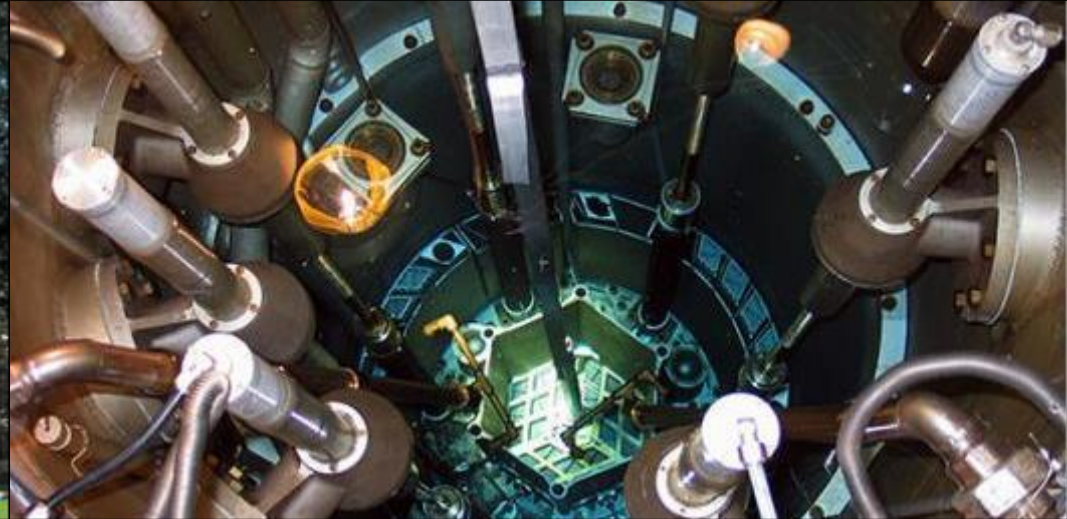




# MIT NUCLEAR REACTOR LABORATORY

*an MIT Interdepartmental Center*



## Development of MITR Simulator Digital Twin for LEU Conversion Planning

Lin-wen Hu\*, Sara Hauptman, MIT Nuclear Reactor Laboratory

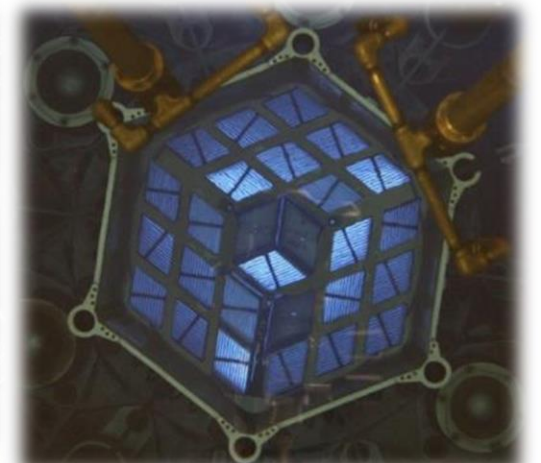
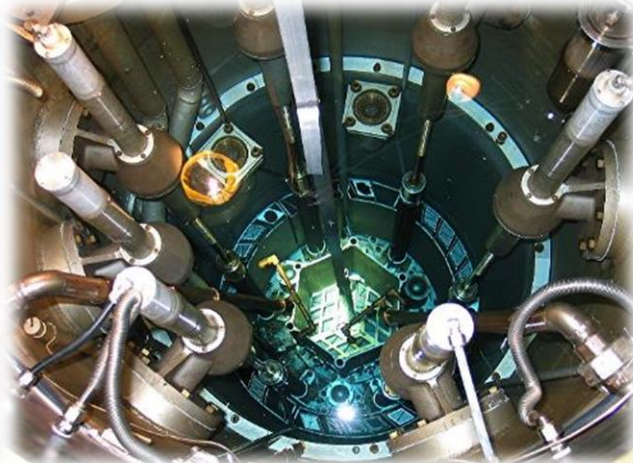
Sero Yang, Kyle Anderson, Erik Wilson, Argonne National Laboratory

TRTR/IGORR Meeting, University of Maryland, 6/20/2023

# MIT Nuclear Reactor Laboratory



- MIT-NRL is an interdepartmental laboratory with missions in nuclear technology applications, neutron science research, and training/education.
- Primary facility is MIT Reactor (MITR), a multi-purpose research reactor.
- Partner facility of DOE's *Nuclear Science User Facilities (NSUF)*.
- Constructed in 1958 (MITR-I), upgraded in 1975 (MITR-II).
- Upgraded from 5 MW to **6 MW<sub>th</sub>** in 2010 (2<sup>nd</sup> largest university reactor in US).
- Core power density similar to an LWR. *Operates 24/7, 10-week cycles.*
- Tank-type, light water-cooled and moderated, D<sub>2</sub>O and graphite reflector.



