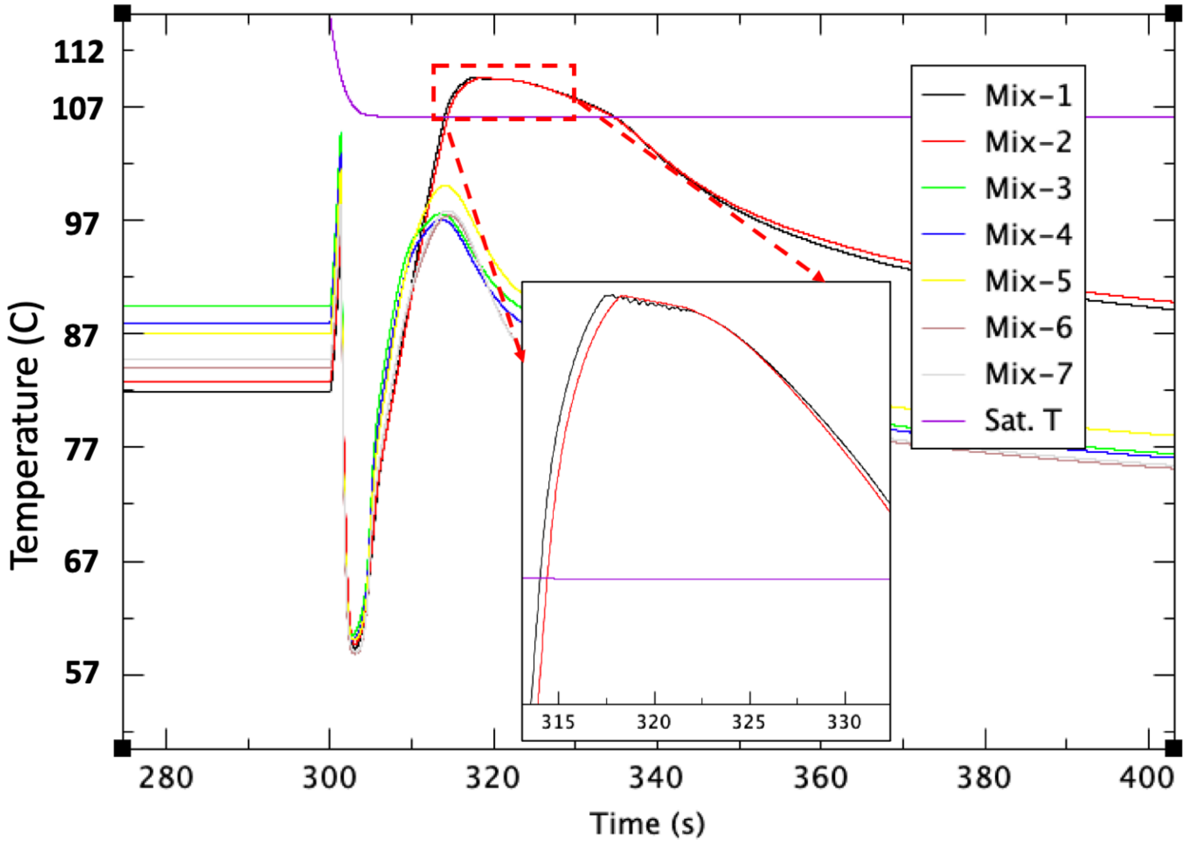


Figure 7-3 HEU hot fuel centerline temperature profile.

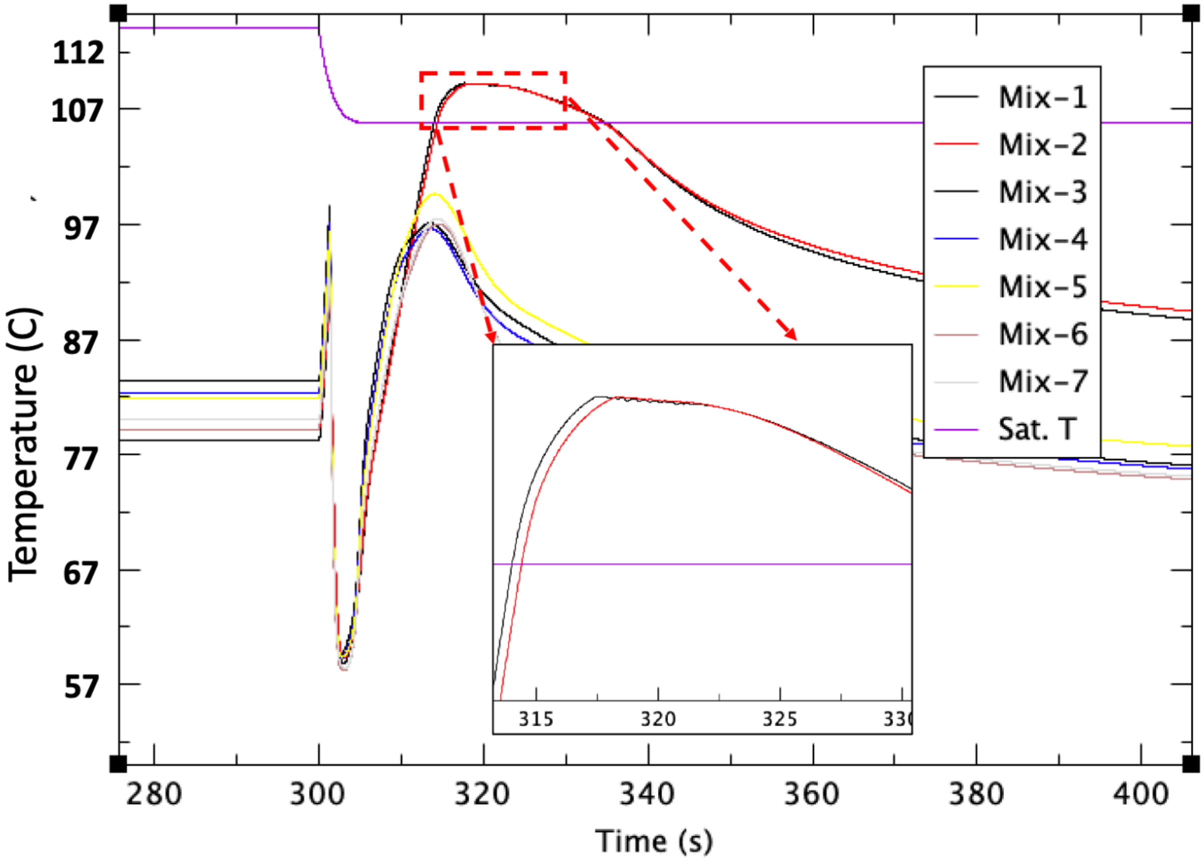


Figure 7-4 HEU hot fuel clad surface temperature profile.

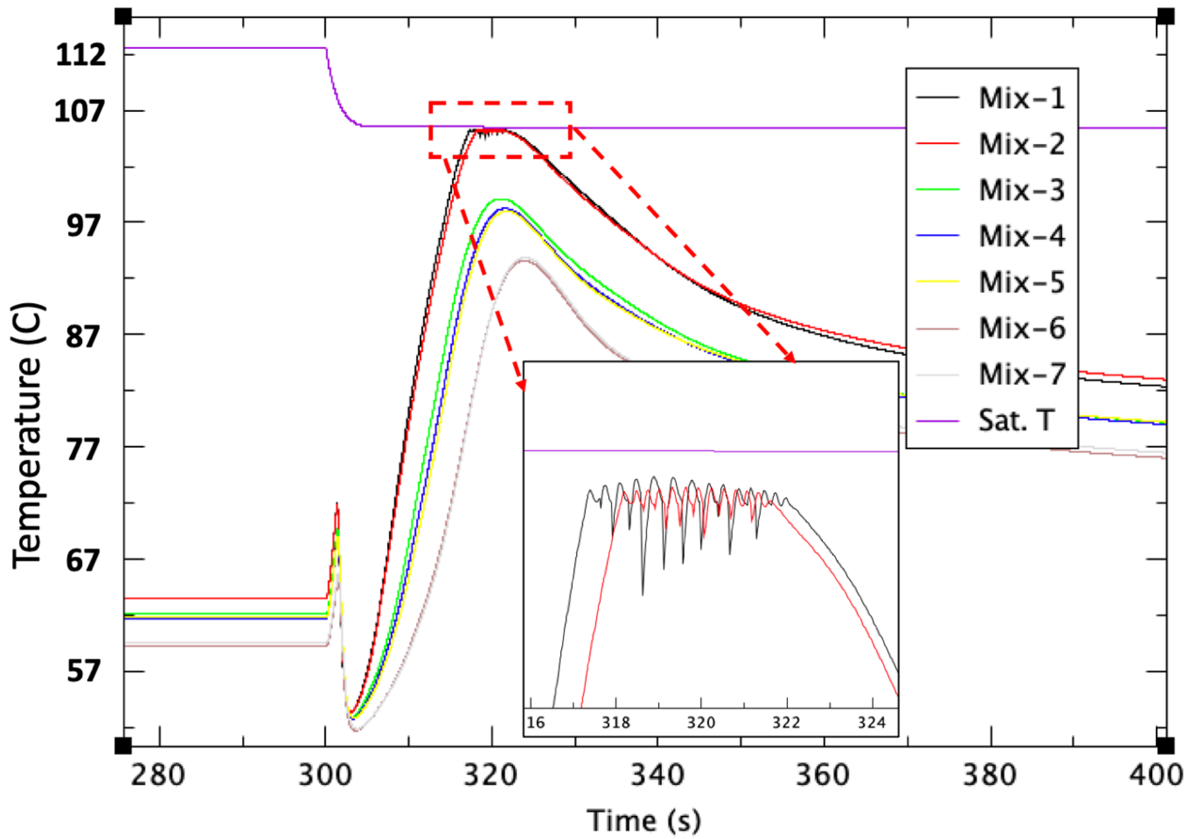


Figure 7-5 HEU hot fuel coolant outlet temperature profile.

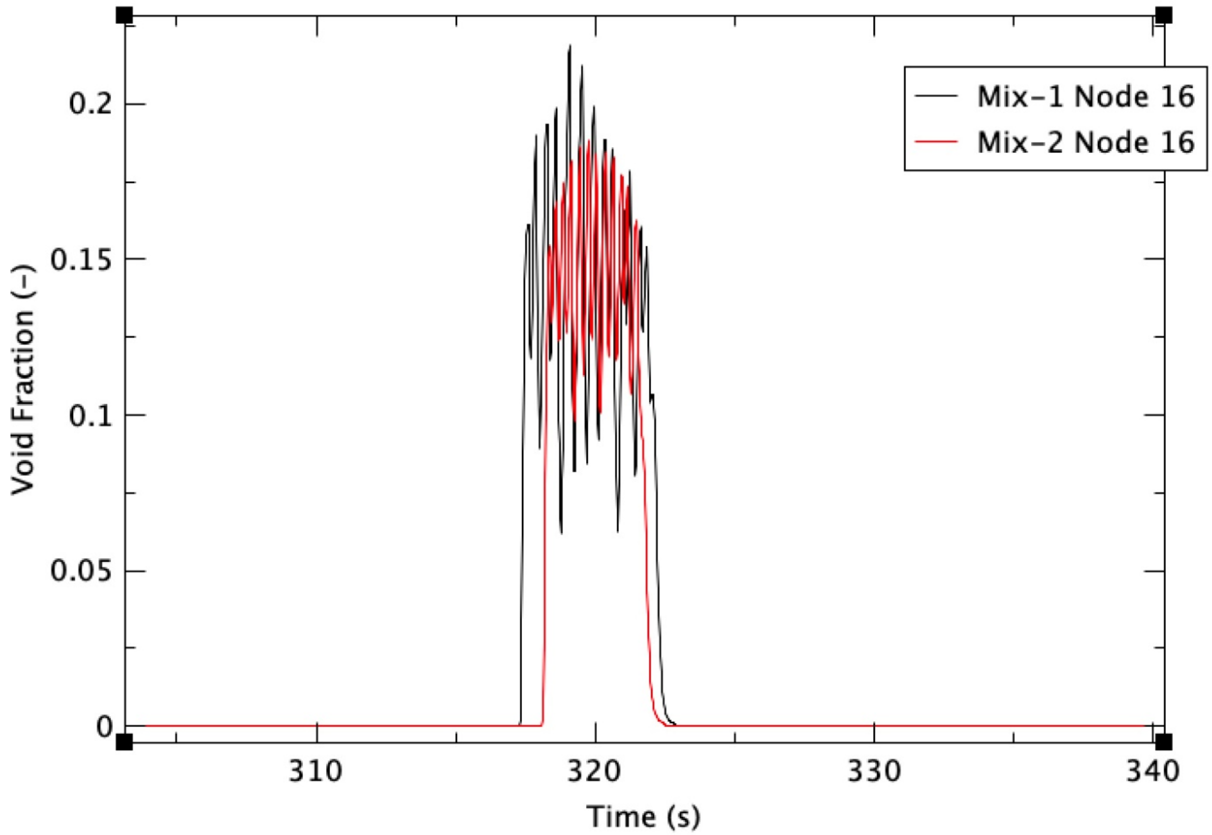


Figure 7-6 Void fraction at node 16 for HEU hot channel in Mix-1 and Mix-2 (node 1 is core inlet, node 16 is core outlet)

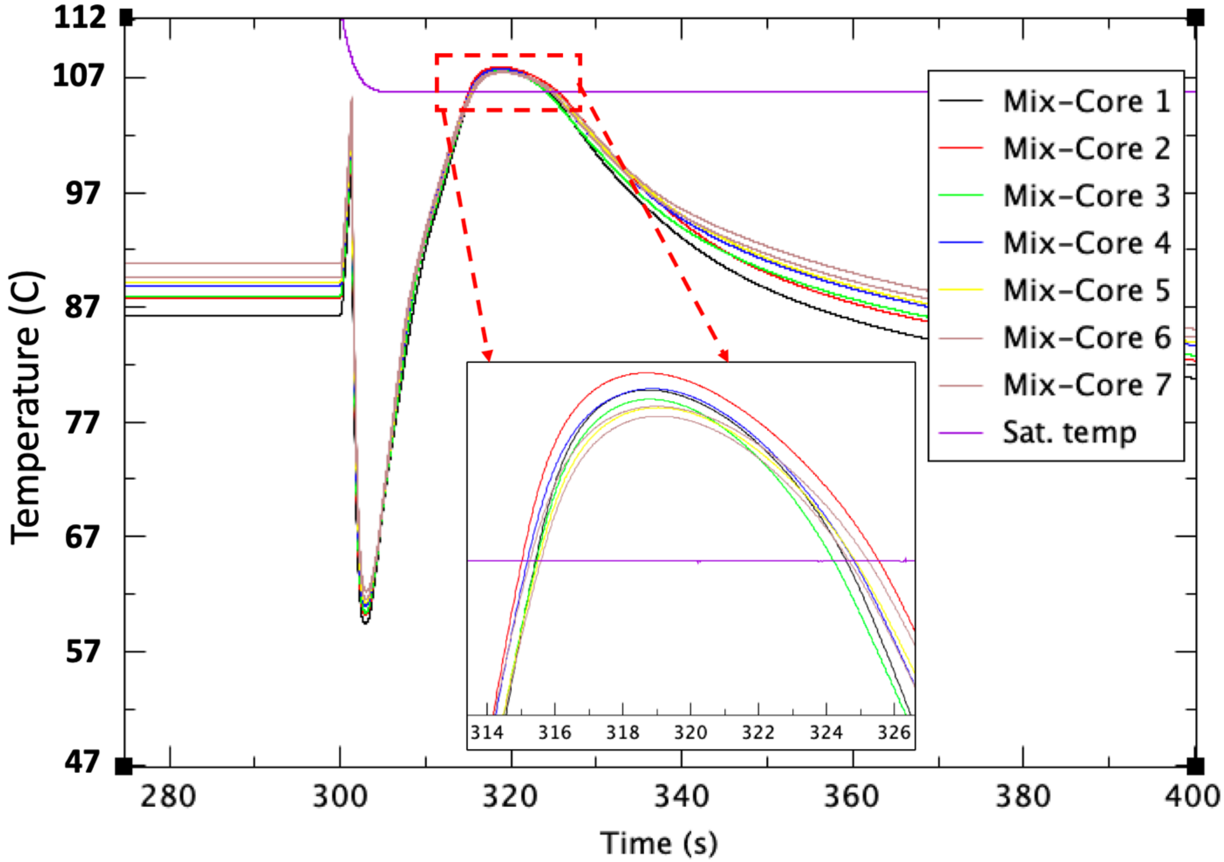


Figure 7-7 LEU hot fuel centerline temperature profile.

