RERTR 2014 — 35th INTERNATIONAL MEETING ON
REDUCED ENRICHMENT FOR RESEARCH AND TEST REACTORS

OCTOBER 12-16, 2014
IAEA VIENNA INTERNATIONAL CENTER
VIENNA, AUSTRIA

Safety Analysis of U-Mo LEU Fuel with Unfinned Cladding for the MIT Research Reactor

T.H. Newton, Jr., L-W Hu, K. Sun, S. M. Don
MIT Nuclear Reactor Laboratory
138 Albany St, Cambridge, MA 02139 -- USA

E. H. Wilson, A. Bergeron, F. E. Dunn
GTRI Program, Nuclear Engineering Division
Argonne National Laboratory
9700 South Cass Ave, Argonne, IL 60430 – USA

ABSTRACT

The Massachusetts Institute of Technology Reactor (MITR) is a 6 MW research reactor operating with highly-enriched uranium (HEU) finned plate-type fuel. The conversion objective is to design a low-enriched uranium (LEU) fuel element that could safely replace the current 15-plate MITR HEU fuel element and maintain performance while requiring minimal, if any, changes to the reactor structures and systems. Recent design analyses of alternatives to 0.25 mm clad finned LEU fuel plates have shown a 19-plate unfinned LEU fuel element with increased cladding thickness and thinner fuel meat thickness on the outer plates to be a feasible alternative.

This study presents the results of neutronic and thermal-hydraulic steady-state analyses of power distribution, and the heating impact of conversion on in-core experiments with use of this alternative fuel. Accident analyses are also provided, including thermal safety margin analysis of loss-of-flow and reactivity insertion accidents.

1. Introduction

The MIT Reactor (MITR-II) core has a hexagonal design that contains twenty-seven fuel positions in three radial rings (A, B, and C), as shown in Figure 1, and is licensed to operate at 6 MW. Typically at least three of these positions (two in the A-ring and one in the B-ring) are filled with either an in-core experimental facility or a solid aluminum dummy element to reduce power peaking. The remaining positions are filled with standard MITR-II fuel elements. Each rhomboid-shaped fuel element currently contains 15 aluminum-clad fuel plates using HEU (93% enriched) in an aluminide cermet matrix with a fuel thickness of 0.76 mm (0.030 inches) and a length of 61 cm (24 inches). The cladding of each fuel plate is machined with 0.25 mm longitudinal fins to increase heat transfer to the coolant. The fuel has an overall density of 3.7 g/cm^3, with a total loading of 506 g of ^{235}U in each element.

The core is light water moderated and cooled and is surrounded by a D_2O reflector. Boron-impregnated stainless steel control blades are located at the periphery of the core on each side of the hexagon, and have a total travel length of 52 cm. In addition, fixed absorbers can be installed in the upper axial region of the core in a hexagonal configuration between the A and B rings as well as in three radial arms extending to the edge of the core.