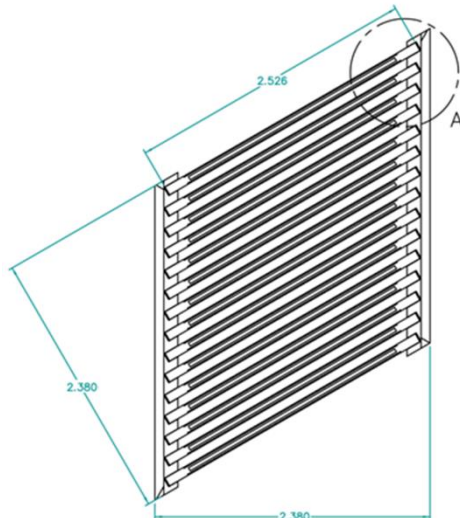


# LEU Fuel Conversion Program

- DOE National Nuclear Security Administration (NNSA) non-proliferation program aims to eliminate domestic and international civilian use of HEU.
- Objectives are to convert to LEU (<20% U-235) fuel by maintaining core housing structure, fuel element outer geometry, neutron flux, and fuel cycle performance of the current 6 MW HEU core.
- It has been demonstrated that a new LEU fuel design with 7 MW, higher flow operation will maintain performance of 6 MW HEU core.
- The fuel matrix, high-density monolithic U-10Mo, is being tested for 4 U.S. High Performance Research Reactors (ATR, NBSR, MURR, MITR), HFIR will utilize high-density silicide fuel.
- MITR LEU Fuel element Design Demonstration Element (DDE) irradiation will be performed at Belgium BR-2 test reactor.
- High-density U-10Mo LEU fuel is currently scheduled to be qualified by 2028, and enable MITR conversion in 2031.

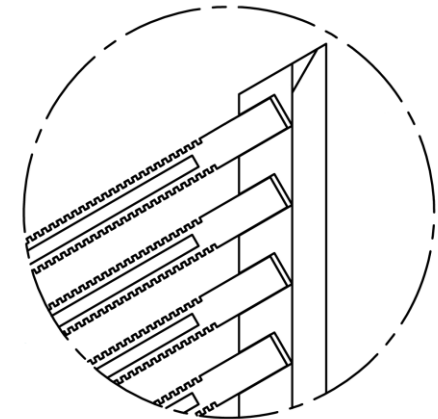
***MITR will be the first High-Performance Research Reactor worldwide to be converted using high-density U-10Mo LEU.***