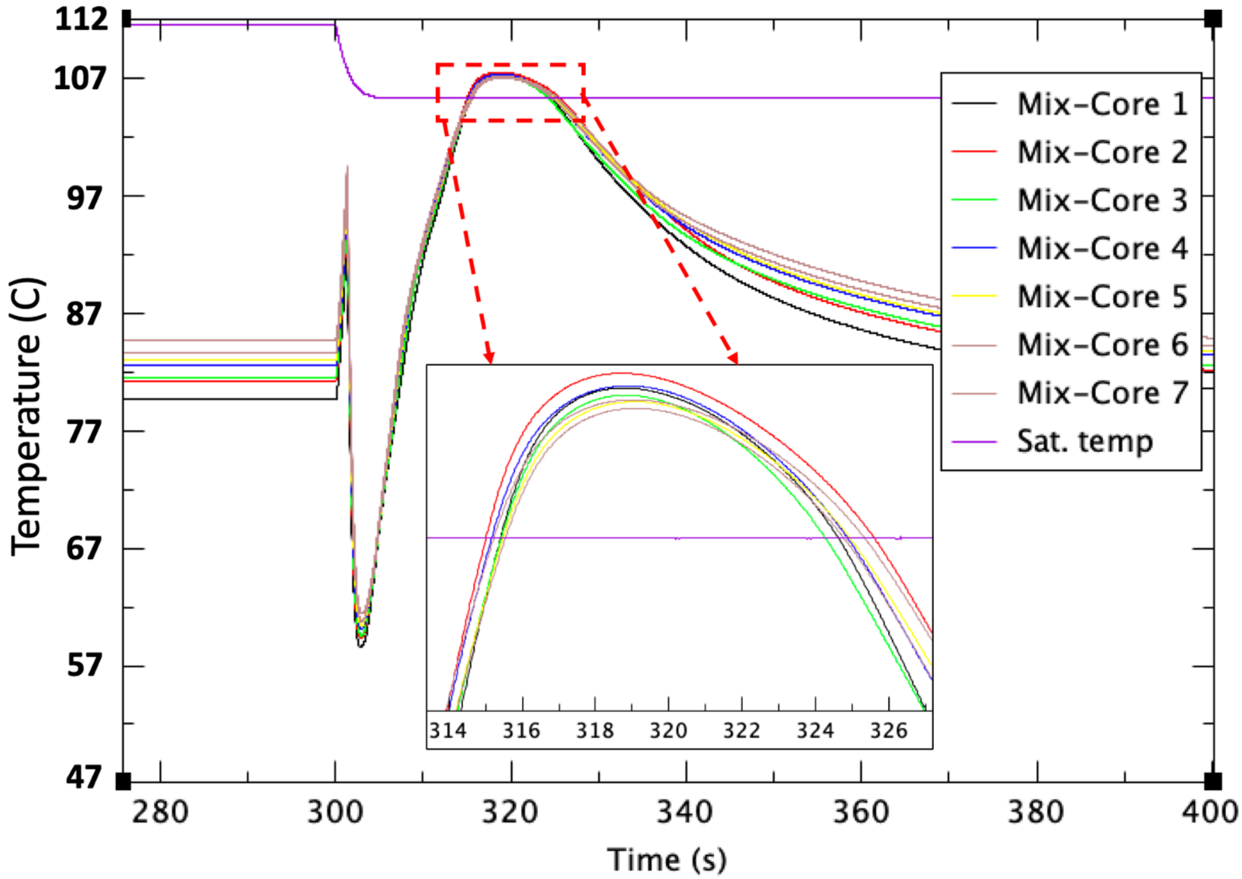


Figure 7-8 LEU hot fuel clad surface temperature profile.

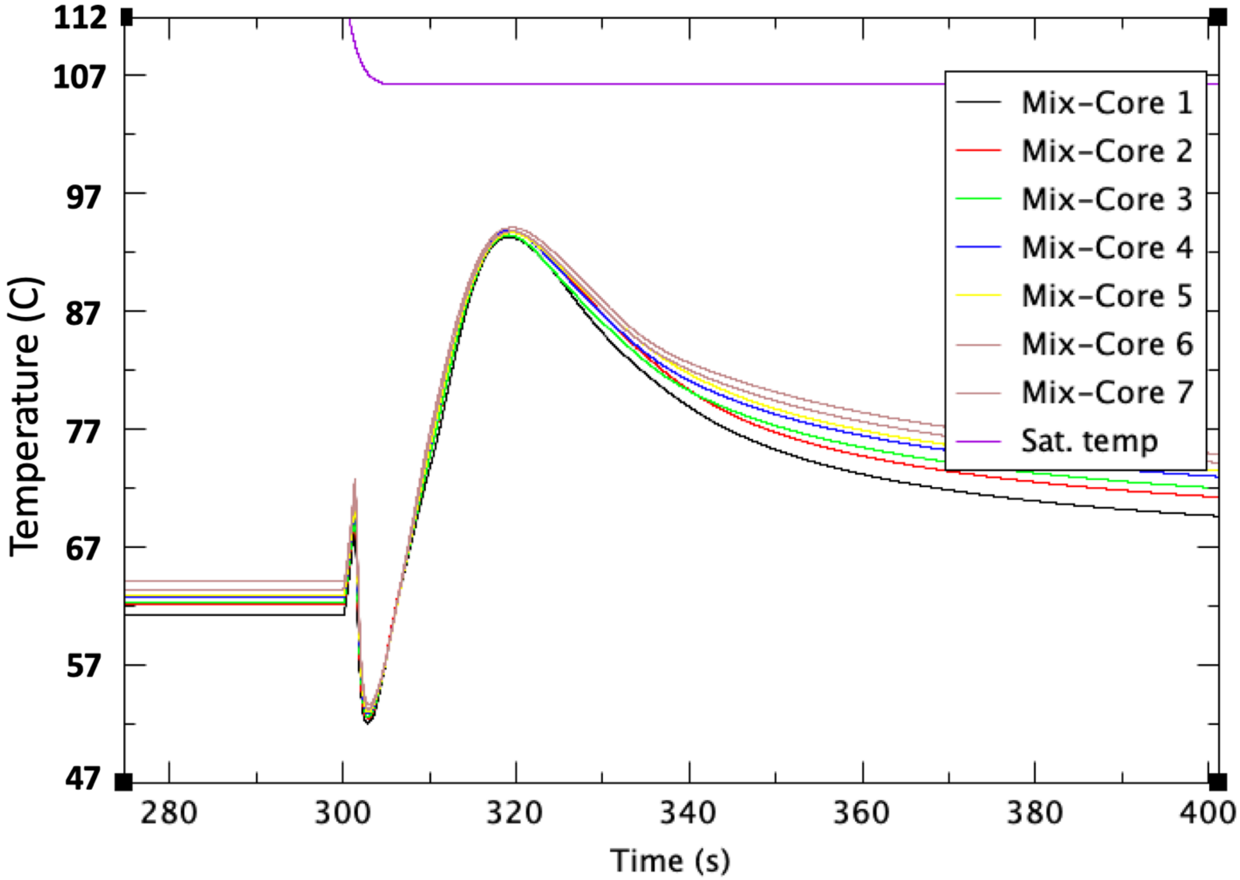


Figure 7-9 LEU hot fuel coolant outlet temperature profile.

7.3 Summary of RELAP5 LOF transient simulation results

In this section, RELAP5 LOF transient was evaluated. HEU and LEU cladding and coolant temperatures during LOF showed similar trends for all transitional core configurations. The most limiting mixed core configuration in terms of peak temperatures is Mix-7 configuration. The HEU fuel element is more limiting than the LEU in transitional cores. During the LOF transient, nucleate boiling is predicted to occur only in the HEU hot channel during the first 50 seconds after the pump coastdown. The peak cladding temperatures reached during the transient are around 108 °C, which are much lower than the 450 °C fuel temperature safety limit of UAl_x fuel plates.

8 STAT7 Mixed Core Steady-State Statistical Analysis

8.1 Introduction

Another computational code, STAT7, was used in this study to analyze statistical propagations of uncertainties in various mixed cores that might be configured for MITR HEU-LEU transition.

STAT7 is a steady-state thermal hydraulic code developed by Argonne National Laboratory specifically for the MITR plate-type reactor and was used in this study to determine the ONB power of the hot fuel element of any mixed core, the goal is to ensure there are large thermal hydraulic safety margin during the mixed core transition.

Argonne National Laboratory verified the accuracy of the code, with hand calculation and PLTEMP code. These verifications were completed to test STAT7's all capabilities and showed good correlation with both the hand calculations and PLTEMP code for all capabilities. Additional research [32] was done to verify STAT7 thermal hydraulic calculations with RELAP5 MOD3.3 and the results showed good agreement between two codes. STAT7 code has also been used in previous study by A. Dave et al. [10] to determine the thermal-hydraulic safety margins of LEU transition core, as discussed in section 1.4.

8.2 Methodology

STAT7 takes various input parameters to determine the flow and temperature profile of a single fuel element or a quarter of a fuel element. Input parameters such as fuel geometry parameters, operation parameters and power profiles, etc. which will be thoroughly discussed in following sections. The power profile used as input file in STAT7 was generated from MCNP5 in previous study by K. Sun et al [13]. During transitional cores, STAT7 models the fission power generation and heat transfer in the LEU element by discretizing each plate into 16 axial nodes, and 4 lateral nodes ("stripes"). HEU element model has 16 axial nodes and only one stripe as consistent with the approved Safety Analysis Report [33]. Figure 1. shows partial cross section view of an LEU element modeled in STAT7 with four stripes. This geometry is intended to enable STAT7 to capture the temperature peak at the side of the MITR fuel element by taking the effect of lateral heat conduction into account. The HEU-LEU transitional core includes 7 mixed core configurations. In each configuration, an HEU hot fuel element and a LEU hot fuel stripe are being identified and modeled as STAT7 input deck. The hot stripe location and hot element location for both LEU and HEU are determined by the evaluation of all core stripes using STAT7 in previous study [34].

Uncertainties are important input parameters of STAT7 and are treated with a Monte-Carlo statistical propagation approach. The statistical propagation approach for MITR-II was initially implemented by L.-W. Hu and K.-Y. Chang [35] using the Oracle spreadsheet program with the Crystal Ball plug-in. A large number of histories are run, and in each history, the value for various parameters (fuel geometry, power level, etc.) are set based on random sampling from the Gaussian uncertainty distribution for the respective parameters.

One of the output parameters from STAT7 in this study is ONB Power (P_{ONB}). P_{ONB} is the maximum core power at which the Onset of Nucleate Boiling (ONB) is precluded. For the steady-state MITR operation, ONB is adopted as the safety criterion for limiting safety system settings (LSSS) [36]. The P_{ONB} is determined through an iterative process, such process is used to repeat the calculations for additional nominal reactor powers until the power at which an exact 0.00135 probability of ONB occurring is predicted. The 0.00135 value represents the power at which there is a 3-σ confidence level of 99.865% that ONB does not occur within the type of fuel element (HEU or LEU) in a given mixed core configuration [32]. P_{ONB} is then compared to the LSSS power to evaluate the thermal safety margin.

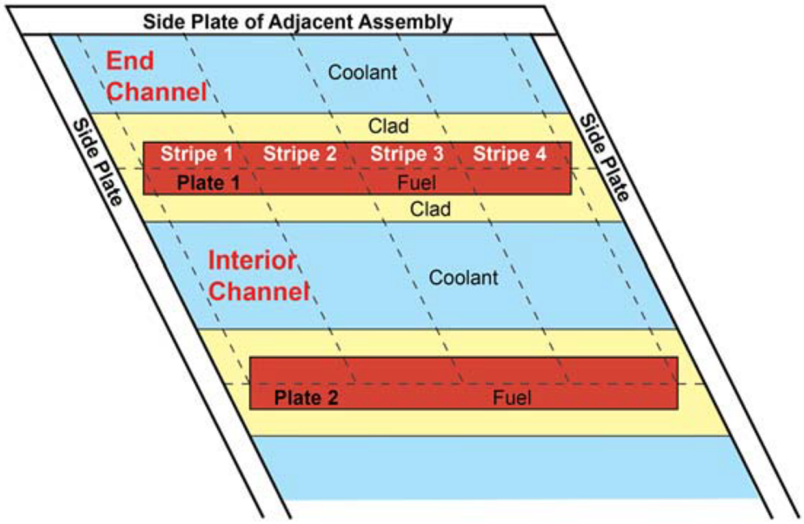


Figure 8-1 STAT7 channel geometry with 4 stripes [37]

8.3 Bergles-Rohsenow Correlation

STAT7 uses the Bergles-Rohsenow correlation [37] for the prediction of ONB. Sudo et al. [38] concluded that the Bergles-Rohsenow correlation predicts the lower limits of the measured ONB temperature for given heat fluxes and that there exists a margin between the predicted and measured ONB temperatures. Previous work by Eric Forrest [39] has confirmed the suitability of the Bergles-Rohsenow correlation in predicting the ONB under forced convection for plain metal surfaces such as MITR fuel. It has mathematical expression as following:

$$T_{clad,ONB} = T_{sat} + 0.556 \left[\frac{q''}{1082 \cdot p^{1.156}} \right]^{0.463 \cdot p^{0.0234}} \quad (8\text{-}1)$$

where $T_{clad,\ ONB}$ is the temperature at which ONB occurs at the outer cladding surface [°C], $T_{sat}$is the saturation temperature of the bulk coolant [°C], q" is the wall heat flux [W/cm^2], and p is the pressure [bar].

8.4 Uncertainty of input parameters for the MITR

The input parameters of STAT7 include the number of plates, fuel plate and coolant channel thickness, coolant flow rate, power distributions and other floating point variable input indicating uncertainty. The reactor operation parameters are tabulated in Table 8-1 with corresponding uncertainty levels tabulated in Table 8-2. Flow distribution factors will be discussed in detail in the next section.

Table 8-1 Plant operation parameters for Nominal Condition.

Operation Parameters	Nominal
Power [MW]	6.00
Power deposition factor	0.95
Outlet Temperature [°C]	60
Flow rate [kg/s] | [gpm]	150.5 | 2400

Table 8-2 Plant uncertainty parameters for Nominal Condition. *[33]*

Parameters	Uncertainty 3σ [%]
Primary flow measurement	5.0
Reactor power measurement	5.0
Local power uncertainty	14.14

8.5 Flow Split during Transitional Cores

The coolant stripe flow rate is calculated by,

$$w_i = w_p \frac{f_f d_f f_{in} f_{sf}}{N_e N_p N_s} \tag{8-2}$$

where w_p is the nominal pump flow rate, f_f is the core flow bypass factor, d_f is the plenum flow disparity factor (accounts for element-to-element flow variation), f_{in} is the ratio of the average interior channel to average channel flow (accounts for average end channel flow being different from the average interior channel flow), and is the fraction of the coolant channel flow in the stripe region (accounts for neglecting flow between the element side plate and the edge of the fuel foil).Among these input parameters, w_p, f_f , f_{in} and d_s Assumed to be constant in all transitional cores, the input value for such parameters is tabulated in Table 8-3. The plenum flow disparity factor, d_f varies in different mix core configuration to adjust the element flow rate as an effect of the addition of more LEU fuel element to the core.