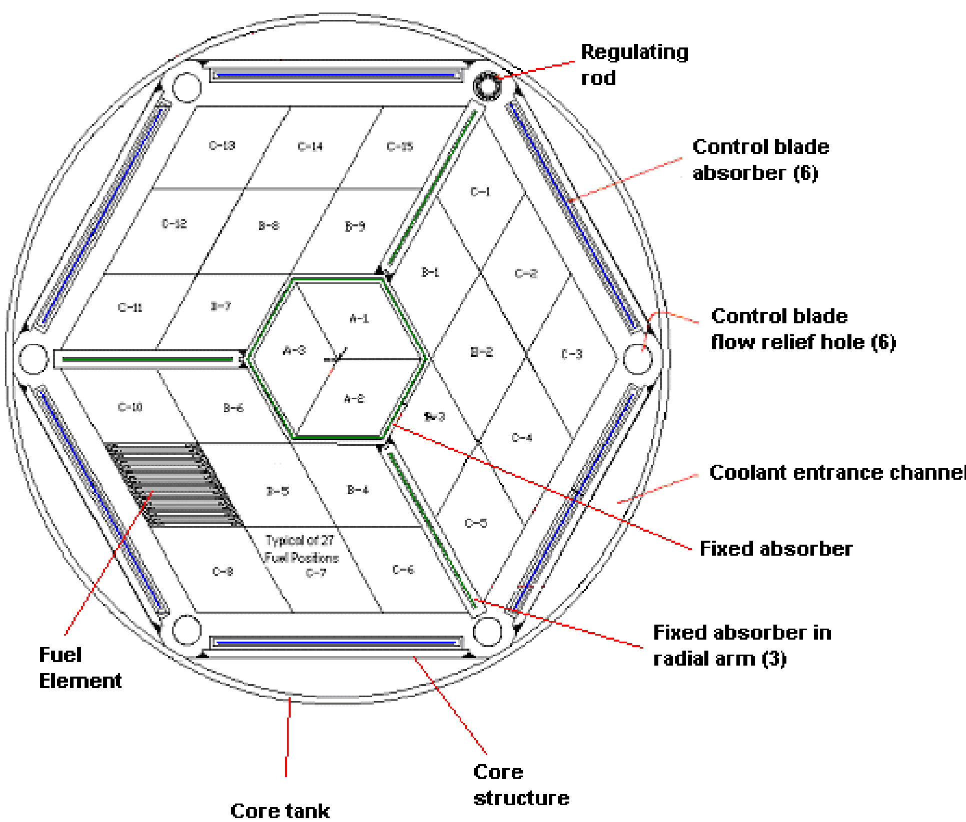

Figure 1. Layout of the MIT Reactor core.

2. LEU Fuel Design

LEU fuel optimization performed for the MIT Reactor has shown that fuels with a density of at least 14 g/cm^3 would be required to reduce the enrichment to 19.75% while maintaining adequate reactor performance. [1] Because of this, monolithic U-10Mo LEU fuel with a density of 17.02 g/cm^3 was chosen for the design. This high density fuel is currently under evaluation by the RERTR program.

An initial feasibility study resulted in the design of a U-10Mo LEU fuel element containing 18 plates with 0.508 mm thick fuel meat and 0.25 mm thick cladding below the fins. [2] This analysis shows that an equivalent 6 MW HEU experimental neutron flux can be generated at an LEU reactor power of 7 MW with sufficient margins to onset of nucleate boiling. A comparison of the HEU and LEU fuel parameters is shown in Table 1.

Table 1. Comparison of current HEU fuel and originally proposed LEU fuel design

MITR Design Parameters	UAl_x (HEU)	Monolithic U-10Mo (LEU)
Enrichment	93%	19.75%
Fuel Density (g U/cm^3)	1.54	15.3
Number of plates per assembly	15	18
Fuel thickness (mm)	0.76	0.51
Cladding Thickness (mm)	0.38	0.25
Operating Power (MW)	6.0	7.0
Cycle length	40-50 days	55-70 days

3. Alternate fuel design

Concerns about machining 0.25mm fins on top of 0.25 mm cladding with monolithic U-10Mo fuel has caused a re-evaluation of the LEU design and has resulted in a study of unfinned designs with thicker cladding. [3] The effect of end channel size, number of plates per element, and fuel meat thickness in the outer-most plates (to reduce power peaking) were evaluated in this study and are discussed here.

The MCNP-ORIGEN linkage code MCODE was used to study burnup and power distribution in the proposed designs. The impact on performance and thermal-hydraulic safety margins have been analyzed by using the MCODE power distributions and by evaluating the margin to Onset of Nucleate Boiling (ONB) using the STAT7 code. Details of these models can be found in reference [3].