# HEU and LEU Fuel Element Design

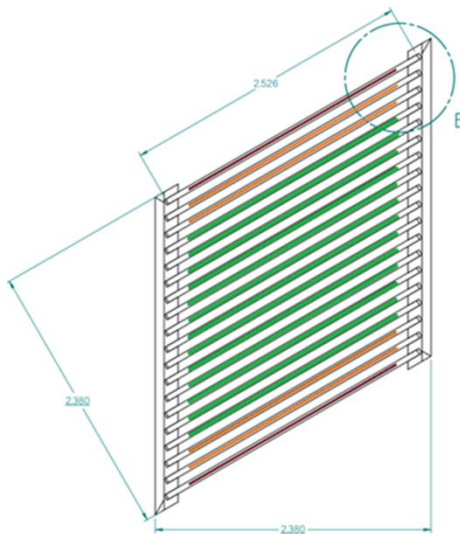


## Current HEU Design

- 15-Plate U-Al<sub>x</sub>
- Finned plates
- Single fuel thickness

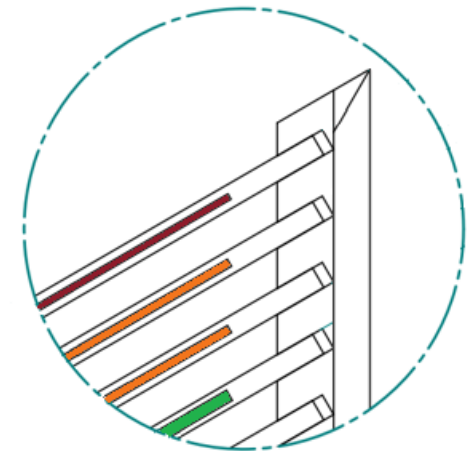


DETAIL A



## LEU "FYT" Element Design

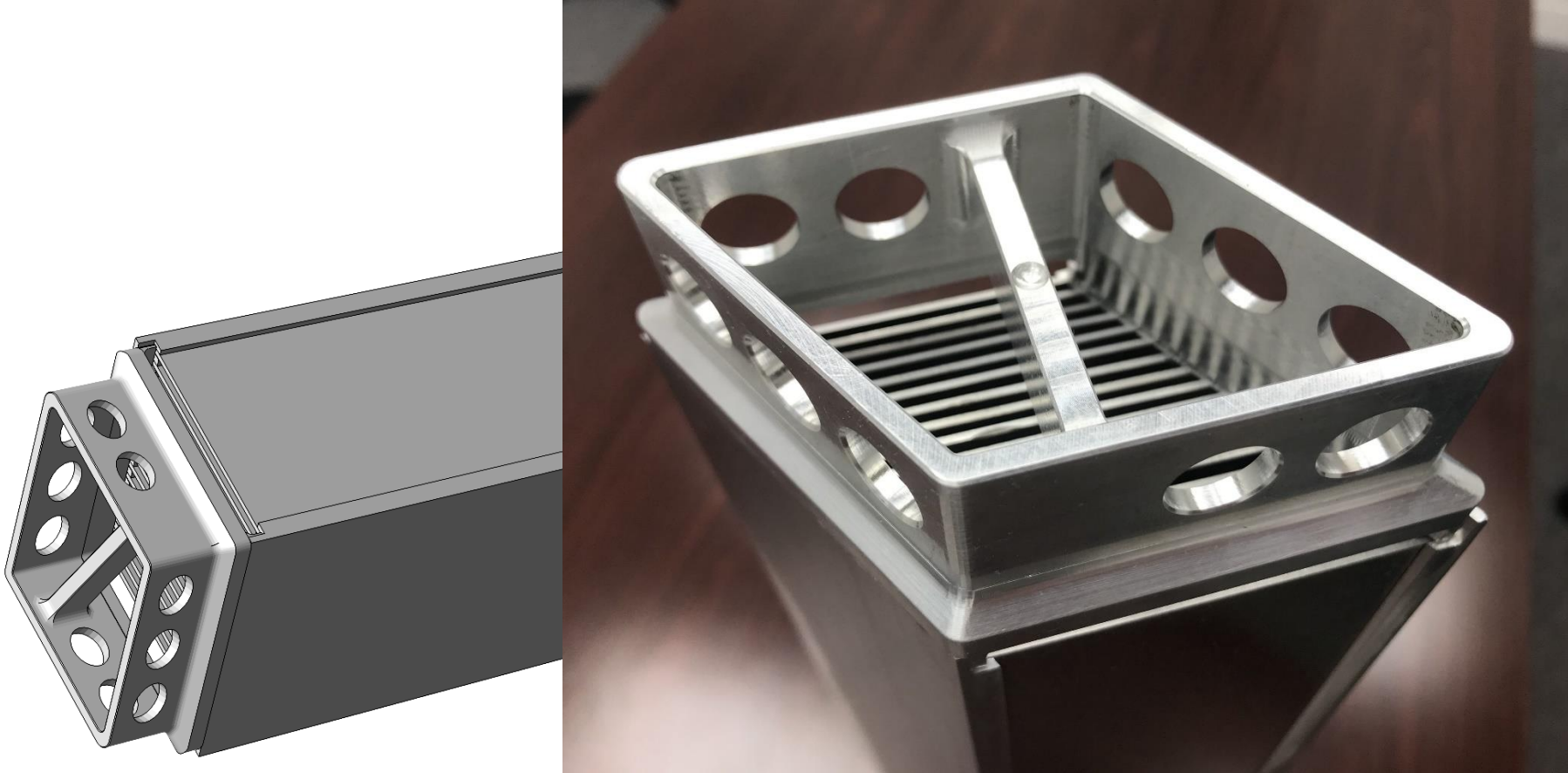
- 19-Plate U-10Mo
- Un-finned plates
- Three fuel thicknesses



DETAIL B

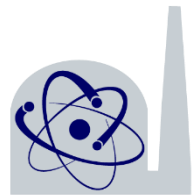


# Detailed LEU Fuel Element Design



- ANL and MITR staff completed engineering drawings and BWXT review for LEU fuel element. A full-size dummy element is fabricated at MIT.