The FYT LEU fuel element and HEU fuel element have different channel and plate geometry. During the transitional cores, the number of the LEU and HEU element in each mix core configuration also varies. There will be a difference in frictional pressure-drop across each element. When placed in the core, the mass flow rate across each element will vary to equalize pressure-drop from the inlet to outlet plenum. The frictional pressure drop is determined by the Darcy-Weisbach equation,

$$\Delta p_f = f \frac{L}{D_h} \frac{1}{2\rho} \left(\frac{\dot{m}}{A}\right)^2 \tag{8-3}$$

where is the transit length, is the hydraulic diameter, is the mass flow rate, and is the flow channel cross-sectional area. In addition, f is Carnavos friction factor for finned, rectangular channel [32],

$$f = \frac{0.184}{N_{Re}^{0.2}\left(\frac{A_{fa}}{A_{fn}}\right)^{0.5}(\sec\alpha)^{0.75}} \quad (8\text{-}4)$$

where A_{fa} is the actual free flow area and A_{fn} is the nominal flow area. Since LEU element does not have fin structure, $A_{fa} = A_{fn}$. α is the helix angle in the finned channel, sec[α] = 1.0 because the fins are parallel to the flow. As more LEU fuel elements are added to the core from Mix-1 to Mix-7 configuration, and LEU fuel element have more flow channels than HEU element, the total channel flow area increases, the mass flow rate in each channel decreases. To accommodate the changes, the STAT7 flow disparity factor is modified such that,

$$d_f^* = d_f \frac{\dot{m}_{mix}}{\dot{m}_{uniform}} \quad (8\text{-}5)$$

Where $\dot{m}_{mix}$ is the HEU/LEU single element mixed core element modified flow rate, which is a function of the number of HEU and LEU fuel element. $\dot{m}_{uniform}$ is the uniform core element, which is fixed number. The flow disparity factor is then calculated and tabulated in Table 8-4

Table 8-3 Flow distribution factors

Parameters	Uncertainty 3σ [%]
Bypass factor (f_f)	0.921
Flow disparity factor (d_f)	See Table 8-4
Stripe disparity factor (d_s)	0.91

Table 8-4 Flow disparity factors for each Mix-core Configuration

Flow disparity factor		
	LEU	HEU
MIX-1	1.345	0.866
MIX-2	1.279	0.815
MIX-3	1.213	0.769
MIX-4	1.151	0.726
MIX-5	1.084	0.687
MIX-6	1.038	0.651
MIX-7	0.998	0.630

8.6 Results

Steady-state simulation were evaluated using both RELAP5 and STAT7, comparisons of the cladding outer surface, and bulk coolant temperatures, for the mixed core with the most limiting ONB margin (Mix-7) calculated by RELAP5 and STAT7 for nominal are displayed in Figure 8-2. The differences between RELAP5 and STAT7 temperatures are less than 4°C. This shows that the STAT7 code provides sufficient degree of accuracy.

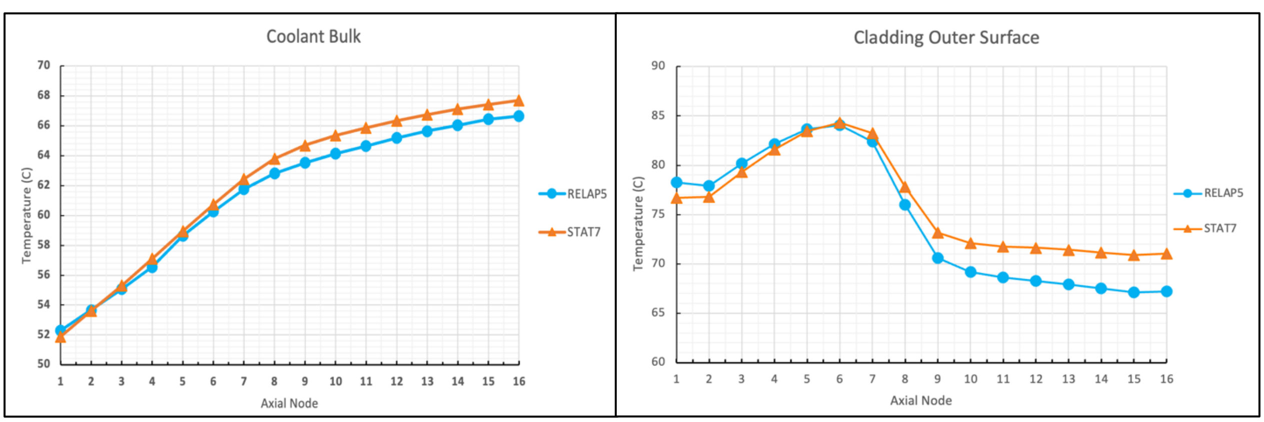


Figure 8-2: A Comparison of RELAP5 and STAT7 bulk coolant and cladding outer surface temperature. Node 1 is toward the core inlet

The hot fuel element input deck for both LEU and HEU for each mix-core configuration is evaluated and the P_{ONB} are tabulated in Table 8-5 and visualized in Figure 8-3. The P_{ONB} is calculated using the Bergles and Rohsenow correlation in STAT7. For the LEU fuel element, the lowest P_{ONB} during the mixed core transition is at Mix-7, 11.43 MW. For the HEU element, the lowest P_{ONB} during the transition is at Mix-2, 8.51 MW. However, both P_{ONB} limits are significantly higher than the LSSS power limit, 7.40 MW. During all 7 mix core transitions, the HEU element is always more limiting.

Table 8-5: Evaluation of the thermal-hydraulic safety margin during Mix-core transition. The fuel position, stripe, and plate of the hot fuel element.

	ONB Power (MW)		Location (element number, S: Stripe number, P: Plate number)	
	LEU	HEU	LEU	HEU
Mix 1	14.22	9.75	B8 S1 P16	A2 P1
Mix 2	13.32	8.51	B7 S1 P4	A2 P1
Mix 3	12.99	9.29	A2 S4 P16	C13 P1
Mix 4	12.56	9.47	B7 S1 P4	C13 P1
Mix 5	12.4	9.29	C9 S4 P4	C8 P15
Mix 6	11.87	10.22	A2 S4 P16	C12 P15
Mix 7	11.43	9.75	A2 S4 P16	C12 P15

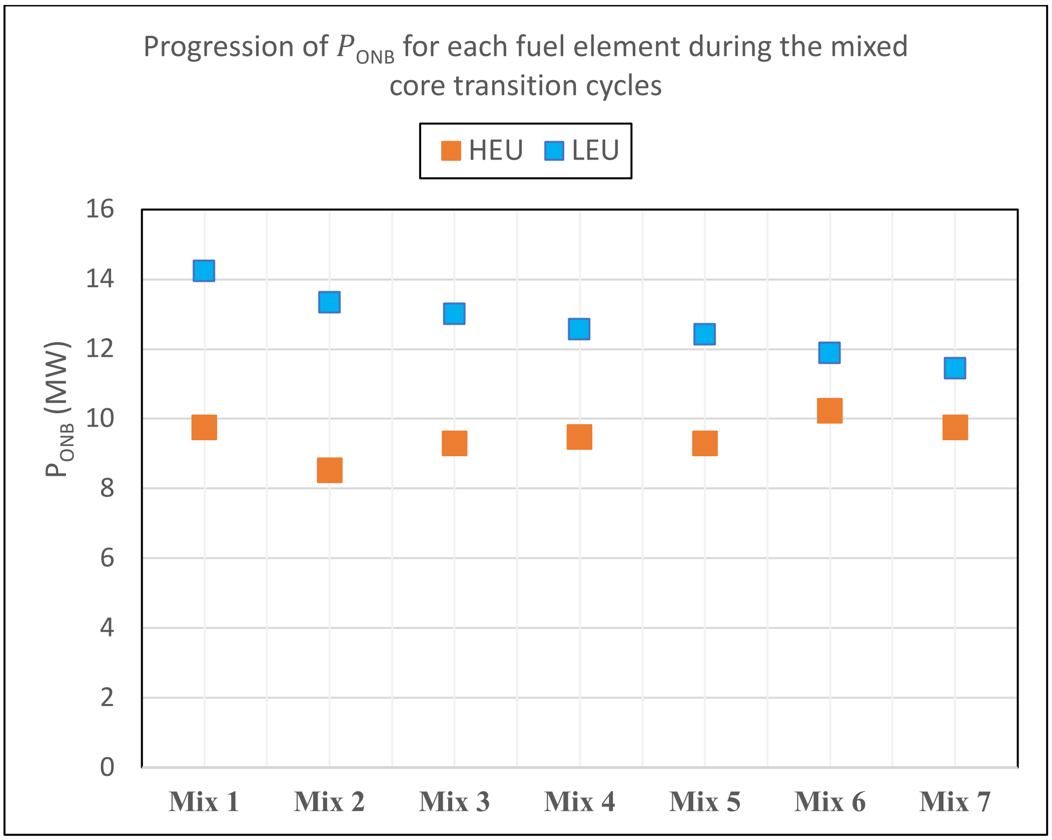


Figure 8-3: Progression of PONB for each fuel element during the mixed core transition cycles.

8.7 Summary

The limiting power level (P_{ONB}) for each mix core was determined using STAT7. Results in Table 8-5 shows that all P_{ONB} level have a significant margin to the LSSS over-power level. The lowest margin for LEU element during the mixed core transition is at Mix-7, 11.43 MW with a 4.03 MW power margin. For the HEU element, the lowest margin during the transition is at Mix-2, 8.51 MW with a 1.11 MW power margin. The location at which ONB is always expected to occur is F-Plate Stripe 1 and 4 for the LEU fuel element; side plate for the HEU fuel element. And the HEU element is always more limiting.

The STAT7 statistical results indicate that the over-power margin is much higher than the steady-state operating power to prevent nucleate boiling during steady-state operation.

9 Conclusion

9.1 Research Overview

In the framework of the Global Threat Reduction Initiative (GTRI), the MIT Research Reactor (MITR) is in the process of converting from the current 93%-enriched U-235 highly-enriched uranium (HEU) fuel to the low-enriched uranium (LEU, <20%-enriched U-235) fuel. A mixed core transition strategy was pursued where 3 HEU elements are replaced each cycle, with maximum power level at 6 MW and primary coolant flow rate at 2400 gpm. The purposes of this study were:

- To perform experimental assessment of flow induced vibration in the primary coolant system.
- To perform STAT7 mixed core steady-state statistical analysis.
- To perform RELAP5 best-estimate steady-state and LOF transient analysis.

The analysis of these assessment will evaluate thermal-hydraulic safety margin for the MITR HEU-LEU transitional mixed cores and the primary coolant system upgrade plan.

9.2 Conclusions

Primary Coolant Upgrade

The first analysis completed was the flow vibration testing at three main hydraulic components in the primary coolant system. Accelerometers were installed at pipe tunnel inlet/outlet, heat exchanger inlet/outlet, and the pump inlet/outlet to record vibration data. The results of this analysis include:

- pipe tunnel outlet is the location where the largest vibration is measured. Flow vibration tests were performed for primary coolant flow from 1000 to 2550 gpm. The maximum vibration velocity is 9.70 mm/s and the maximum vibration acceleration is 0.98 G measured at 2000 gpm.
- The Fourier transform analysis shows there was no significant spectral change in the vibration profile.

The maximum vibration velocity is well below the threshold vibration velocity for more detailed stress investigations, as suggested in an NRC technical report NUREG-1061. No significant spectral change in the vibration profile was observed. Therefore, it can be concluded that pipe vibration up to 2550 gpm should not be a concern.

RELAP5 mixed core steady-state simulation

The next analysis completed was the steady-state mixed core simulation using RELAP5, the core operates at a power level of 6 MW with primary coolant flow rate of 2400 gpm. The parameters calculated are hot channel flow rate, temperature at coolant outlet, clad surface, and fuel centerline. The results show that:

- As more LEU fuel elements are inserted in the core, coolant mass flow rate in each coolant channel decreases, since the LEU fuel element contains more coolant channels than HEU.
- the maximum clad surface temperature for LEU is around 82 °C which occurs at Mix-7, the maximum clad surface temperature for HEU element is around 90 °C at Mix-3.
- There is sufficient safety margin (> 10 °C) to onset of nucleate boiling for both HEU and LEU fuel.

These results indicate that there is sufficient thermal hydraulic safety margin for all mixed cores operating at 6 MW with coolant flow rate of 2400 gpm in steady-state.

RELAP5 mixed core LOF transient analysis

The next analysis completed was mixed core the loss-of-flow transient simulation using RELAP5, the core operates at a power level of 6 MW with primary coolant flow rate of 2400 gpm for 300 seconds. At t=300 second, LOF accident occurs, due to pump trip. The parameters calculated are hot channel flow rates, temperatures at coolant outlet, clad surface, and fuel centerline. The results show that:

- The maximum fuel temperature reached during the transient was around 108 °C, the maximum clad temperature reached was 107 °C in HEU element at Mix-7.
- For LEU fuel, the maximum coolant outlet temperature does not exceed 95 °C with approximately 10 °C margin to saturation temperature.
- The HEU fuel element is more limiting than the LEU in all transitional mixed cores. During the LOF transient, nucleate boiling is predicted to occur only in the HEU hot channel during the first 50 seconds after the pump coastdown. The peak cladding temperatures are much lower than the 450 °C fuel temperature safety limit of UAl_x fuel plates.

These results indicate that there is significant safety margin for all mixed cores operating at 6 MW with coolant flow rate of 2400 gpm during the LOF transient accident. With the results from both steady-state and LOF transient, it can be concluded that LEU conversion through transitional cores appears to be feasible.

STAT7 mixed core steady-state statistical analysis

The last analysis completed was mixed core steady-state statistical analysis using STAT7, and the limiting power level (P_{ONB}) for each mix core was determined. The results show that:

- All P_{ONB} level have a significant margin to the LSSS over-power level. The lowest margin for LEU element during the mixed core transition is at Mix-7, 11.43 MW with a 4.03 MW power margin. For the HEU element, the lowest margin during the transition is at Mix-2, 8.51 MW with a 1.11 MW power margin.
- The location at which ONB is always expected to occur is F-Plate Stripe 1 and 4 for the LEU fuel element; side plate for the HEU fuel element.

- The HEU element is always more limiting than LEU fuel element.

The STAT7 statistical results also indicate that the predicted ONB power is much higher than the 6 MW operating power to prevent nucleate boiling during steady-state mixed core operation.