The minimum margin to ONB occurs in the reference design in the end channel adjacent to the first plate located in a C-ring position. Accordingly, the influence of the end channel size on the ONB margin was investigated. Increasing the end channel dimension is important, as seen in Figure 2, where the red point indicates the End Channel Ratio (ECR: ratio of end channel to interior channel gap width) of the prior reference design after removal of fins. The ONB-limiting power (also referred to as the Limiting Safety System Setting (LSSS)) is 8.4 MW for nominal operation at 7 MW. Although increasing the ECR increases the ONB-limiting power, Figure 2 shows insufficient margin to ONB and thus modifying the ECR cannot be the only design modification considered. Setting the ECR to 88% leads to an improvement of 10% in the limiting ONB power, and is thus chosen for further evaluations. No significant impact on other parameters such as neutron flux, core lifetime, and shutdown margin has been observed by changing the ECR to 88%.

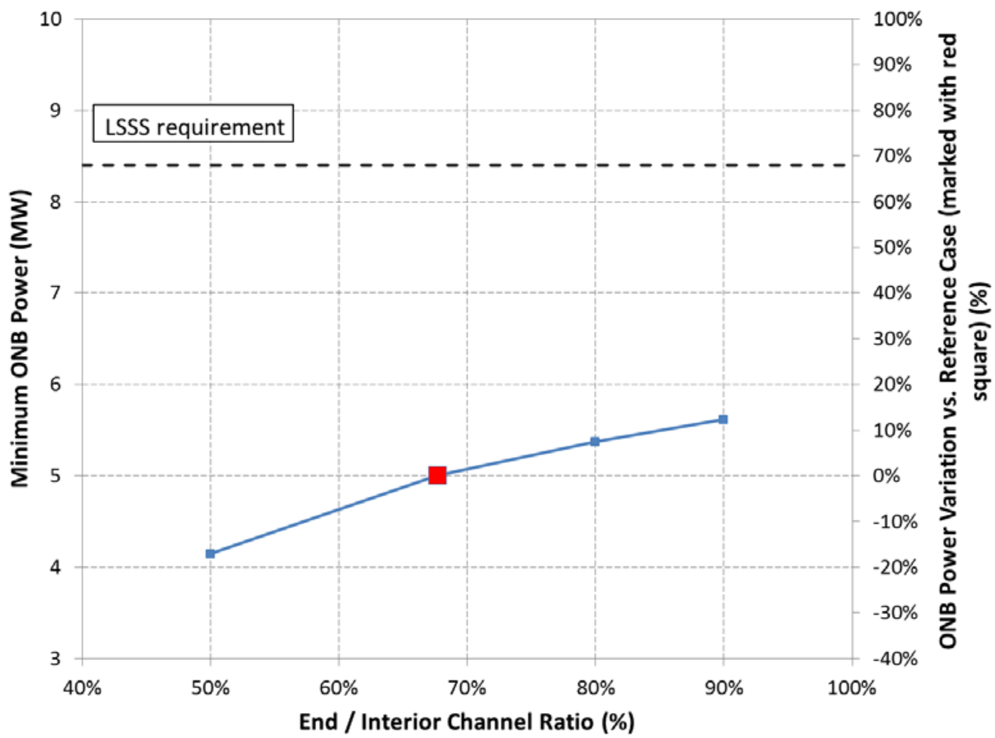

Figure 2. Effect of varying the end channel ratio on ONB-limiting power level.

Since the ONB-limiting power density occurs on the edges of the element, the impact of a fuel meat thickness reduction in the outer plates on both sides of the element was also considered. Four fuel meat reduction schemes were considered. In each case, the fuel thickness of 3 or 4 plates on each side of the element was reduced. For reasons of economy of fabrication it has been assumed as a constraint that there would be only three distinct fuel foil thicknesses in each element design, and the thickness of all the plates is kept constant. In other words, if a plate has a reduced fuel meat thickness, the cladding thickness increases accordingly to achieve the same plate thickness as all others. The selected combinations are shown in Table 2.

Table 2. Fuel Meat Thickness Reduction Schemes.