# LEU Fuel and Core Design



	HEU (UAl <sub>x</sub> )	LEU – FYT element (U-10Mo)
Enrichment	93.15%	19.75%
Operating Power	6 MW	7 MW
Nominal Flow Rate	2000 gpm	2400 gpm
Plates per Element	15	19
<b>Fuel Density (gU/cm<sup>3</sup>)</b>	<b>1.54</b>	<b>15.3</b>
U-235 per element (g)	508	968
Fuel Core Thickness	0.76 mm	0.64 mm (F-plate) 0.43 mm (Y-plate) 0.33 mm (T-plate)
Zr Interlayer (2x)	-	0.03 mm
AA6061 Cladding Thickness	0.38 mm	0.28 mm (F-plate) 0.38 mm (Y-plate) 0.43 mm (T-plate)
Plate Thickness	1.52 mm	1.24 mm
Fins on Cladding	Yes	No

# LEU Conversion Accomplishments



- ✓ U-10Mo LEU Fuel Design (19B25 or **FYT** fuel element)
- ✓ Conversion Impacts on In-core Experiments
- ✓ Preliminary Safety Analysis Report (PSAR)
  - ✓ PSAR submission to NRC
    - Response to PSAR RAI
- ❑ LEU Core Start-up and Transition Planning
  - ✓ All LEU transitional cores analysis to equilibrium
  - ✓ Fresh LEU Core Start-up Plan (report issued)
- ❑ Development of LEU Fuel Specifications
  - ✓ **LEU fuel fabrication tolerances impact assessment (completed Phase I study)**
  - ✓ **MITR LEU fuel specifications and engineering drawings issued (Oct. 2021)**
- ❑ **Facility modifications (on-going)**
  - ✓ Fresh and spent fuel shipments (ANL report completed)
- ❑ **Mixed HEU-LEU cores conversion study (feasibility study completed)**





# Major Equipment Procurement



Plate-and-Frame heat exchanger



Primary and secondary coolant pumps, motors, and VFD control



# Fresh/Spent Fuel Storage Racks



Three 5x5 fuel storage racks were fabricated by MIT central machine shop. The rack design was modified based on the HEU spent fuel storage rack design. One fuel rack will be used for fresh LEU fuel elements.