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Appendix A: MCODE Power Profiles

Figure A-1: Power profile Mix-1

Number	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127
Position	A-1	A-2	A-3	B-1	B-2	B-3	B-4	B-5	B-6	B-7	B-8	B-9	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	C-9	C-10	C-11	C-12	C-13	C-14	C-15
1 (Top)	0.0	16159.7	0.0	12378.7	14411.0	0.0	12344.3	14427.3	12812.6	13071.4	14515.6	12703.9	7066.1	6305.1	6129.1	6824.7	7271.4	6700.0	7339.2	5986.4	7312.8	7454.6	7596.4	6890.5	6347.1	6845.3	6840.0
2	0.0	14224.2	0.0	11127.3	12852.2	0.0	11097.8	12807.3	11524.4	11749.1	12848.3	11421.8	6663.7	5865.3	5909.3	6313.7	7114.3	6494.1	6605.6	5897.1	6724.9	7213.7	7251.3	6366.5	6165.4	6313.8	6571.9
3	0.0	15942.4	0.0	12928.9	15015.3	0.0	12958.2	15260.5	13452.2	13634.2	15266.2	13298.7	7992.7	6877.0	7028.8	7299.9	8323.6	7650.8	7817.7	7053.0	7958.4	8698.8	8666.6	7509.4	7353.2	7452.1	7918.2
4	0.0	17881.1	0.0	14737.6	17323.8	0.0	14896.3	17660.6	15375.0	15649.8	17718.6	15228.5	9288.6	7881.0	8197.9	8359.5	9587.3	8797.5	9029.5	8191.2	9230.9	10054.4	10051.9	8646.9	8553.7	8645.0	9199.9
5	0.0	19774.0	0.0	16503.5	19449.1	0.0	16654.8	19910.3	17179.5	17500.3	19955.8	17002.0	10451.5	8799.3	9311.2	9319.3	10815.6	9847.3	10179.9	9295.6	10354.3	11329.1	11296.9	9721.8	9679.0	9770.5	10342.4
6	0.0	21405.5	0.0	18014.5	21412.2	0.0	18252.0	21986.6	18790.5	19190.1	22017.9	18627.6	11563.3	9656.9	10335.3	10187.4	11935.9	10823.0	11192.2	10404.0	11389.5	12525.5	12463.3	10753.9	10780.3	10828.1	11465.1
7	0.0	22626.0	0.0	19216.7	23017.9	0.0	19559.1	23736.7	20111.7	20477.9	23789.2	19911.4	12649.7	10482.4	11569.3	10994.8	13035.0	11827.4	12259.0	11703.3	12373.7	13734.9	13647.5	11698.9	12044.9	11844.0	12487.2
8	0.0	22758.1	0.0	19785.4	24276.1	0.0	20127.3	25112.9	20557.9	21116.7	25185.1	20423.1	13796.0	11497.3	13403.7	11930.8	14272.6	13059.1	13483.3	13638.2	13527.8	15104.5	14957.6	12839.1	13926.4	13059.6	13696.2
9	0.0	22684.2	0.0	20116.7	25188.1	0.0	20488.9	26132.9	20806.5	21466.3	26249.6	20716.1	15511.1	13207.4	15834.0	13639.3	15925.5	14772.0	15346.0	16142.1	15476.2	17048.8	16754.2	14715.0	16408.4	14899.7	15439.4
10	0.0	22793.1	0.0	20392.9	25739.5	0.0	20787.4	26713.6	21120.5	21731.7	26796.4	21041.8	17077.3	15249.3	17579.8	15563.2	17377.8	16329.1	17398.0	18015.6	17672.6	18685.4	18351.4	16852.1	18220.4	16922.6	17095.3
11	0.0	22688.3	0.0	20429.6	25747.0	0.0	20758.6	26720.6	21105.0	21736.8	26774.8	21045.5	17940.6	16242.4	18273.3	16394.6	18109.1	17090.4	18172.9	18900.5	18467.9	19287.0	18927.1	17797.6	18902.4	17936.2	18009.2
12	0.0	22203.8	0.0	20108.8	25189.9	0.0	20344.3	26065.7	20749.1	21322.0	26119.1	20680.4	18177.7	16433.8	18174.6	16501.4	18228.8	17290.3	18035.3	18998.8	18387.6	19234.0	18868.0	17826.9	18788.1	18054.6	18232.1
13	0.0	21291.1	0.0	19664.9	23927.3	0.0	19726.3	24678.4	20251.7	20775.6	24735.9	20150.1	18007.5	16045.3	17493.1	16054.1	18211.0	17215.4	17260.5	18504.3	17648.2	18926.0	18597.5	17282.6	18203.3	17475.5	18070.7
14	0.0	20109.0	0.0	18657.0	22118.3	0.0	18491.8	22524.5	19190.9	19644.6	22645.9	19162.1	17198.5	15151.5	16458.6	15138.3	17602.9	16600.8	15983.1	17428.4	16429.1	17986.1	17634.4	16182.8	17093.8	16391.8	17302.0
15	0.0	19201.6	0.0	17233.1	20028.1	0.0	16928.3	20051.1	17716.5	18082.8	20210.4	17674.2	15970.7	14093.8	15303.6	14055.5	16563.3	15507.6	14659.0	16219.5	15028.6	16571.8	16286.8	14890.0	15918.8	15069.2	16014.6
16 (Bottom)	0.0	23135.1	0.0	20560.2	23847.6	0.0	20147.0	23805.7	20942.0	21407.2	24120.5	21172.2	18240.1	16308.2	17144.2	16020.8	18779.3	17516.7	16819.9	18192.3	17026.9	18500.5	18212.5	17012.3	17724.5	17493.0	18145.6

Figure A-2: Power profile Mix-2

Number	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127
Position	A-1	A-2	A-3	B-1	B-2	B-3	B-4	B-5	B-6	B-7	B-8	B-9	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	C-9	C-10	C-11	C-12	C-13	C-14	C-15
1 (Top)	0.0	15329.9	0.0	14484.8	13705.6	0.0	14327.4	13791.7	12280.6	15081.1	13902.8	12191.5	6599.2	6012.3	6015.1	6656.4	7019.7	6236.0	6965.9	5866.7	7183.0	7243.0	7077.6	6569.5	6256.7	6760.3	6676.4
2	0.0	13415.3	0.0	13124.3	12149.9	0.0	12981.6	12224.3	11045.0	13677.2	12272.1	10950.8	6211.7	5570.0	5813.3	6168.5	6860.4	6035.2	6297.7	5775.5	6644.9	6997.5	6748.4	6071.8	6074.1	6280.0	6421.3
3	0.0	14959.4	0.0	15431.3	14234.4	0.0	15275.2	14593.4	12900.8	16091.5	14629.9	12719.2	7416.5	6528.7	6897.7	7124.4	8048.8	7095.7	7443.0	6919.9	7863.5	8452.1	8077.3	7142.5	7247.3	7387.2	7731.0
4	0.0	16793.5	0.0	17729.2	16391.9	0.0	17626.4	16940.8	14769.3	18538.7	16979.9	14578.2	8642.8	7485.5	8057.2	8178.9	9214.7	8166.9	8627.1	8063.3	9051.6	9840.1	9358.8	8267.8	8443.4	8564.5	8983.9
5	0.0	18577.1	0.0	19891.6	18484.7	0.0	19792.4	19128.8	16502.7	20780.2	19143.9	16296.6	9739.8	8354.2	9110.1	9128.5	10404.9	9141.7	9720.5	9160.7	10228.4	11099.1	10556.0	9329.5	9565.4	9676.0	10094.3
6	0.0	20194.4	0.0	21763.3	20363.4	0.0	21729.6	21142.6	18036.9	22775.9	21153.3	17869.6	10769.7	9184.2	10181.1	9940.4	11496.3	10053.8	10722.7	10254.9	11295.0	12292.6	11660.2	10273.0	10672.8	10688.8	11211.9
7	0.0	21296.4	0.0	23354.7	21969.7	0.0	23242.8	22893.3	19300.9	24370.0	22874.1	19122.0	11811.1	10031.4	11364.2	10753.7	12582.0	11021.6	11698.7	11562.1	12252.3	13423.1	12744.9	11214.5	11931.3	11758.8	12222.6
8	0.0	21383.2	0.0	24136.4	23163.1	0.0	24108.4	24160.4	19705.5	25249.1	24254.3	19569.8	12950.7	11008.8	13204.8	11687.8	13739.9	12187.0	12856.6	13466.3	13414.6	14759.4	14123.7	12358.2	13781.1	12899.9	13418.6
9	0.0	21259.1	0.0	24688.3	24013.3	0.0	24649.5	25163.8	19927.5	25783.2	25286.8	19813.8	14627.0	12725.9	15611.8	13353.6	15381.6	13889.7	14756.8	15975.2	15298.0	16706.3	15862.4	14202.2	16280.7	14833.0	15210.6
10	0.0	21382.4	0.0	25063.3	24450.9	0.0	25075.9	25757.1	20231.3	26204.6	25909.4	20148.9	16183.0	14767.9	17349.9	15288.5	16854.4	15450.0	16767.8	17810.5	17465.9	18296.7	17417.7	16350.9	18074.9	16924.2	16823.0
11	0.0	21259.7	0.0	25083.9	24598.4	0.0	25076.5	25780.1	20268.7	26220.1	25907.2	20154.1	17064.3	15708.9	18045.2	16179.5	17574.3	16157.6	17579.1	18691.1	18341.0	18950.1	18052.7	17258.8	18764.7	17885.8	17705.2
12	0.0	20781.7	0.0	24717.9	24017.6	0.0	24585.9	25186.0	19854.6	25683.3	25225.9	19767.7	17315.2	15917.5	17946.5	16235.3	17688.9	16397.6	17518.7	18762.3	18209.2	18935.9	18020.3	17336.7	18665.0	17964.7	17954.3
13	0.0	19988.2	0.0	24047.4	22918.2	0.0	23735.0	23835.6	19455.6	24951.8	23970.9	19338.6	17168.4	15568.6	17329.1	15791.5	17679.3	16331.1	16741.0	18299.0	17497.3	18645.0	17731.3	16789.5	18075.7	17390.4	17828.9
14	0.0	18901.0	0.0	22631.5	21242.5	0.0	22209.9	21783.8	18457.1	23506.0	21902.7	18402.3	16410.6	14739.3	16312.0	14868.1	17139.1	15814.1	15532.9	17249.6	16282.1	17718.9	16840.4	15730.2	16995.9	16347.7	17110.9
15	0.0	18088.3	0.0	20678.5	19186.7	0.0	20104.0	19344.7	17057.3	21366.4	19497.7	17037.8	15231.8	13676.1	15188.8	13861.3	16156.7	14723.8	14217.4	16020.0	14873.6	16327.7	15604.6	14488.6	15801.9	15023.9	15823.2
16 (Bottom)	0.0	21917.5	0.0	24626.2	22942.3	0.0	23780.6	23005.6	20322.5	25179.1	23322.8	20570.0	17545.5	15824.2	16928.2	15807.1	18349.6	16766.4	16372.0	18009.2	16879.2	18273.6	17532.9	16616.1	17576.5	17398.2	17926.4

Figure A-3: Power profile Mix-3

Number	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127
Position	A-1	A-2	A-3	B-1	B-2	B-3	B-4	B-5	B-6	B-7	B-8	B-9	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	C-9	C-10	C-11	C-12	C-13	C-14	C-15
1 (Top)	0.0	17711.5	0.0	13706.5	13354.2	0.0	13589.2	13137.8	14312.7	14210.2	13232.8	14062.0	6386.3	5963.0	5951.7	6532.0	6836.8	6147.5	6916.6	5797.8	6886.7	6827.4	6901.9	6472.5	6120.5	6449.0	6259.7
2	0.0	15505.2	0.0	12291.1	11789.6	0.0	12242.8	11621.8	12888.3	12805.9	11635.1	12613.5	6044.1	5521.4	5736.0	6064.8	6674.7	5931.3	6232.6	5723.8	6324.5	6568.9	6537.4	5972.2	5943.1	5955.1	6010.0
3	0.0	17519.6	0.0	14425.0	13867.3	0.0	14461.0	13844.9	15232.9	15083.3	13882.2	14860.8	7220.2	6460.2	6875.9	7009.6	7816.8	7000.4	7372.7	6852.8	7525.9	7913.9	7878.1	7058.1	7103.2	7020.4	7220.6
4	0.0	19847.4	0.0	16543.9	15983.1	0.0	16656.5	16112.0	17506.0	17255.6	16065.1	17088.6	8388.5	7426.3	8007.6	8027.1	9032.0	8057.3	8565.4	7973.1	8687.7	9199.5	9128.0	8135.8	8317.1	8166.2	8421.1
5	0.0	22059.6	0.0	18486.6	18010.1	0.0	18668.5	18207.0	19637.3	19312.5	18184.6	19143.9	9473.9	8294.9	9070.1	8977.4	10149.4	9038.6	9671.0	9062.8	9792.1	10437.3	10276.4	9182.5	9434.4	9220.9	9476.3
6	0.0	23959.5	0.0	20251.9	19801.2	0.0	20440.1	20127.4	21530.6	21178.8	20098.3	20974.5	10460.7	9088.8	10120.2	9791.6	11237.8	9957.0	10685.3	10190.2	10845.1	11575.6	11370.0	10152.4	10504.0	10210.2	10480.7
7	0.0	25317.6	0.0	21655.7	21358.3	0.0	21964.1	21736.0	23128.6	22715.7	21750.5	22501.9	11486.4	9926.3	11303.7	10576.6	12303.7	10935.4	11656.5	11466.3	11785.0	12671.0	12488.9	11069.8	11741.2	11220.3	11491.7
8	0.0	25648.9	0.0	22401.7	22501.5	0.0	22686.5	23070.0	23816.2	23430.6	23085.6	23226.5	12642.7	10901.8	13111.8	11537.3	13472.4	12071.7	12827.6	13388.0	12925.5	14005.9	13746.1	12182.5	13581.5	12437.8	12652.0
9	0.0	25700.4	0.0	22843.0	23410.9	0.0	23162.4	23986.9	24269.2	23927.4	24080.1	23627.3	14238.6	12584.0	15494.7	13163.3	15042.8	13762.9	14703.1	15878.7	14811.0	15912.5	15536.7	14046.0	16112.4	14282.7	14405.5
10	0.0	25963.8	0.0	23296.7	23949.2	0.0	23586.7	24630.1	24720.8	24381.7	24680.6	24016.3	15830.7	14603.7	17220.7	15072.9	16525.3	15287.6	16709.7	17771.7	17035.8	17538.2	17042.8	16187.6	17900.0	16333.1	15985.0
11	0.0	25813.7	0.0	23305.1	23974.3	0.0	23665.6	24706.2	24747.1	24348.6	24750.4	24065.2	16719.8	15596.6	17910.5	15976.9	17237.8	16026.2	17476.9	18636.9	17878.9	18140.5	17671.5	17078.2	18585.8	17279.8	16885.8
12	0.0	25300.5	0.0	22988.7	23460.0	0.0	23231.4	24135.9	24324.1	23922.1	24106.5	23723.9	16961.3	15808.1	17868.1	16071.6	17395.1	16291.7	17381.8	18740.7	17760.3	18102.9	17722.7	17209.0	18510.3	17416.7	17116.1
13	0.0	24182.3	0.0	22470.8	22410.0	0.0	22455.4	22817.8	23595.3	23325.4	22828.8	23129.3	16883.2	15478.7	17272.1	15626.3	17414.1	16279.4	16663.8	18282.2	17082.6	17873.8	17458.6	16661.6	17910.5	16867.5	17080.9
14	0.0	22779.5	0.0	21282.4	20708.1	0.0	21024.4	20913.1	22212.5	22018.3	20938.7	21844.5	16179.5	14642.4	16226.6	14757.0	16885.8	15717.0	15501.4	17191.1	15912.0	17030.8	16632.4	15607.1	16826.7	15853.2	16370.4
15	0.0	21411.7	0.0	19437.8	18751.1	0.0	19023.3	18498.4	20260.5	20063.3	18633.8	19964.4	15023.2	13577.8	15101.2	13733.6	15947.1	14699.3	14203.4	15975.3	14504.7	15727.7	15405.2	14376.7	15653.7	14574.6	15200.6
16 (Bottom	0.0	26044.1	0.0	23369.0	22462.9	0.0	22609.5	22239.1	24146.7	23874.4	22428.3	24003.3	17276.2	15751.9	16840.6	15662.2	18149.9	16684.7	16352.0	17916.7	16527.5	17717.2	17291.2	16485.1	17394.3	16929.2	17309.9