Combination	Fraction of nominal fuel meat thickness (%)			
	1st plates	2nd plates	3rd plates	4th plates
A	45	60	60	100
B	55	70	70	100
C	50	50	70	70
D	60	60	80	80

These selected fuel meat reduction combinations were studied with an assembly containing plates with 0.38 mm thick unfinned cladding, an ECR of 88%, and a core flow of 2200 gpm. While an LSSS flow rate of 2200 gpm represents an increase from the current flow rate of 1800 gpm, flow rates up to 2400 gpm have been successfully demonstrated during pre-operational tests with the current pumps.

The selected combinations decrease the edge power significantly. All designs are based on the 7 MW LEU power required to maintain experimental performance equivalent to 6 MW HEU operation. [4] Figure 3 shows an axial heat flux profile for the reference configuration (constant fuel meat thickness) as well as for an example of an unfinned configuration.

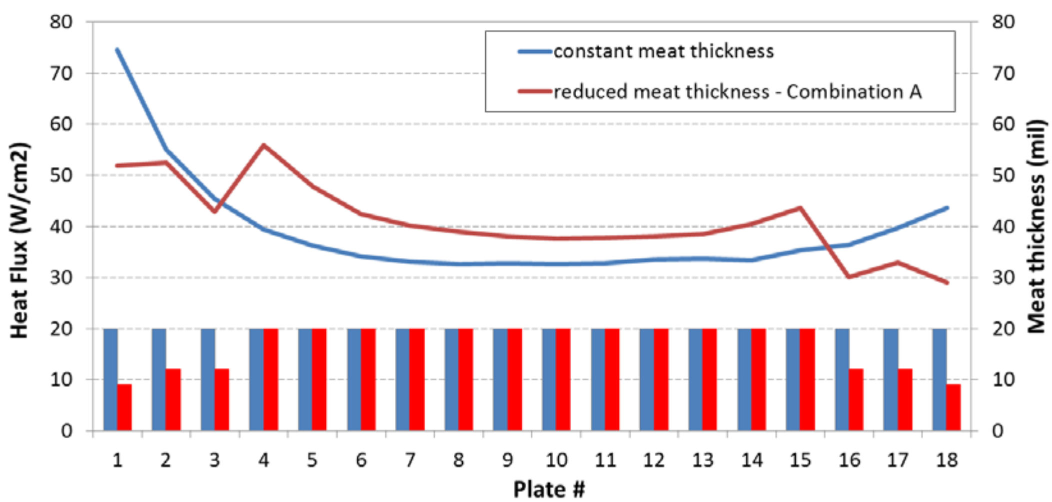

Figure 3. Heat flux profile for a configuration with constant fuel thickness and reduced fuel thickness combination A.

Of the sixteen design configurations analyzed, six of the combinations met the overall criteria of having adequate core lifetime, margin to ONB-limiting power level, and comparable performance at 7 MW to the reference 6 MW HEU core. These combinations are shown in Table 3, for both a 22-element core configuration with fresh fuel and a 24-element core in a representative quasi-equilibrium state (some fresh, some burned). Note that the element design configuration name denotes the number of plates in the element, the fuel thickness reduction combination A, B, C, or D as described earlier, and the thickness of the interior full-thickness fuel (in mils). For example, 18B25 contains 18 plates, fuel meat reduction configuration B, with interior plate nominal fuel meat thickness of 25 mils.

The design with the largest margin to onset of nucleate boiling for the 24 element core is a nineteen-plate element in configuration B, designated as 19B25, which contains unfinned plates with overall plate thicknesses of 1.24 mm. This design has been selected as the new LEU fuel design for the MITR. Fuel and cladding thickness on each side of the fuel are given in Table 4 for the various configurations studied.

Table 3. Summary of six unfinned fuel designs meeting performance and ONB margin criteria vs. the finned reference design.