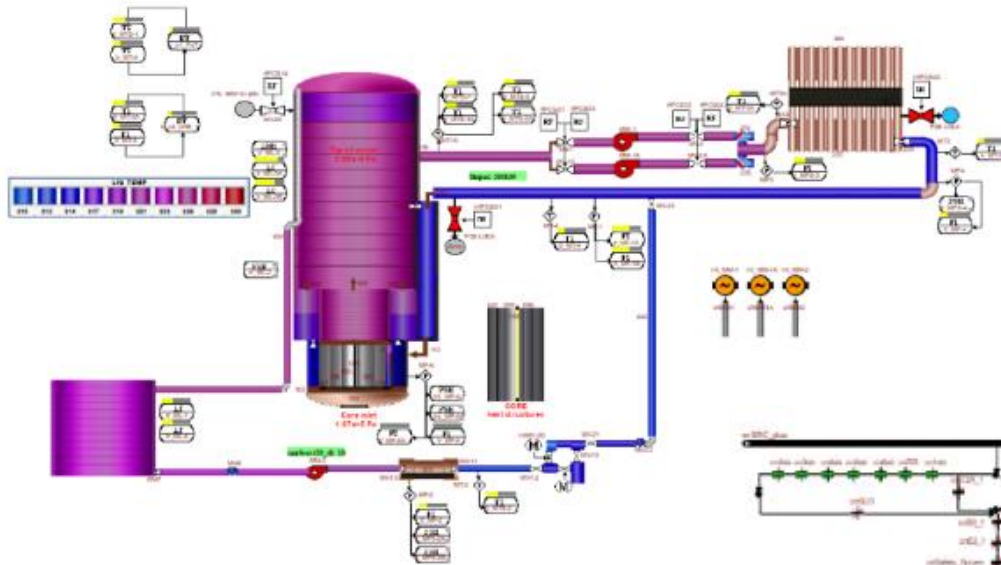
# MITR Simulator Overview



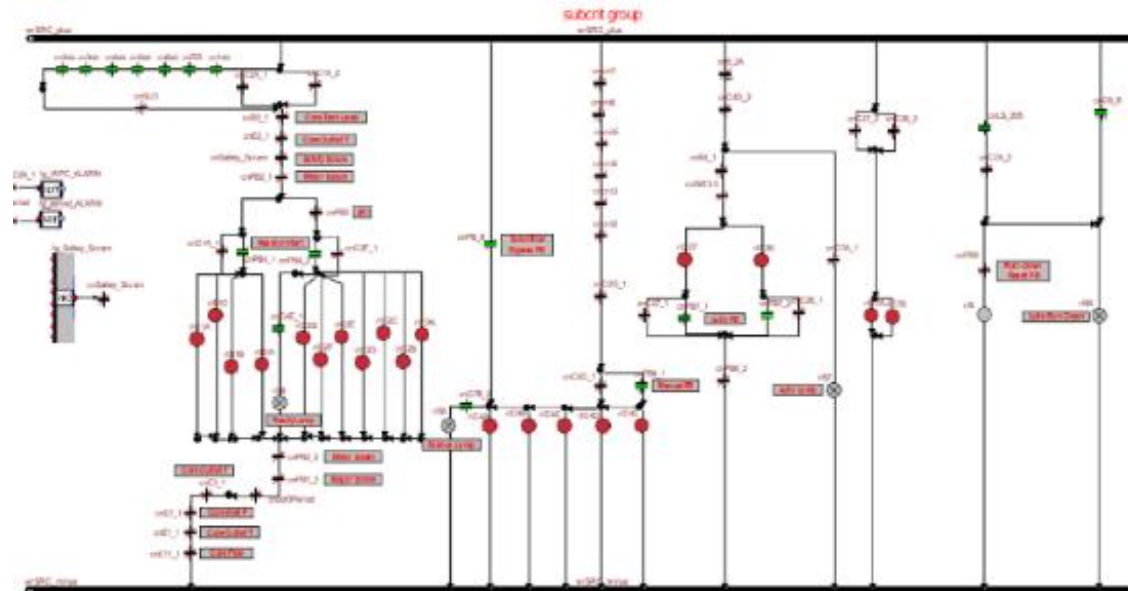
- MITR simulator was developed with demonstrated commercial-grade software with GUI that incorporates:
  - Fuel and Core model (currently point kinetics)
  - Primary and secondary coolant systems including pumps, HX
  - Reactor instrumentation and control logics and circuitry
- Selected vendor is WS-Corp (WSC), 3KEYMaster software suite with RELAP5 computer code
- MITR RELAP5 model that has been validated and verified by ANL staff.
- The MITR Simulator can expand hands-on training for students and operators, classroom instructions, public outreach, and
  - evaluate system response from component modifications (e.g., LEU fuel, higher flow rate/power, new pumps/HX, instrumentations)
  - use as a test bed for innovative control strategies for micro-reactors, e.g., operator aide, automatic control demonstration.