Figure A-4: Power profile Mix-4

Number	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127
Position	A-1	A-2	A-3	B-1	B-2	B-3	B-4	B-5	B-6	B-7	B-8	B-9	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	C-9	C-10	C-11	C-12	C-13	C-14	C-15
1 (Top)	0.0	17204.4	0.0	13817.9	12910.4	0.0	13759.5	12753.3	13908.9	14363.4	12544.8	13517.8	6325.7	5858.3	5853.4	6245.4	8704.3	5934.0	6681.7	7375.1	6681.4	6705.2	6761.6	6326.0	5754.2	8118.9	5966.5
2	0.0	15089.0	0.0	12422.6	11371.8	0.0	12364.6	11252.4	12512.6	12943.9	10992.8	12132.7	5949.6	5443.5	5650.2	5725.3	8366.7	5737.4	5988.1	7249.1	6106.0	6450.3	6415.5	5853.0	5569.9	7507.8	5689.0
3	0.0	17102.0	0.0	14649.8	13356.8	0.0	14668.0	13355.4	14811.8	15243.9	13077.1	14283.0	7137.1	6360.6	6754.0	6650.0	9916.4	6735.3	7103.1	8771.2	7227.9	7807.0	7716.1	6887.1	6684.2	9015.4	6866.6
4	0.0	19206.6	0.0	16859.4	15373.0	0.0	16956.7	15507.4	17002.7	17600.6	15122.7	16414.6	8262.5	7296.0	7839.3	7582.6	11460.0	7759.0	8246.9	10314.6	8385.8	9073.6	8985.5	7971.2	7781.2	10514.1	7997.8
5	0.0	21269.9	0.0	18903.8	17248.5	0.0	19047.4	17459.9	19058.7	19752.2	17067.1	18318.6	9318.9	8158.5	8882.3	8481.5	12959.6	8748.4	9255.6	11794.1	9409.0	10263.8	10117.4	8987.7	8809.8	11950.1	9002.7
6	0.0	23151.9	0.0	20759.6	18960.1	0.0	20935.3	19261.8	20869.2	21710.2	18798.6	20055.2	10295.8	8954.7	9940.7	9265.4	14361.9	9635.4	10269.4	13231.0	10348.7	11358.3	11180.6	9937.3	9837.9	13270.7	9962.4
7	0.0	24458.0	0.0	22258.0	20437.8	0.0	22501.2	20779.6	22350.5	23264.8	20257.3	21476.7	11274.6	9763.9	11089.7	10019.5	15716.0	10539.5	11169.0	14810.1	11279.7	12484.4	12266.6	10821.4	10993.2	14590.0	10881.6
8	0.0	24791.9	0.0	22985.4	21549.0	0.0	23221.5	22004.1	23032.2	24022.4	21507.2	22082.3	12431.6	10696.3	12851.5	10919.6	17142.9	11598.8	12251.4	17093.6	12339.7	13767.6	13490.1	11893.0	12753.7	16003.8	11960.7
9	0.0	24737.1	0.0	23467.4	22331.4	0.0	23667.2	22900.3	23423.3	24508.7	22396.8	22469.6	14004.1	12356.2	15230.9	12443.9	19041.8	13210.8	14063.9	19968.8	14105.3	15639.3	15230.6	13689.4	15093.3	18158.4	13572.7
10	0.0	24903.5	0.0	23830.1	22813.9	0.0	24074.4	23479.4	23821.0	24914.7	22972.8	22839.1	15491.1	14363.9	16909.5	14291.4	20760.8	14683.1	15947.1	22118.2	16176.8	17169.0	16752.0	15766.5	16802.1	20511.6	15054.3
11	0.0	24809.7	0.0	23879.8	22836.4	0.0	24134.6	23562.3	23871.6	24935.3	22994.4	22918.1	16367.2	15255.1	17535.5	15072.3	21422.7	15394.7	16714.8	22981.5	16938.7	17822.9	17335.8	16656.9	17443.6	21437.3	15922.3
12	0.0	24314.9	0.0	23556.0	22413.7	0.0	23587.5	22991.8	23436.0	24471.1	22415.5	22600.0	16611.5	15466.4	17480.8	15173.2	21428.4	15599.6	16635.1	22849.2	16918.9	17797.7	17373.3	16729.9	17361.3	21391.3	16185.6
13	0.0	23278.8	0.0	22985.4	21439.2	0.0	22878.9	21805.4	22802.0	23821.5	21359.0	21998.3	16541.6	15149.7	16900.8	14781.9	21032.6	15697.8	15956.6	22024.9	16295.4	17527.7	17118.5	16253.2	16844.9	20459.8	16112.5
14	0.0	21906.3	0.0	21657.4	19801.1	0.0	21411.5	19945.7	21516.3	22435.8	19574.9	20840.0	15824.8	14317.8	15868.4	13977.3	20082.6	15171.0	14820.9	20501.6	15167.0	16696.9	16290.7	15221.0	15856.6	19046.7	15480.3
15	0.0	20632.7	0.0	19753.9	17889.3	0.0	19269.0	17693.8	19618.8	20381.9	17441.0	19146.5	14683.7	13302.4	14805.8	13014.0	18620.0	14205.1	13560.5	18675.8	13919.5	15373.9	15092.1	14019.5	14741.4	17246.6	14366.5
16 (Bottom	0.0	25160.3	0.0	23753.3	21459.6	0.0	23045.1	21180.7	23313.6	24222.3	20991.3	22922.6	16935.7	15421.5	16526.6	14959.6	21391.1	16191.4	15707.6	21225.6	15847.9	17308.0	16935.7	16060.7	16537.1	20232.9	16506.6

Figure A-5: Power profile Mix-5

Number	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127
Position	A-1	A-2	A-3	B-1	B-2	B-3	B-4	B-5	B-6	B-7	B-8	B-9	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	C-9	C-10	C-11	C-12	C-13	C-14	C-15
1 (Top)	0.0	16473.8	0.0	12822.2	12403.5	0.0	12763.5	12190.4	13165.5	13205.8	12174.0	12986.9	7139.7	5601.5	5420.2	7971.2	6403.9	7666.6	5778.8	5645.3	7859.9	5917.9	7635.7	5804.8	5570.5	7652.2	5542.7
2	0.0	14392.4	0.0	11446.6	10926.4	0.0	11391.2	10683.7	11685.8	11813.3	10631.0	11543.3	6775.5	5112.2	5256.6	7362.9	6042.5	7227.8	5287.1	5473.2	7320.9	5590.7	7233.0	5309.5	5405.8	7121.1	5190.4
3	0.0	16311.8	0.0	13568.8	12814.2	0.0	13542.7	12806.7	13876.3	13988.1	12712.6	13603.8	8270.7	6019.1	6303.0	8801.2	7149.5	8793.8	6264.1	6583.4	8861.7	6801.6	8876.4	6265.2	6501.7	8645.0	6323.9
4	0.0	18509.4	0.0	15660.8	14848.2	0.0	15724.4	14978.4	16054.9	16205.2	14813.6	15753.5	9749.2	7000.6	7346.0	10233.5	8272.9	10344.9	7271.7	7717.2	10395.2	7961.8	10494.2	7277.5	7608.2	10141.1	7423.9
5	0.0	20600.9	0.0	17646.9	16694.0	0.0	17678.8	16932.6	18101.6	18178.1	16770.3	17678.0	11137.3	7982.0	8408.0	11650.6	9310.0	11795.6	8265.8	8807.5	11911.5	9078.2	12043.2	8304.0	8709.4	11542.5	8390.1
6	0.0	22375.8	0.0	19367.6	18464.5	0.0	19492.1	18728.8	19846.1	20031.3	18556.5	19426.6	12478.1	8891.4	9449.4	12976.8	10272.5	13178.5	9223.4	9946.4	13289.6	10079.6	13433.6	9259.6	9819.5	12934.7	9286.8
7	0.0	23739.5	0.0	20786.5	19937.2	0.0	20945.8	20366.0	21358.5	21518.4	20177.0	20874.2	13764.3	9809.8	10702.8	14240.1	11215.2	14604.6	10216.2	11282.9	14662.5	11095.0	14905.6	10235.7	11172.8	14290.7	10288.5
8	0.0	24122.9	0.0	21512.8	21100.3	0.0	21776.6	21579.5	21999.8	22301.9	21430.3	21518.5	15292.8	10978.2	12690.4	15720.0	12414.2	16271.0	11405.8	13366.8	16283.7	12375.1	16678.8	11452.3	13207.9	15846.7	11409.0
9	0.0	24226.3	0.0	22061.1	21863.4	0.0	22214.9	22575.2	22458.1	22810.4	22465.2	21963.1	17353.3	12904.2	15089.1	17997.6	13930.4	18425.6	13373.8	15876.1	18761.1	14097.1	18954.9	13502.4	15711.1	18284.0	12937.8
10	0.0	24457.0	0.0	22560.3	22453.7	0.0	22736.1	23219.3	22910.8	23277.2	23066.4	22476.5	19083.1	14837.7	16661.7	20126.3	15115.9	20106.0	15374.6	17543.6	21091.6	15423.9	20697.8	15553.4	17423.2	20512.7	14309.2
11	0.0	24435.3	0.0	22626.1	22608.5	0.0	22773.4	23316.4	23017.2	23309.3	23187.9	22563.1	20106.9	15693.7	17294.3	20902.2	15672.5	20795.9	16211.5	18216.1	21934.2	15976.2	21392.3	16349.7	18023.5	21459.3	15140.0
12	0.0	23948.9	0.0	22268.2	22202.8	0.0	22451.6	22793.3	22663.7	22900.1	22682.7	22263.5	20391.9	15814.7	17257.7	20829.5	15718.5	20745.6	16270.9	18088.4	21836.1	16034.4	21340.6	16454.6	17951.4	21393.8	15396.2
13	0.0	23008.1	0.0	21805.2	21195.9	0.0	21736.2	21606.1	22151.8	22432.1	21590.1	21797.6	20262.2	15422.1	16671.8	20063.3	15761.8	20396.2	15841.9	17530.8	20945.2	15983.7	21044.6	15970.4	17338.3	20617.9	15477.4
14	0.0	21726.9	0.0	20693.1	19687.5	0.0	20399.3	19800.6	20980.8	21200.8	19772.9	20667.3	19325.5	14580.5	15744.6	18778.1	15321.9	19367.9	14925.3	16483.1	19438.8	15375.6	19999.3	15091.6	16334.5	19171.5	14987.3
15	0.0	20497.8	0.0	18906.0	17874.9	0.0	18481.3	17572.7	19209.5	19322.4	17638.4	19080.3	17828.3	13568.2	14673.5	17134.3	14491.5	17729.3	13740.2	15309.2	17573.4	14258.2	18269.3	13919.7	15244.3	17380.3	14036.4
16 (Bottom	0.0	25060.2	0.0	22829.2	21710.9	0.0	22189.9	21289.0	23053.6	23064.9	21438.1	23104.8	20950.9	16173.3	16629.7	19863.4	16441.6	20625.0	16195.9	17162.6	20275.6	16190.1	21098.0	16349.5	17154.0	20318.3	16186.1

Figure A-6: Power profile Mix-6

Number	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127
Position	A-1	A-2	A-3	B-1	B-2	B-3	B-4	B-5	B-6	B-7	B-8	B-9	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	C-9	C-10	C-11	C-12	C-13	C-14	C-15
1 (Top)	0.0	16308.6	0.0	12704.9	12268.1	0.0	12628.1	12017.8	13075.7	13106.4	11980.6	12925.7	7080.3	5439.2	6353.1	7765.9	6354.2	7574.0	5598.1	6643.2	7653.0	5865.4	7582.3	5609.5	6533.0	7447.1	5490.1
2	0.0	14270.1	0.0	11339.8	10756.3	0.0	11314.4	10550.0	11591.2	11697.3	10507.7	11425.5	6706.2	4932.5	6189.8	7191.6	5967.9	7181.3	5115.0	6474.2	7150.9	5537.8	7190.8	5125.0	6386.4	6918.5	5134.5
3	0.0	16165.2	0.0	13424.1	12631.4	0.0	13429.7	12606.7	13771.0	13850.7	12551.3	13506.5	8184.0	5770.7	7482.3	8536.3	7091.3	8730.1	6011.8	7860.5	8631.9	6733.5	8806.6	6015.7	7764.1	8379.0	6270.3
4	0.0	18281.4	0.0	15528.1	14598.7	0.0	15585.5	14694.6	15902.1	16029.9	14595.4	15573.5	9702.7	6733.7	8810.8	9929.7	8194.7	10235.3	6992.1	9251.2	10102.1	7914.2	10377.5	7020.2	9135.0	9835.6	7357.7
5	0.0	20365.6	0.0	17485.8	16441.5	0.0	17527.6	16612.9	17920.8	18038.4	16509.0	17547.1	11050.3	7644.7	10071.4	11306.3	9196.0	11661.8	7933.6	10573.8	11555.8	8953.1	11898.8	7987.1	10479.7	11189.7	8298.1
6	0.0	22173.2	0.0	19173.8	18150.5	0.0	19324.4	18409.7	19704.5	19844.9	18256.3	19241.0	12322.0	8500.6	11370.2	12540.5	10141.1	13027.3	8811.4	11893.2	12894.5	9959.4	13301.7	8891.4	11759.6	12524.9	9217.3
7	0.0	23536.0	0.0	20589.6	19592.4	0.0	20754.1	19983.8	21147.5	21286.3	19757.6	20626.0	13630.4	9397.9	12815.2	13791.1	11106.6	14407.2	9760.8	13453.7	14180.4	10991.3	14773.6	9846.6	13304.2	13813.8	10125.5
8	0.0	23899.3	0.0	21300.8	20692.4	0.0	21513.2	21186.4	21825.6	22089.3	21006.8	21315.4	15110.0	10514.9	14980.8	15155.8	12233.3	16040.3	10889.4	15765.7	15689.1	12276.8	16483.4	10979.4	15573.0	15260.2	11241.2
9	0.0	23940.0	0.0	21788.4	21518.6	0.0	21975.0	22099.8	22259.4	22627.0	22004.9	21733.0	17143.6	12315.5	17624.2	17393.1	13716.2	18171.1	12779.3	18470.7	18062.2	13889.1	18708.2	12911.4	18309.1	17631.9	12735.4
10	0.0	24172.8	0.0	22255.3	22042.7	0.0	22433.3	22759.5	22686.3	23021.7	22579.2	22186.6	18867.5	14186.2	19353.6	19413.4	14944.2	19869.3	14698.3	20301.9	20358.8	15223.8	20400.8	14836.9	20100.5	19807.5	14139.9
11	0.0	24154.0	0.0	22342.8	22168.3	0.0	22542.8	22839.0	22729.6	23108.7	22665.8	22320.0	19841.5	14988.1	20064.6	20117.4	15431.9	20467.9	15458.2	21068.9	21155.7	15774.4	21010.7	15599.2	20793.6	20654.2	14917.0
12	0.0	23674.8	0.0	22051.2	21744.5	0.0	22143.3	22287.3	22434.6	22730.4	22206.7	22039.6	20083.4	15122.8	20011.7	20032.8	15483.6	20461.0	15590.7	21020.8	20994.7	15814.1	21050.2	15737.1	20804.6	20564.1	15192.7
13	0.0	22729.4	0.0	21574.1	20805.7	0.0	21463.8	21176.6	21859.9	22136.1	21071.7	21552.7	19999.5	14781.9	19457.5	19334.2	15545.7	20042.4	15113.6	20316.4	20237.3	15734.3	20691.5	15260.0	20107.0	19822.8	15283.1
14	0.0	21423.9	0.0	20412.4	19285.8	0.0	20157.1	19406.8	20721.1	20957.8	19401.6	20408.1	19076.9	13968.9	18339.2	18107.6	15098.5	19076.1	14199.3	19095.0	18777.9	15099.3	19663.6	14416.3	18895.4	18479.2	14788.0
15	0.0	20253.2	0.0	18661.8	17511.5	0.0	18234.3	17209.3	18996.8	19074.4	17270.2	18818.4	17514.6	12978.7	16926.2	16462.2	14282.4	17498.1	13145.2	17527.8	16943.2	14042.3	17971.6	13289.9	17464.7	16736.7	13800.8
16 (Bottom	0.0	24752.4	0.0	22554.2	21296.2	0.0	21903.6	20862.4	22792.7	22815.2	21012.3	22789.0	20633.2	15533.5	19413.8	19297.5	16253.6	20324.2	15535.7	20003.4	19646.3	15947.3	20780.1	15731.9	19978.5	19657.0	15959.1