LEU Design Parameter	Reference Design	18B25	18A30	19D20	19A25	19B25	19B30
Geometry & uranium mass							
^{235}U mass per element (g)	831	910	1058	767	940	968	1169
Number of plates / assembly	18	18	18	19	19	19	19
Finned Plate	yes	no	no	no	no	no	no
Plate thickness (mm)	1.02	1.24	1.37	1.12	1.24	1.24	1.37
Fuel in 1st plates (mm)	0.51	0.33	0.33	0.30	0.28	0.33	0.41
Fuel in 2nd plates (mm)		0.43	0.46	0.30	0.38	0.43	0.53
Fuel in 3rd plates (mm)		0.43	0.46	0.41	0.38	0.43	0.53
Fuel in 4th plates (mm)		0.64	0.76	0.41	0.64	0.64	0.76
Fuel in all other plates (mm)		0.64	0.76	0.51	0.64	0.64	0.76
Limiting power to ONB for flow = 2200gpm (MW)*							
22 element fresh core	11.75	9.12	9.54	9.32	9.98	9.28	8.84
24 element fuel management	9.17	8.59	9.01	9.10	9.09	9.67	9.31

* Power to ONB >8.4 MW is required based on 20% margin to 7 MW LEU operating power.

Table 4. Plate dimensions for the new 19-plate LEU fuel design

	Middle plates (4-16)	Plates 2,3,17 and 18	End plates (1 and 19)
Fuel Thickness (mm)	0.64	0.43	0.33
Clad Thickness (mm)	0.30	0.41	0.46

4. Steady State and Accident Analyses of Revised Design

The revised 19- plate fuel design was analyzed through a representative core series with MCODE to establish fuel cycle and for generation of power profiles. Three models were used; a 22-element fresh core, a middle-of-life 24-element core and an end-of-life 24-element core. The power profiles were then analyzed in the thermal-hydraulics codes STAT7 and RELAP5 to determine temperature profiles and margin to ONB. Steady state analyses show that the minimum margin to ONB occured in an edge stripe of an interior plate of a fresh element at the beginning-of-life with the particular representative fuel management modeled. [4] In transient RELAP-5 analysis, results show that, despite lower fuel loading, peak heat fluxes and peak temperatures still occur in the end plates. For design 19B25, the highest peak heat fluxes occurred in the fresh core. Thus, the fresh core model was used for subsequent accident analyses for conservatism, where other effects of the depleted cores were incorporated as needed.

A loss-of-flow transient was studied using the RELAP5 model of the fresh core. [5] The transient was assumed to begin from the LSSS minimum pump flow of 2200 gallons/minute, with a scram delay of one second resulting from detection and signal processing delays. The RELAP5 input parameters are shown in Figure 4. Both interior and end channels are modelled explicitly.