**MITR simulator is the first replica simulator and “Digital Twin” of a University Research Reactor**

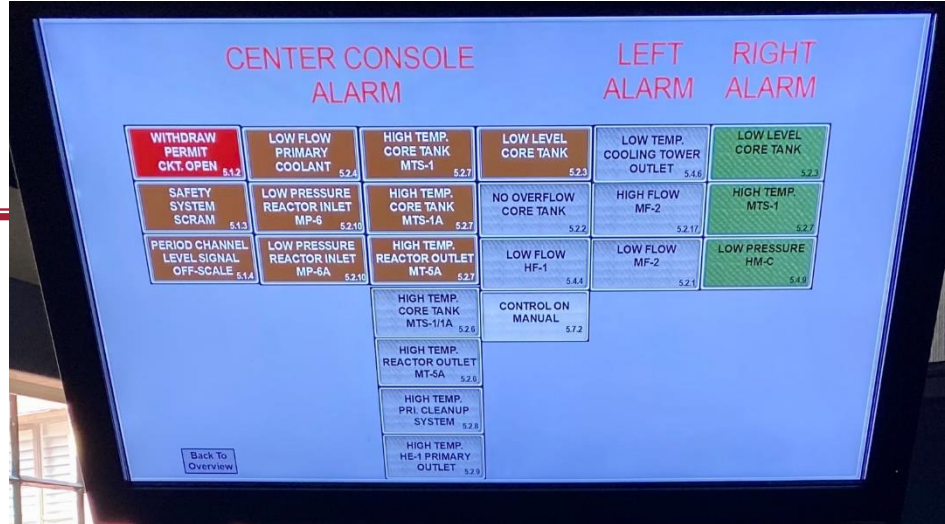
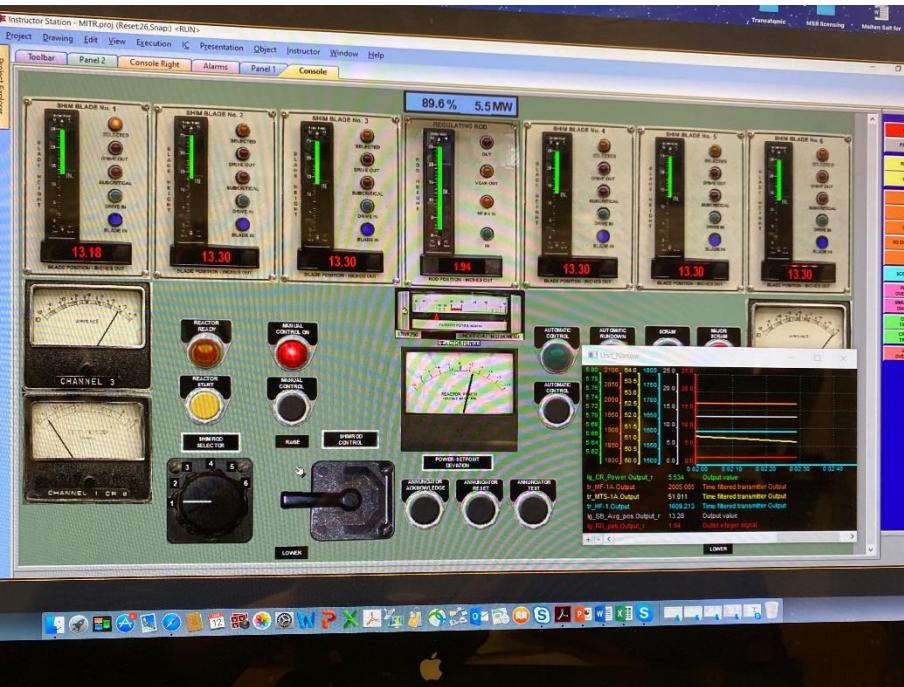
# Industry Standard, Validated Software