Figure A-7: Power profile Mix-7

Number	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127
Position	A-1	A-2	A-3	B-1	B-2	B-3	B-4	B-5	B-6	B-7	B-8	B-9	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	C-9	C-10	C-11	C-12	C-13	C-14	C-15
1 (Top)	0.0	16118.3	0.0	12539.7	12101.1	0.0	12424.6	11896.6	12721.6	12949.5	11876.7	12598.1	6872.0	5371.1	6273.0	7448.8	7492.8	7344.5	5539.8	6547.7	7374.8	7042.3	7374.5	5569.1	6500.4	7210.3	6605.0
2	0.0	14123.1	0.0	11184.8	10641.3	0.0	11106.7	10419.8	11291.0	11568.7	10406.4	11115.3	6489.5	4890.3	6140.3	6856.5	7082.2	6931.8	5057.7	6365.2	6846.2	6713.2	6952.0	5085.8	6327.7	6684.3	6253.3
3	0.0	16004.2	0.0	13241.5	12479.1	0.0	13239.6	12500.4	13416.3	13726.6	12400.6	13144.9	7942.0	5753.2	7450.2	8207.5	8500.0	8445.6	5949.2	7765.7	8287.8	8225.6	8520.8	5988.8	7675.1	8054.3	7716.9
4	0.0	18098.1	0.0	15321.7	14406.3	0.0	15338.3	14566.9	15501.9	15829.3	14444.6	15191.5	9401.8	6679.9	8748.2	9520.4	9880.7	9917.2	6937.5	9145.7	9725.5	9714.9	10057.1	6966.0	8997.0	9432.7	9081.8
5	0.0	20141.6	0.0	17238.2	16259.7	0.0	17240.5	16459.5	17407.3	17813.1	16304.7	17018.9	10656.1	7575.9	9954.2	10809.6	11116.3	11297.3	7892.0	10432.1	11079.7	10952.3	11484.7	7912.6	10336.0	10778.1	10278.3
6	0.0	21892.9	0.0	18908.9	17883.5	0.0	18973.9	18287.6	19104.7	19556.6	18088.0	18688.8	11895.9	8427.2	11203.2	11984.3	12315.7	12620.3	8756.0	11753.0	12313.6	12230.0	12836.5	8813.5	11624.7	11987.8	11412.9
7	0.0	23278.6	0.0	20305.7	19312.7	0.0	20420.9	19768.4	20513.6	21022.0	19615.8	20083.0	13126.3	9303.3	12662.3	13179.7	13519.0	13908.6	9653.2	13306.0	13564.9	13469.1	14203.9	9707.8	13167.9	13238.3	12582.0
8	0.0	23540.0	0.0	20964.8	20415.0	0.0	21092.9	20980.2	21150.6	21728.6	20868.5	20629.9	14587.1	10363.9	14849.4	14524.1	14815.9	15470.2	10744.3	15546.4	15047.6	14980.4	15790.9	10846.7	15406.8	14649.3	13927.5
9	0.0	23567.2	0.0	21508.2	21213.4	0.0	21554.5	21920.3	21531.5	22232.2	21704.8	21020.4	16554.9	12182.9	17378.1	16595.7	16545.4	17511.7	12641.3	18216.0	17340.2	16939.9	17929.7	12733.6	18115.0	16880.6	15733.8
10	0.0	23835.0	0.0	21874.5	21672.1	0.0	22007.1	22484.1	21981.5	22683.3	22336.1	21484.1	18153.6	14046.9	19152.8	18561.2	17907.9	19091.9	14515.8	20009.2	19454.8	18477.2	19576.0	14652.6	19836.9	18958.6	17283.5
11	0.0	23754.0	0.0	21953.1	21827.0	0.0	22053.2	22568.3	22031.0	22758.3	22443.4	21585.3	19102.9	14785.0	19787.0	19243.2	18452.2	19752.1	15306.2	20735.1	20206.6	19056.0	20254.3	15458.3	20568.3	19804.7	18178.5
12	0.0	23284.7	0.0	21740.2	21411.5	0.0	21669.0	22022.5	21692.6	22375.4	22015.7	21349.7	19409.2	14960.3	19755.5	19175.7	18551.7	19688.2	15408.2	20703.6	20077.5	19101.5	20325.9	15588.8	20516.3	19707.3	18487.3
13	0.0	22402.3	0.0	21272.3	20457.2	0.0	21078.8	20925.5	21174.3	21828.2	20915.9	20865.5	19301.5	14591.8	19194.4	18536.7	18398.8	19422.0	14949.8	20045.8	19300.2	18931.6	20001.1	15145.6	19879.1	19053.9	18453.4
14	0.0	21122.2	0.0	20170.4	19005.9	0.0	19823.0	19190.3	20014.5	20688.6	19215.2	19811.7	18493.7	13760.7	18072.0	17330.6	17834.9	18479.1	14088.4	18809.7	17954.9	18102.5	19068.5	14259.8	18651.6	17732.3	17711.8
15	0.0	19963.4	0.0	18402.4	17262.7	0.0	17939.7	17050.9	18362.7	18836.1	17103.9	18217.7	16954.9	12842.4	16678.3	15792.0	16630.3	16941.5	13004.6	17306.3	16204.7	16586.4	17380.3	13188.0	17230.8	16096.6	16360.0
16 (Bottom	0.0	24407.5	0.0	22257.8	21003.2	0.0	21585.8	20664.4	22112.0	22516.3	20749.7	22151.0	20014.7	15391.5	19147.6	18478.7	19176.6	19771.6	15420.3	19724.8	18869.0	19103.6	20236.1	15566.4	19729.6	18946.0	19151.3