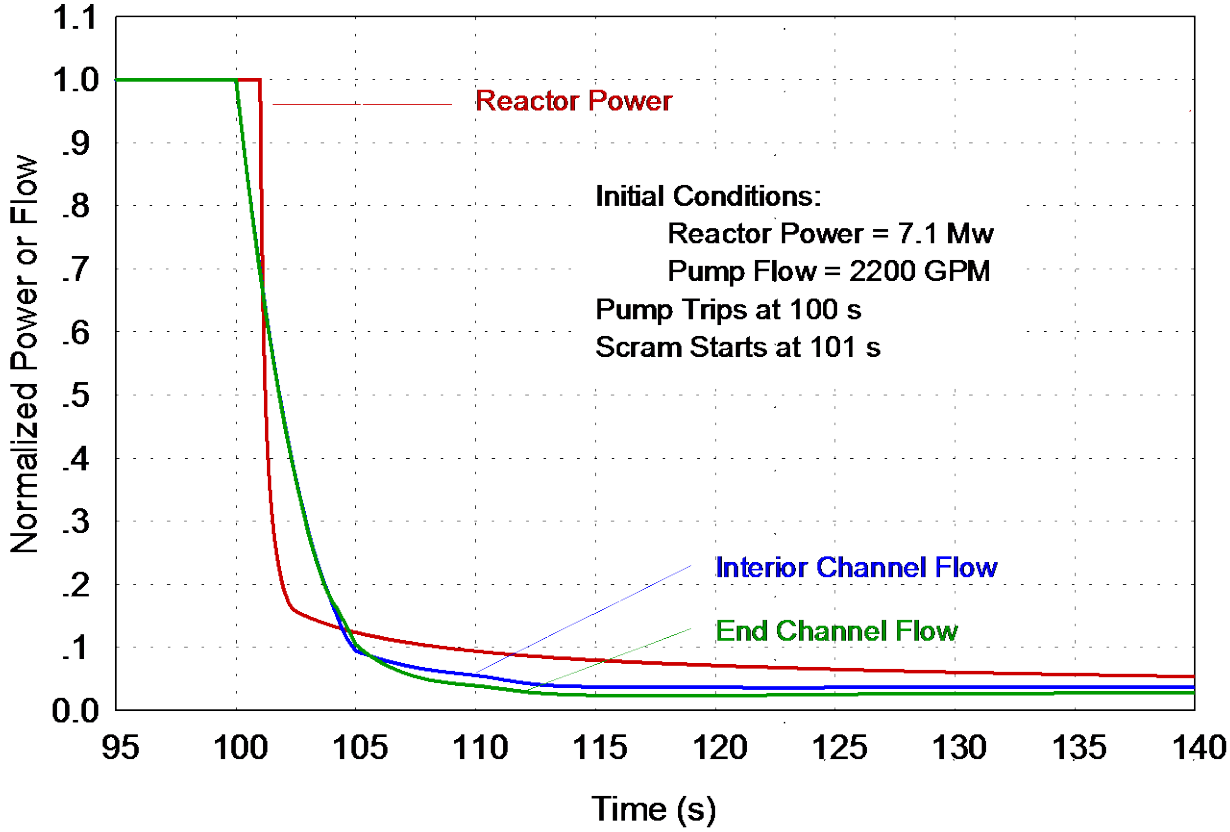

Figure 4. Loss-of-Flow transient conditions

Results from the transient are shown in Figure 5. This shows that all plate surfaces remain below saturation for the duration of the transient, even during the momentary rise at the beginning of the transient.

In addition to the nominal case, additional loss-of-flow analyses were performed using fuel thermal conductivity reduced by 20%, as would be the bounding case with fully burned fuel due to chemical and structural changes in the fuel meat and oxidation on the cladding surface. These results are shown in Table 5. Though there was no vapour production in any case analysed, at an initial LSSS power of 8.4 MW there was some sub-cooled boiling. It should be noted, however, that this case is extremely conservative, using a fresh fuel neutronics model with spent fuel conductivities.