Appendix B: RELAP5 Mixed core 1 (Mix-1) Input deck

```
= MIT case1, pump coast-down
*   first 300 seconds is steady-state, pump trip is defined in transient input
*   Homogeneous core: HEU + LEU Power 6 MW, 21 HEU elements, 3 LEU elements, mfl 2400
gpm 151.4 kg/s
100 new transnt
102 si si * use SI units
105 5.0 6.0 1000. * max computer time = 1000 seconds
*
*    time step
*
*201 300. 1.0-9 .005 3 100 1000 500 * SJK 5/12/2011 time step control 3, minimum time
step=0.005 sec
*202 675. 1.0-9 .000125 23 200 1000 500 * SJK 05/12/2011 time step control 23, max time
step=0.000125 sec
*203 900. 1.0-9 .005 23 20 1000 500 * SJK 05/12/2011 time step control 23, max time
step=0.005 sec

201 300. 1.0-9 1. 3 100 1000 500 * SJK 5/12/2011 time step control 3, minimum time
step=0.005 sec
202 675. 1.0-9 .000125 23 200 1000 500 * SJK 05/12/2011 time step control 23, max time
step=0.000125 sec
203 900. 1.0-9 1. 23 20 1000 500 * SJK 05/12/2011 time step control 23, max time step=0.005
sec

*
*           minor edit variables
*
301 count 0
302 cputime 0
303 dt 0
304 dtcrnt 0
*
*          trips, open ASV and NCV
*
403 time 1 ge null 1 300. l * YW 210928: pump trip
401 time 1 ge timeof  403  4.4  l * trip ASV at t = 4.4 and latch *SJK 070309
402 time 1 ge timeof  403  4.4  l * trip NCV at t = 4.4 and latch *SJK 070309*
611  403  and  403   n    -1.  * SJK @Rxtrip*
```

```
*        hydrodynamic components
*
1000000 snkref tmdpvol * sink reference volume, sets system pressure
1000101 1.0 1.0 1.0 0. 0. 0. .00001 0. 0000000
1000200 103
1000201 0. 1.02+5 320.4 * initial p, T, by MULCH S.S. compinent #1 SJK 6/1/2011
*
1010000 outlet sngljun
1010101 103010002 100010001 .032 1.0 1.0 100 1.0 1.0 *SJK word 9 left out (11/04/2010)
1010201 1 124.9 0. 0.
*
1020000 cldleg tmdpvol * cold leg inlet temperature
1020101 1.0 1.0 1.0 0. 0. 0. .00001 0. 0000000
1020200 103
1020201 0. 1.03+5 319.0 * initial p, T
*
1030000 upppln snglvol
1030101 .923 .1 .0923 0. 90. .1 .00001 1.1 11000
1030200 103 1.025+5 333.15 * initial p, T
*
1040000 uppjn1 sngljun
1040101  105010002 103010001 .5 .01 .01 100 1.0 1.0 *SJK word 9 left out (11/04/2010)
1040201 1 124.9 0. 0.
*
1050000 uppl2 snglvol * middle volume for upper plenum
1050101 .923 1.12 1.03376 0. 90. 1.12 .00001 1.1 11000 *YCK 022807
1050200 103 1.04+5 333.15 * initial p, T
*
1060000 uppjn2 sngljun
1060101 108010002 105010001 .13 .01 .01 100 1.0 1.0 *SJK word 9 left out (11/04/2010)
1060201 1 124.9 0. 0. * initial flow rate
*
1070000 uppjn3 sngljun
1070101 105010001 109010001 .5 .01 .01 100 1.0 1.0 *SJK word 9 left out (11/04/2010)
1070201 1 0. 0. 0.
*
1080000 uppl3 snglvol
1080101 .130 .76 .0988 0. 90. .76 .00001 .387 11000  *YCK 022807
1080200 103 1.05+5 333.15 * initial p, T
*
1090000 uppl4 snglvol
1090101 .973 .80 .7784 0. -90. -.80 .00001 1.282 11000  *YCK2 022807
1090200 103 1.05+5 333.15 * initial p, T
*
1100000 inltpl snglvol
```

```
1100101 .130 .0658 .008554 0. 90. .0658 .00001 .387 11000  *YCK 022807
1100200 103 1.10+5 320.4 * initial p, T
*
2010000 pump tmdpjun * pump
2010101 102010002 203010001 .032
2010200 1  403 *SJK 071409
2010201 -1. 151.42 0. 0. *SJK 071409
2010202 0. 151.42 0. 0. * t,w  new pump coastdown SJK 05/12/2011
2010203 0.1 146.204 0. 0.
2010204 0.2 141.114 0. 0.
2010205 0.3 136.147 0. 0.
2010206 0.4 131.303 0. 0.
2010207 0.6 121.973 0. 0.
2010208 0.8 113.115 0. 0.
2010209 1.0 104.714 0. 0.
2010210 1.5 85.635 0. 0.
2010211 2.0 69.150 0. 0.
2010212 2.5 55.071 0. 0.
2010213 3.0 43.205 0. 0.
2010214 3.5 33.364 0. 0.
2010215 4.0 25.354 0. 0.
2010216 4.5 18.987 0. 0.
2010217 5.0 14.073 0. 0.
2010218 6.0 7.837 0. 0.
2010219 7.0 5.124 0. 0.
2010220 8.0 4.407 0. 0.
2010221 10.0 2.868 0. 0.
2010222 11.0 0.0 0. 0.
2010223 100000.0 0.0 0. 0.
*
2020000 ASV valve
2020101 105010002 203010001 .007674 6.90 7.90 100 1.0 1.0 * 2 valves - 8Words
2020201 1 0. 0. 0. * initial flow rate
2020300 trpvlv * trip valve
2020301 401 * trip 401
*
2030000 regn1 pipe * region 1
2030001 10 * number of nodes
2030101 .339,10 * area
2030301 .122,10 * node lengths * YCK 022807
2030601 -90.,10 *  vertical angles
2030801 .00001,.180,10 * roughness, Dw
2031001 11000,10 * volume control flags
2031101 1020,9 * junction control flags
2031201 103,1.04+5,320.4,0.,0.,0.,10 * initial pressure, temperature
2031300 1 * use mass flows below
```

```
2031301 124.9,0.,0.,9 * initial junction flow rates
*
2040000 rgn1to2 sngljun * region 1 to region 2 junction
2040101 203100002 205010001 .111 .3 .3 100 *YCK 022807
2040201 1 124.9 0. 0. * initial flow rate
*
2050000 regn2 pipe * region 2
2050001 10 * number of nodes
2050101 .111,10 * area
2050301 .06899,10 * node lengths  YCK 022807
2050601 -90.,10 * vertical angles  YCK 022807
2050801 .00001,.063,10 * roughness, Dw
2051001 11000,10 * volume control flags
2051101 1020,9 * junction control flags
2051201 103,1.05+5,320.4,0.,0.,0.,10 * initial pressure, temperature
2051300 1 * use mass flows below
2051301 124.9,0.,0.,9 * initial junction flow rates
*
2060000 rgn2to3 sngljun * region 2 to region 3 junction
*2060101 205100002 207010001 .0044 .18 .18 100  * YCK 022807
2060101 205100002 207010001 .111 .18 .18 100  * SJK 5/12/2011
2060201 1 124.9 0. 0. * initial flow rate
*
2070000 regn3 pipe * region 3
2070001 10 * number of nodes
*2070101 .0044,10 * area  * YCK 022807
2070101 .12566,10 * area  * SJK 5/12/2011 Downcomer 3 area pi*D*th (D=40 cm, th=10 cm)
2070301 .364,10 * node lengths  * YCK 022807
2070601 -0.16,10 * vertical angles * YCK 022807
2070801 .00001,.220,10 * roughness, Dw
2071001 11000,10 * volume control flags
2071101 1020,9 * junction control flags
2071201 103,1.06+5,320.4,0.,0.,0.,10 * initial pressure, temperature
2071300 1 * use mass flows below
2071301 124.9,0.,0.,9 * initial junction flow rates
*
2080000 NCV valve * NCV
2080101 109010002 210010001 .029 52.0 46.3 100 1.0 1.0 * 4 valves - 8 words
2080201 1 0. 0. 0. * initial flow rate
2080300 trpvlv * trip valve
2080301 402 * trip 402
*
2090000 rgn3to4 sngljun * region 3 to region 4 junction
*2090101 207100002 210010001 .0044 .1 .1 100  * YCK 022807
2090101 207100002 210010001 .029 .1 .1 100  * SJK 5/12/2011
2090201 1 124.9 0. 0. * initial flow rate
```

```
*
2100000 regn4 pipe * region 4
2100001 10 * number of nodes
2100101 .029,10 * area
2100301 .061,10 * node lengths  * YCK 022807
2100601 -90.,10 *  vertical angles
2100801 .00001,.040,10 * roughness, Dw
2101001 11000,10 * volume control flags
2101101 1020,9 * junction control flags
2101201 103,1.07+5,320.4,0.,0.,0.,10 * initial pressure, temperature
2101300 1 * use mass flows below
2101301 124.9,0.,0.,9 * initial junction flow rates
*
2110000 rgn4toi sngljun * region 4 to inlet plenum
2110101 210100002 110010001 .029 2.05 2.05 100 * YCK 022807
2110201 1 124.9 0. 0. * initial flow rate
*
************************                    *********************
************************    Yinjie Zhao  Average HEU  *********************
************************                    *********************
*
3010000 avginl sngljun * inlet to the average core channel
3010101 110010002 302010001 3.922e-02 .3 .2 100  *$ SJK 05/12/11
3010201 1 103.3 0. 0. * initial flow rate * YCK 032407
*
3020000 avgchn pipe * average core channel
3020001 16 * number of nodes
3020101 3.922e-02,16 * volume area  *
3020301 0.036513,16 * node lengths
3020601 90.,16 * vertical angles
3020801 .00001,.0021864,16 * roughness, Dw
3021001 11000,16 * volume control flags
3021101 1020,15 * junction control flags
3021201 103,1.08+5,320.4,0.,0.,0.,16 * initial pressure, temperature
3021300 1 * use mass flows below
3021301 103.3,0.,0.,15 * initial junction flow rates *
*
3030000 avgout sngljun * outlet from the average core channel
3030101 302160002 108010001 3.922e-02 .2 .3 100  *
3030201 1 103.3 0. 0. * initial flow rate * YCK 032407
*
*     average fuel plate
*
13021000 16 10 1 0 0. 0 0 2 *
13021100 0 2 * mesh flags
13021101 .0000762,5,.00009525,9 * mesh intervals
```

```
13021201 1,5 2,9 * compositions
13021301 0.,5 1.,9 * radial source distribution
13021401 320.4,10 * initial temperatures
13021501 302010000,10000,1,0,2.4928,16 * left boundary condition *
13021601 0,0,0,0,2.4928,16 * right boundary condition, insulated *
13021701 1000 0.02924651  0. 0. 1 * axial source distribution
13021702 1000 0.02707666  0. 0. 2
13021703 1000 0.03182421  0. 0. 3
13021704 1000 0.036634389  0. 0. 4
13021705 1000 0.04157189  0. 0. 5
13021706 1000 0.045820344  0. 0. 6
13021707 1000 0.050116857  0. 0. 7
13021708 1000 0.054214834  0. 0. 8
13021709 1000 0.059475228  0. 0. 9
13021710 1000 0.064033114  0. 0. 10
13021711 1000 0.065694375  0. 0. 11
13021712 1000 0.065456406  0. 0. 12
13021713 1000 0.063874842  0. 0. 13
13021714 1000 0.060086636  0. 0. 14
13021715 1000 0.055772943  0. 0. 15
13021716 1000 0.06425952  0. 0. 16
13021800 0
13021801 .002353,10.,10.,0.,0.,0.,0.,1.0,16 * additional left boundary * Dh
13021900 0
13021901 .002353,10.,10.,0.,0.,0.,0.,1.0,16 * additional right boundary * Dh
*

************************              *********************
************************       Yinjie Zhao  Average LEU  *********************
************************              *********************
*
*
3110000 avginl sngljun * inlet to the average core channel
3110101 110010002 312010001 6.222e-03  .3 .2 100  *
3110201 1 103.3 0. 0. * initial flow rate * YCK 032407
*
3120000 avgchn pipe * average core channel
3120001 16 * number of nodes
3120101 6.222e-03,16 * volume area  *
3120301 0.036513,16 * node lengths
3120601 90.,16 * vertical angles
3120801 .00001,.003671,16 * roughness, Dw
3121001 11000,16 * volume control flags
3121101 1020,15 * junction control flags
3121201 103,1.08+5,320.4,0.,0.,0.,16 * initial pressure, temperature
3121300 1 * use mass flows below
```

```
3121301 103.3,0.,0.,15 * initial junction flow rates *
*
3130000 avgout sngljun * outlet from the average core channel
3130101 312160002 108010001 6.222e-03 .2 .3 100  *
3130201 1 103.3 0. 0. * initial flow rate *
*
*     average fuel plate
*
13121000 16 50 1 0 0. 0 0 2 * YCK 658 average half-plates
13121100 0 2 * mesh flags
13121101 1.27e-5 49 * mesh intervals
13121201 12,24 14,49 * compositions
13121301 0.0,24 1.0,49 * radial source distribution
13121401 320.4,50 * initial temperatures
13121501 312010000,10000,1,0,0.23312,16 * left boundary condition *
13121601 0,0,0,0,0.23312,16 * right boundary condition, insulated *
13121701 1000 0.007069132  0. 0. 1 * axial source distribution
13121702 1000 0.006278035  0. 0. 2
13121703 1000 0.007424587  0. 0. 3
13121704 1000 0.008592752  0. 0. 4
13121705 1000 0.009670005  0. 0. 5
13121706 1000 0.01066576  0. 0. 6
13121707 1000 0.01150286  0. 0. 7
13121708 1000 0.012161375  0. 0. 8
13121709 1000 0.012651502  0. 0. 9
13121710 1000 0.012925197  0. 0. 10
13121711 1000 0.01292675  0. 0. 11
13121712 1000 0.012621422  0. 0. 12
13121713 1000 0.01196411  0. 0. 13
13121714 1000 0.010975898  0. 0. 14
13121715 1000 0.009833095  0. 0. 15
13121716 1000 0.011711782  0. 0. 16
13121800 0
13121801 .003671,10.,10.,0.,0.,0.,0.,1.0,16 * additional left boundary * Dh
13121900 0
13121901 .003671,10.,10.,0.,0.,0.,0.,1.0,16 * additional right boundary * Dh
*
*
************************                    *********************
************************      Yinjie Zhao Hot HEU   *********************
************************                    *********************
4010000 avginl sngljun * inlet to the average core channel
4010101 110010002 402010001 1.182e-4 .3 .2 100  *
4010201 1 .259 0. 0. * initial flow rate *
*
*
```

```
4020000 hotchn pipe * hot core channel
4020001 16 * number of nodes
4020101 1.182e-4,16 * area  *
4020301 0.036513,16 * node lengths
4020601 90.,16 * vertical angles
4020801 .00001, 2.1249-3,16 * roughness, Dh *
4021001 11000,16 * volume control flags
4021101 1020,15 * junction control flags
4021201 103,1.08+5,320.4,0.,0.,0.,16 * initial pressure, temperature
4021300 1 * use mass flows below
4021301 .259,0.,0.,15 * initial junction flow rates *
*
4030000 avgout sngljun * outlet from the average core channel
4030101 402160002 108010001 1.182-4 .2 .3 100  *
4030201 1 .259 0. 0. * initial flow rate *
*
*
*      peak fuel plate
*
14021000 16 10 1 0 0. 0 0 2 *  half-plates
14021100 0 2 * mesh flags
14021101 .0000762,5,.00009525,9 * mesh intervals
14021201 1,5 2,9 * compositions
14021301 0.,5 1.,9 * radial source distribution
14021401 320.4,10 * initial temperatures
14021501 402010000,10000,1,0,.0077256,16 * left boundary condition *
14021601 0,0,0,0,.0077256,16 * right boundary condition, insulated *
14021701 1000 0.00020982 0. 0. 1 * axial source distribution, 2 peak half plates *
14021702 1000 0.00019093 0. 0. 2 *
14021703 1000 0.00020707 0. 0. 3 *
14021704 1000 0.00023682 0. 0. 4 *
14021705 1000 0.00026111 0. 0. 5 *
14021706 1000 0.00028275 0. 0. 6 *
14021707 1000 0.00030075 0. 0. 7 *
14021708 1000 0.00028808 0. 0. 8 *
14021709 1000 0.00028294 0. 0. 9 *
14021710 1000 0.00028471 0. 0. 10 *
14021711 1000 0.00027720 0. 0. 11 *
14021712 1000 0.00028131 0. 0. 12 *
14021713 1000 0.00027132 0. 0. 13 *
14021714 1000 0.00026193 0. 0. 14 *
14021715 1000 0.00026053 0. 0. 15 *
14021716 1000 0.00031161 0. 0. 16 *
14021800 0
14021801 .0021738,10.,10.,0.,0.,0.,1.0,16 * additional left boundary
14021900 0
```

```
14021901 .0021738,10.,10.,0.,0.,0.,0.,1.0,16 * additional right boundary *
*
************************                    ********************* Location B8 P16
************************       Yinjie Zhao  Hot LEU Stripe 1  *********************
************************                    *********************
4110000 avginl sngljun * inlet to the average core channel
4110101 110010002 412010001 2.505e-05 .3 .2 100  *
4110201 1 .259 0. 0. * initial flow rate *
*
*
4120000 hotchn pipe * hot core channel
4120001 16 * number of nodes
4120101 2.505e-05,16 * area  *
4120301 0.036513,16 * node lengths
4120601 90.,16 * vertical angles
4120801 .00001, 3.790e-03,16 * roughness, Dh *
4121001 11000,16 * volume control flags
4121101 1020,15 * junction control flags
4121201 103,1.08+5,320.4,0.,0.,0.,16 * initial pressure, temperature
4121300 1 * use mass flows below
4121301 .259,0.,0.,15 * initial junction flow rates *
*
4130000 avgout sngljun * outlet from the average core channel
4130101 412160002 108010001 2.505e-05 .2 .3 100  *
4130201 1 .259 0. 0. * initial flow rate *
*
*     LEU peak fuel stripe 1
*
14121000 16 50 1 0 0. 0 0 2 * average half-plates
14121100 0 2 * mesh flags
14121101 1.27e-5 49 * mesh intervals
14121201 12,24 14,49 * compositions
14121301 0.0,24 1.0,49 * radial source distribution
14121411 320.4,50 * initial temperatures
14121501 412010000,10000,1,0,0.00096540,16 * left boundary condition *
14121601 0,0,0,0,0.00096540,16 * right boundary condition, insulated *
14121701 1000 0.000048393 0. 0. 1 * axial source distribution, 2 peak half plates *
14121702 1000 0.000043512 0. 0. 2 *
14121703 1000 0.000049665 0. 0. 3 *
14121704 1000 0.000056096 0. 0. 4 *
14121705 1000 0.000063209 0. 0. 5 *
14121706 1000 0.000069595 0. 0. 6 *
14121707 1000 0.000073804 0. 0. 7 *
14121708 1000 0.000076121 0. 0. 8 *
14121709 1000 0.000077425 0. 0. 9 *
14121710 1000 0.000079542 0. 0. 10 *
```

```
14121711 1000 0.000078389 0. 0. 11 *
14121712 1000 0.000076303 0. 0. 12 *
14121713 1000 0.000072610 0. 0. 13 *
14121714 1000 0.000067769 0. 0. 14 *
14121715 1000 0.000063480 0. 0. 15 *
14121716 1000 0.000074318 0. 0. 16 *
14121800 0
14121801 3.790e-03,10.,10.,0.,0.,0.,0.,1.0,16 * additional left boundary *
14121900 0
14121901 3.790e-03,10.,10.,0.,0.,0.,0.,1.0,16 * additional right boundary *

************************                    *********************
************************    Yinjie Zhao  Hot LEU Stripe 2  *********************
************************                    *********************
4210000 avginl sngljun * inlet to the average core channel
4210101 110010002 422010001 2.505e-05 .3 .2 100  *
4210201 1 .259 0. 0. * initial flow rate *
*
*
4220000 hotchn pipe * hot core channel
4220001 16 * number of nodes
4220101 2.505e-05,16 * area  *
4220301 0.036513,16 * node lengths
4220601 90.,16 * vertical angles
4220801 .00001, 3.790e-03,16 * roughness, Dh *
4221001 11000,16 * volume control flags
4221101 1020,15 * junction control flags
4221201 103,1.08+5,320.4,0.,0.,0.,16 * initial pressure, temperature
4221300 1 * use mass flows below
4221301 .259,0.,0.,15 * initial junction flow rates *
*
4230000 avgout sngljun * outlet from the average core channel
4230101 422160002 108010001 2.505e-05 .2 .3 100  *
4230201 1 .259 0. 0. * initial flow rate *

*     LEU peak fuel stripe 2
*
14221000 16 50 1 0 0. 0 0 2 * average half-plates
14221100 0 2 * mesh flags
14221101 1.27e-5 49 * mesh intervals
14221201 12,24 14,49 * compositions
14221301 0.0,24 1.0,49 * radial source distribution
14221411 320.4,50 * initial temperatures
14221501 422010000,10000,1,0,0.00096540,16 * left boundary condition *
14221601 0,0,0,0,0.00096540,16 * right boundary condition, insulated *
14221701 1000 0.000036261 0. 0. 1 * axial source distribution, 2 peak half plates *
```

14221702 1000 0.000032084 0. 0. 2 *
14221703 1000 0.000038408 0. 0. 3 *
14221704 1000 0.000044771 0. 0. 4 *
14221705 1000 0.000050512 0. 0. 5 *
14221706 1000 0.000054839 0. 0. 6 *
14221707 1000 0.000058681 0. 0. 7 *
14221708 1000 0.000061515 0. 0. 8 *
14221709 1000 0.000064370 0. 0. 9 *
14221710 1000 0.000065751 0. 0. 10 *
14221711 1000 0.000064731 0. 0. 11 *
14221712 1000 0.000063295 0. 0. 12 *
14221713 1000 0.000060204 0. 0. 13 *
14221714 1000 0.000055358 0. 0. 14 *
14221715 1000 0.000049250 0. 0. 15 *
14221716 1000 0.000057210 0. 0. 16 *
14221800 0
14221801 3.790e-03,10.,10.,0.,0.,0.,0.,1.0,16 * additional left boundary *
14221900 0
14221901 3.790e-03,10.,10.,0.,0.,0.,0.,1.0,16 * additional right boundary *

************************* **********************
************************* Yinjie Zhao Hot LEU Stripe 3 **********************
************************* **********************
4310000 avginl sngljun * inlet to the average core channel
4310101 110010002 432010001 2.505e-05 .3 .2 100 *
4310201 1 .259 0. 0. * initial flow rate *
*
*
4320000 hotchn pipe * hot core channel
4320001 16 * number of nodes
4320101 2.505e-05,16 * area *
4320301 0.036513,16 * node lengths
4320601 90.,16 * vertical angles
4320801 .00001, 3.790e-03,16 * roughness, Dh *
4321001 11000,16 * volume control flags
4321101 1020,15 * junction control flags
4321201 103,1.08+5,320.4,0.,0.,0.,16 * initial pressure, temperature
4321300 1 * use mass flows below
4321301 .259,0.,0.,15 * initial junction flow rates *
*
4330000 avgout sngljun * outlet from the average core channel
4330101 432160002 108010001 2.505e-05 .2 .3 100 *
4330201 1 .259 0. 0. * initial flow rate *

* LEU peak fuel stripe 3
*

```
14321000 16 50 1 0 0. 0 0 2 * average half-plates
14321100 0 2 * mesh flags
14321101 1.27e-5 49 * mesh intervals
14321201 12,24 14,49 * compositions
14321301 0.0,24 1.0,49 * radial source distribution
14321411 320.4,50 * initial temperatures
14321501 432010000,10000,1,0,0.00096540,16 * left boundary condition *
14321601 0,0,0,0,0.00096540,16 * right boundary condition, insulated *
14321701 1000 0.000033523 0. 0. 1 * axial source distribution, 2 peak half plates *
14321702 1000 0.000030182 0. 0. 2 *
14321703 1000 0.000036314 0. 0. 3 *
14321704 1000 0.000041884 0. 0. 4 *
14321705 1000 0.000047646 0. 0. 5 *
14321706 1000 0.000052511 0. 0. 6 *
14321707 1000 0.000056985 0. 0. 7 *
14321708 1000 0.000060234 0. 0. 8 *
14321709 1000 0.000062571 0. 0. 9 *
14321710 1000 0.000063747 0. 0. 10 *
14321711 1000 0.000063149 0. 0. 11 *
14321712 1000 0.000062308 0. 0. 12 *
14321713 1000 0.000058200 0. 0. 13 *
14321714 1000 0.000053388 0. 0. 14 *
14321715 1000 0.000047370 0. 0. 15 *
14321716 1000 0.000054472 0. 0. 16 *
14321800 0
14321801 3.790e-03,10.,10.,0.,0.,0.,0.,1.0,16 * additional left boundary *
14321900 0
14321901 3.790e-03,10.,10.,0.,0.,0.,0.,1.0,16 * additional right boundary *

*************************                    **********************
*************************    Yinjie Zhao  Hot LEU Stripe 4  **********************
*************************                    **********************
4410000 avginl sngljun * inlet to the average core channel
4410101 110010002 442010001 2.505e-05 .3 .2 100  *
4410201 1 .259 0. 0. * initial flow rate *
*
*
4420000 hotchn pipe * hot core channel
4420001 16 * number of nodes
4420101 2.505e-05,16 * area  *
4420301 0.036513,16 * node lengths
4420601 90.,16 * vertical angles
4420801 .00001, 3.790e-03,16 * roughness, Dh *
4421001 11000,16 * volume control flags
4421101 1020,15 * junction control flags
4421201 103,1.08+5,320.4,0.,0.,0.,16 * initial pressure, temperature
```

```
4421300 1 * use mass flows below
4421301 .259,0.,0.,15 * initial junction flow rates *
*
4430000 avgout sngljun * outlet from the average core channel
4430101 442160002 108010001 2.505e-05 .2 .3 100  *
4430201 1 .259 0. 0. * initial flow rate *

*


*      LEU peak fuel stripe 4
*
14421000 16 50 1 0 0. 0 0 2 * average half-plates
14421100 0 2 * mesh flags
14421101 1.27e-5 49 * mesh intervals
14421201 12,24 14,49 * compositions
14421301 0.0,24 1.0,49 * radial source distribution
14421411 320.4,50 * initial temperatures
14421501 442010000,10000,1,0,0.00096540,16 * left boundary condition *
14421601 0,0,0,0,0.00096540,16 * right boundary condition, insulated *
14421701 1000 0.000038351 0. 0. 1 * axial source distribution, 2 peak half plates *
14421702 1000 0.000034159 0. 0. 2 *
14421703 1000 0.000041366 0. 0. 3 *
14421704 1000 0.000048324 0. 0. 4 *
14421705 1000 0.000054497 0. 0. 5 *
14421706 1000 0.000060082 0. 0. 6 *
14421707 1000 0.000064955 0. 0. 7 *
14421708 1000 0.000069765 0. 0. 8 *
14421709 1000 0.000072544 0. 0. 9 *
14421710 1000 0.000074013 0. 0. 10 *
14421711 1000 0.000074031 0. 0. 11 *
14421712 1000 0.000072464 0. 0. 12 *
14421713 1000 0.000068480 0. 0. 13 *
14421714 1000 0.000062361 0. 0. 14 *
14421715 1000 0.000055070 0. 0. 15 *
14421716 1000 0.000064496 0. 0. 16 *
14421800 0
14421801 3.790e-03,10.,10.,0.,0.,0.,0.,1.0,16 * additional left boundary *
14421900 0
14421901 3.790e-03,10.,10.,0.,0.,0.,0.,1.0,16 * additional right boundary *
*
************************                ********************
************************    Yinjie Zhao    *********************
************************                ********************
5010000 bypinl sngljun * inlet to the bypass flow
5010101 110010002 502010001 3.7502-3 .3 .2 100  *$ SJK 5/12/2011
```

```
5010201 1 8.91 0. 0. * initial flow rate * YCK 032407
*
5020000 bypass pipe * bypass flow
5020001 10 * number of nodes
5020101 3.7502-3,10 * area  *$ SJK 05/12/2011
5020301 .06478,1 .05683,9 .06478,10 * node lengthss
5020601 90.,10 * vertical angles
5020801 .00001, 2.0174e-3,10 * roughness, Dw SJK 5/12/2011
5021001 11000,10 * volume control flags
5021101 1020,9 * junction control flags
5021201 103,1.08+5,320.4,0.,0.,0.,10 * initial pressure, temperature
5021300 1 * use mass flows below
5021301 8.91,0.,0.,9 * initial junction flow rates * YCK 032407
*
5030000 bypout sngljun * outlet from the bypass flow
5030101 502100002 108010001 3.7502-3 .2 .3 100  *$ SJK 5/12/2011
5030201 1 8.91 0. 0. * initial flow rate * YCK 032407
*
*
*
*       tables
*
*
20100100 tbl/fctn 1 1 * thermal properties table 1 for Al
20100101 97.297 * Al thermal conductivity *SJK 5/12/2011
20100151 1.7431e6 * Al rho*Cp *SJK 05/27/2011
*
20100200 tbl/fctn 1 1 * thermal properties table 2 for HEU fuel
20100201 298.  25.622 * k, SJK 5/12/2011
20100202 873.  28.486 *
20100203 1073. 29.568 *
20100251 273.15  1.5538e6 * rho*Cp *SJK 5/12/2011
20100252 298.15  1.5747e6 * rho*Cp *
20100253 373.15  1.6374e6 * rho*Cp *
20100254 473.15  1.7210e6 * rho*Cp *
20100255 573.15  1.8046e6 * rho*Cp *
20100256 673.15  1.8882e6 * rho*Cp *
20100257 773.15  1.9718e6 * rho*Cp *
20100258 873.15  2.0555e6 * rho*Cp *
20100259 973.15  2.1391e6 * rho*Cp *
20100260 1073.15 2.2227e6 * rho*Cp *
20100261 1173.15 2.3063e6 * rho*Cp *
20100262 1273.15 2.3899e6 * rho*Cp *
*

*  type       tflag       vflag
```

```
20100300     tbl/fctn          1          1
*          thcond
20100301        2.25
*       heat Capacity
20100351       3.12e6
*
*              type        tflag        vflag
20100400     tbl/fctn          1          1
*              temp        thcond
20100401       293.15        167.5
20100402       533.15        184.3
20100403       810.95        201.1
20100404      1922.05        268.1
*              temp      capacity
20100451       293.15      2.539e6
20100452       533.15      2.688e6
20100453       810.95      2.828e6
20100454      1922.05      3.391e6
*
*              type        tflag        vflag
20100500     tbl/fctn          1          1
*              temp        thcond
20100501       293.15         21.4
20100502       366.45         20.0
20100503       477.55         19.1
20100504       550.55         19.0
20100505       644.25         19.1
20100506        810.0        20.0
20100507       2000.0         20.0
*              temp      capacity
20100551       293.15      1.866e6
20100552       477.55      2.019e6
20100553       810.95      2.244e6
20100554       2000.0      3.108e6
*
*              type        tflag        vflag
20100600     tbl/fctn          1          1
*              temp        thcond
20100601       293.15        13.36
20100602       373.15        16.34
20100603       413.15        17.71
20100604       673.15        24.81
*              temp      capacity
20100651       293.15      2.362e6
20100652       366.45       2.43e6
20100653       477.55      2.538e6
```

```
20100654       588.75      2.655e6
20100655       699.85      2.781e6
20100656        800.0      2.877e6
20100657       2000.0      4.111e6
*
*              type        tflag        vflag
20101200     tbl/fctn          1            1
*            thcond
20101201        160.0
*       heat Capacity
20101251       2.4192e6
*
*              type        tflag        vflag
20101400     tbl/fctn          1            1
*            Temp       thcond
20101401        293.15      11.3
20101402        373.15      13.2
20101403        473.15      17.1

*            Temp     heat Capacity
20101451        273.15     2.346e6
20101452        373.15     2.390e6
20101453        473.15     2.462e6
20101454        573.15     2.566e6

*
*
* YW 210928: Reactor Trip
20200100 reac-t 0 * General table 1, scram reactivity
20200101 0. 0.  * t, reactivity ($)
20200102 300. 0.  * SJK 071509
20200103 301.3 0.  * SJK 071509
20200104 302.3 -7.5  * SJK 071509
20200105 303.3 -10.0  * SJK 071509
20200106 10000. -10.0 * SJK 071509
*
*
*  point kinetics
*
30000000 point separabl
30000001 gamma-ac 6.0e6 0. 150. 1.0 0.7 *SJK 5/30/2011 6.6 MW LSSS power for 6 MW
operation
30000002 ans79-1
30000401 6.0e6 52. wk *$ SJK 12/20/2010 7.4 MW LSSS power
30000011 1
30000501 500. 0. * moderator density reactivity  SJK 062009 w1: mod density w2: reactivity
```

```
30000502 2000. 0.
30000601 300. 0. * doppler reactivity SJK 062009 w1: fuel temp w2: reactivity
30000602 1000. 0.
30000701 302010000 0 1. 0. * Volume weighting factors
30000801 3021001 0 1.0 0.
.  end of input file
```

Appendix C: STAT7 Mixed core 1 (Mix-1) LEU Stripe Input deck

```
 S7-MIT-AJD.i, STAT7 deck for MITR MIXED transition, with sigmas
nelm  |  nplt | nstrp |  nz   | nbatch| nsmpl | isd1  | isd2  |  iprt | idbstt|
    24      19       4      16      25    4000      21       3       2       1
nchan | iaxpow| irndmn|  ipow | iterpw| iend1 | iendn |  ivsc | niter | ilocp |
    20       0       0       1       2       1       1       0       2       1
ipwshp| ifatl | iflwnc|   idf | itprt |  inom | ipronb| ibypas| ivscfl| ioptn |
                                       1                     5
thdbug  |  fcore  |  ffuel  |  flwfac | df      | flwinc  | pow0    |  powsgm | cnveps
0.        0.95      1.0       .921     1.34       .964       6.00      .016667   0.01
plocsg  | sigmax  | tout    | wp0      | wpsgm   | coolht  |  fl     | fw      |
.04714    8.0       60.00     151.4     .016667   3.048     .56832    .0529
grvdml  | grvwml  | grvtml  | gapml   | gapsg   | fdumy3  | htcsgm  | epsonb  |
0.        10.       10.       74.6      .02055    .03333    .06667    .00135
gapml0  | flstrf  | fuelthnu| fuelk nu| afrv    |  xke    | bfrv    | xkf     |
74.6      0.91                         .184      160.      1.0       14.
 ich  |    gapmli | gapsgi  |
     1   65.7      .08625
     2   74.6      .02055
     3   74.6      .02055
     4   74.6      .02055
     5   74.6      .02055
     6   74.6      .02055
     7   74.6      .02055
     8   74.6      .02055
     9   74.6      .02055
    10   74.6      .02055
```

11 74.6 .02055
12 74.6 .02055
13 74.6 .02055
14 74.6 .02055
15 74.6 .02055
16 74.6 .02055
17 74.6 .02055
18 74.6 .02055
19 74.6 .02055
20 65.7 .08625
iplate| thkf | thke |
1 17. 17.5
2 13.00 18.00
3 17.00 16.00
4 17.00 16.00
5 25.00 12.00
6 25.00 12.00
7 25.00 12.00
8 25.00 12.00
9 25.00 12.00
10 25.00 12.00
11 25.00 12.00
12 25.00 12.00
13 25.00 12.00
14 25.00 12.00
15 25.00 12.00
16 25.00 12.00
17 25.00 12.00
18 17.00 16.00
19 17.00 16.00
20 13.00 18.00
21 17. 17.5
iplate| fstrp | axpow
1 0.
.00015734 .00014866 .00015620 .00016540 .00016617 .00016957 .00017154 .00017229
.00017074 .00016900 .00016331 .00015103 .00013971 .00011928 .00009326 .00006457
iplate| fstrp | axpow
2 1.277
10.000 7.953 8.853 9.615 10.170 10.466 10.406 10.239
9.683 9.240 8.536 7.640 6.775 5.764 4.939 5.797

iplate| fstrp | axpow
3 1.459
10.000 8.129 9.144 9.918 10.445 10.726 10.706 10.439
9.992 9.484 8.753 7.848 7.053 6.064 5.136 5.927
iplate| fstrp | axpow
4 1.345
10.000 8.246 9.151 9.878 10.421 10.829 10.725 10.461
10.004 9.507 8.823 7.932 7.046 6.033 5.126 5.890
iplate| fstrp | axpow
5 1.754
10.000 8.386 9.304 10.193 10.709 10.951 10.985 10.724
10.220 9.787 9.044 8.139 7.198 6.195 5.225 5.990
iplate| fstrp | axpow
6 1.675
10.000 8.312 9.211 10.105 10.642 10.940 10.867 10.662
10.258 9.644 8.941 8.117 7.291 6.135 5.255 6.006
iplate| fstrp | axpow
7 1.635
10.000 8.302 9.356 10.056 10.647 10.866 10.864 10.662
10.236 9.613 8.958 8.144 7.273 6.241 5.332 6.083
iplate| fstrp | axpow
8 1.618
10.000 8.266 9.313 10.040 10.717 10.873 10.888 10.824
10.417 9.725 9.032 8.268 7.184 6.263 5.356 6.158
iplate| fstrp | axpow
9 1.616
10.000 8.199 9.140 9.917 10.436 10.735 10.665 10.570
10.174 9.606 8.886 8.069 7.136 6.260 5.308 6.021
iplate| fstrp | axpow
10 1.623
10.000 8.278 9.213 10.124 10.628 10.903 10.874 10.765
10.402 9.771 9.181 8.226 7.331 6.427 5.464 6.283
iplate| fstrp | axpow
11 1.636
10.000 8.198 9.145 9.887 10.465 10.768 10.760 10.601
10.282 9.774 9.040 8.250 7.312 6.426 5.477 6.177
iplate| fstrp | axpow
12 1.656
10.000 8.306 9.090 9.894 10.366 10.683 10.711 10.564
10.241 9.805 9.049 8.270 7.343 6.414 5.509 6.250

```
iplate|   fstrp |    axpow
    13   1.678
10.000    8.415    9.130    9.832    10.451    10.772    10.736    10.544
10.333    9.844    9.120    8.391    7.471    6.501    5.557    6.290
iplate|   fstrp |    axpow
    14   1.714
10.000    8.287    8.962    9.868    10.349    10.524    10.672    10.447
10.236    9.839    9.099    8.294    7.435    6.456    5.609    6.325
iplate|   fstrp |    axpow
    15   1.760
10.000    8.367    8.997    9.707    10.312    10.525    10.597    10.402
10.243    9.845    9.146    8.348    7.450    6.551    5.677    6.311
iplate|   fstrp |    axpow
    16   1.832
10.000    8.421    9.101    9.801    10.339    10.557    10.644    10.403
10.265    9.885    9.228    8.374    7.538    6.657    5.831    6.427
iplate|   fstrp |    axpow
    17   1.952
10.000    8.542    9.119    9.770    10.267    10.548    10.703    10.418
10.243    9.931    9.364    8.505    7.548    6.683    5.855    6.512
iplate|   fstrp |    axpow
    18   1.513
10.000    8.449    8.974    9.656    10.107    10.377    10.440    10.345
10.172    9.801    9.247    8.390    7.545    6.683    5.879    6.687
iplate|   fstrp |    axpow
    19   1.656
10.000    8.427    8.970    9.703    10.013    10.332    10.411    10.317
10.140    9.871    9.218    8.375    7.626    6.701    5.861    6.689
iplate|   fstrp |    axpow
    20   1.450
10.000    8.432    8.954    9.682    10.043    10.322    10.330    10.272
10.132    9.856    9.270    8.525    7.716    6.813    5.981    6.784
iplate|    fstrp  |    axpow
    21   0.
 .00015734 .00014866 .00015620 .00016540 .00016617 .00016957 .00017154 .00017229
.00017074 .00016900 .00016331 .00015103 .00013971 .00011928 .00009326 .00006457
```