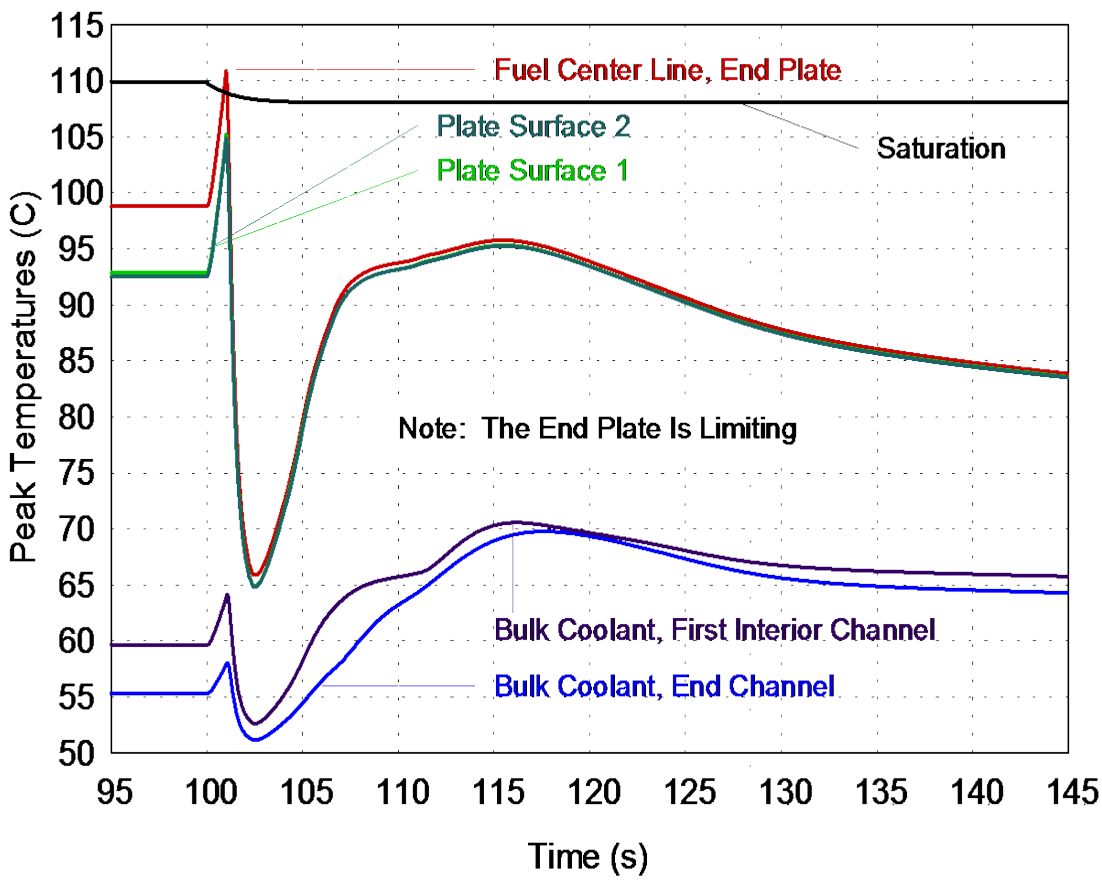

Figure 5. RELAP5 results from loss-of-flow transient

Table 5. Loss of flow results with reduced fuel conductivity

Power (MW)	Fuel Conductivity	Initial Peak Temperatures (°C)		Transient Peak Temperatures (°C)	
		Fuel Centerline	Surface	Fuel Centerline	Surface
7.1	nominal	110.4	105.2	95.8	95.3
7.1	20% reduced	110.9	105.2	95.8	95.3
7.7	20% reduced	115.8	109.7	98.5	98.0
8.4	20% reduced	121.0	114.3	101.5	101.0

Temperature differences across a fuel plate were calculated using the approximate peak heat flux of 60 W/cm^2, a nominal fuel thermal conductivity of 16.3 W/m°C, and an oxide layer with a conductivity of 2.25 W/m°C. The differences with variation of power, fuel conductivity, and oxide layer thickness are shown in Table 6. These results show that, even under worst case conductivity conditions, the temperature changes are very modest.

Table 6. Impact of fuel conductivity and oxide layer thickness

	Thickness (mm)	Conductivity	ΔT (°C)
Fuel	0.635	nominal	5.9
Fuel	0.635	50%	11.8
Fuel	0.331	nominal	3.1
Fuel	0.331	50%	6.2
Oxide	0.051	nominal	13.5

Analysis of reactivity insertion accidents has been initiated using the thermal-hydraulics code PARET-ANL. The HEU core design basis accident for a reactivity insertion of 1.8 % ΔK/K over 0.5 s has been made for the revised LEU design. Results, as seen in Figure 6, show that the cladding surface temperature reaches 100°C only momentarily, demonstrating an adequate safety margin.

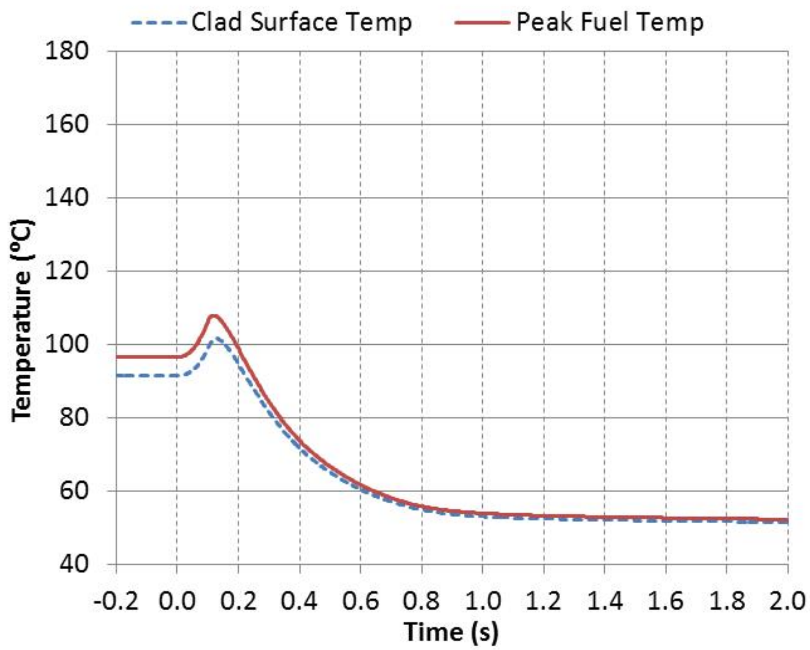

Figure 6. PARET results of a reactivity insertion of 1.8%ΔK/K over 0.5 s.

5. Conclusions

A revised LEU fuel design has been proposed for the MIT Reactor. An optimization study of unfinned fuel plates has resulted in the design of a 19-plate fuel assembly with reduced fuel thicknesses in the outer three plates. This design, combined with a primary coolant flow increase of 20%, has been shown to significantly reduce power peaking, and has an adequate margin to the Onset of Nucleate Boiling.

Loss-of-flow analyses of the revised design show adequate heat removal, even with reduced fuel conductivity and oxide buildup. Reactivity transient analysis also shows that the revised LEU design has adequate ONB margin in the design basis accident event. Although further accident analyses are in progress, this revised design is anticipated to meet the safety criteria of the MIT Reactor and the operational and experimental needs of the Laboratory.

Acknowledgments

This work was supported by the U.S. Department of Energy, National Nuclear Security Administration Office of Global Threat Reduction.

References

[1] T. Newton, E. Pilat and M. Kazimi, "Development of a Low-Enriched-Uranium Core for the MIT Reactor," Nuclear Science and Engineering, 157: p. 264-279, (2007).

[2] T. Newton, L-W Hu, G. E. Kohse, E. E. Pilat, B. Forget, P. Romano, Y-C Ko, S. Wong, Y. Wang, B. Dionne, J. Thomas and A. Olson, "Completion of Feasibility Studies on Using LEU Fuel in the MIT Reactor," Proc. RERTR Conference, Beijing, China, November, 2009.

[3] A. Bergeron, E. Wilson, G. Yesilyurt, F. "Low Enriched Uranium Core Design for the MITR with Un-finned 12 mil-thick Clad UMo Monolithic Fuel," ANL/GTRI/TM-13-15, Argonne National Laboratory, November, 2013.

[4] E. Wilson, A. Bergeron, G. Yesilyurt, F. Dunn, J. Stevens, L. Hu, and T. Newton, " Low Enrichment Uranium Fuel Element Designs with Monolithic U-10Mo Fuel and Un-finned Cladding for the MIT Research Reactor," Proc. of the RRFM Conference, Ljubljana, Slovenia, April, 2014.

[5] S. Don, "Loss-of-Flow Analysis of an Unfinned, Graded Fuel Meat, LEU Monolithic U-10Mo Fuel Design in Support of the MITR-II Fuel Conversion," M.S. Thesis, Massachusetts Institute of Technology, September, 2014.