**MITR RELAP5 model  
incorporated in 3KEYMaster  
software suite (left) and  
instrumentation control logic  
(right)**







# MITR LEU Simulator

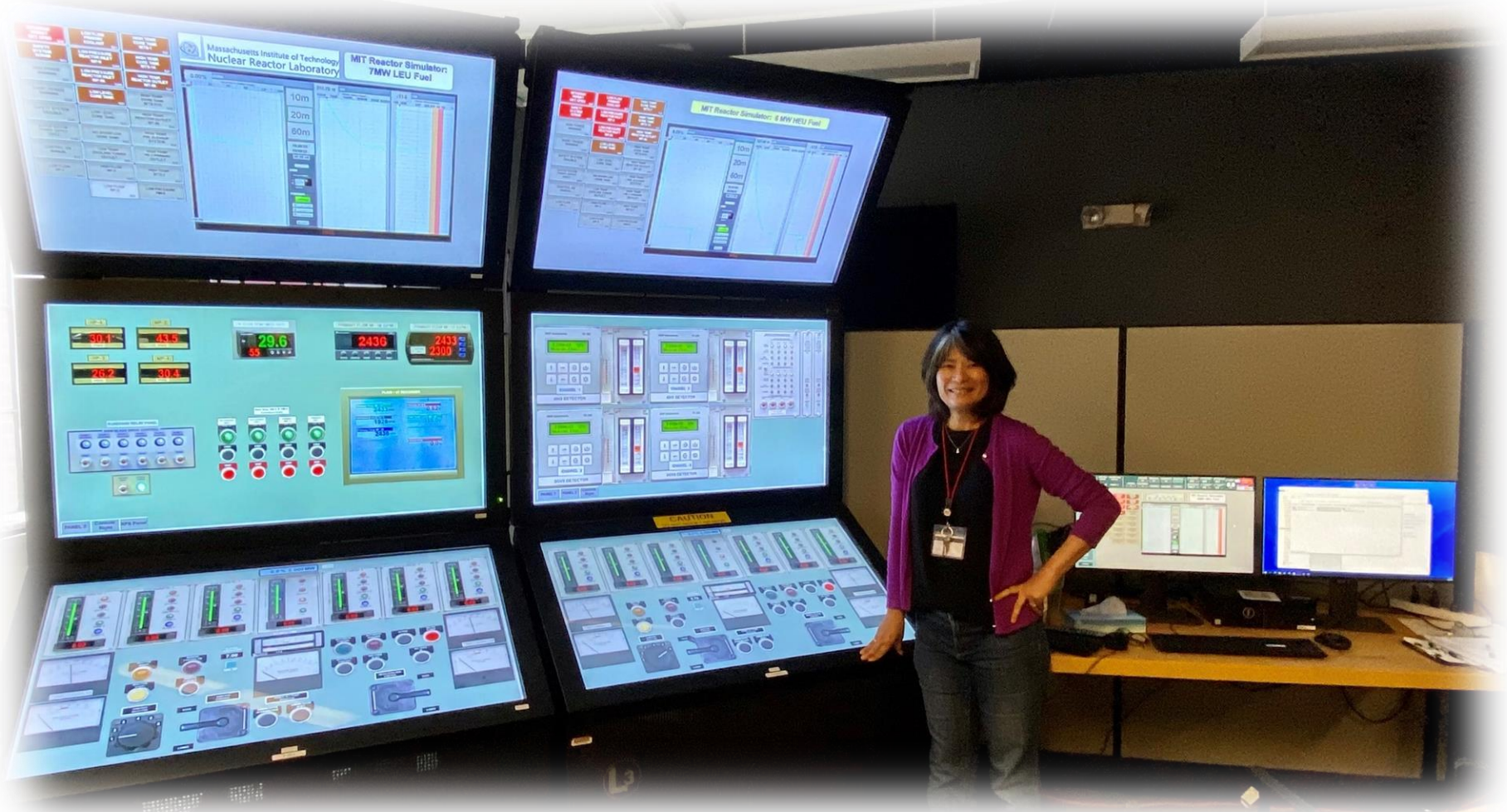


- MITR LEU Simulator was funded by the DOE-NNSA Reactor Conversion program. The core model incorporates MITR LEU fuel element design and all-fresh element core configuration #1. The LEU simulator completed acceptance testing and was installed in June 2022.
- The goal for the MITR LEU Simulator is to provide operator training in preparation of fuel conversion.
- Adopting MITR Simulator as part of operator training and requalification has recently started at the MITR due to extended outage\*.
- Future work includes incorporation of new pump curves, instrumentation response etc. Other R&D opportunities exist such as supporting NRC licensing review for LEU core safety analysis report.

\* *S. Hauptman, L. Hu, "Application of MITR Simulator for licensed operator requalification and training"*



# MITR HEU and LEU Simulators



*MITR HEU and LEU Simulators running on two glasstop modules*



# Licensed Operator Training Experience



- Review of feedback mechanisms
- Interaction between reactor systems and core physics
- Demonstration of transient scenarios that cannot be practiced on physical reactor



*Annual Reactor Physics Requalification training, March 2023*

- Demonstration of reactivity transients that are prevented by procedure control:
  - Cold slug accident by restarting a stopped secondary pump
    - Overcools primary, inserts positive reactivity, trips reactor off auto control
  - Xenon decay/burnout as reactivity insertion from precluded state
    - Startup procedure calls for “critical” at 50 kW on a +50sec period
    - Sitting with all absorbers full out leads to power increase, scram at 6.5 MW, shortest period 165 sec

# Summary

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- Significant progress has been made in LEU fuel design/specifications, safety analysis, startup plan, facility modifications, and fuel development for the MITR LEU fuel conversion.
- The MITR LEU simulator is developed and models the LEU core with higher flow and upgraded heat exchanger to support engineering analysis and operator training.
- Future work includes incorporation of new pump curves, new instrumentation response etc. Other R&D opportunities using the MITR LEU simulator will be evaluated such as supporting NRC licensing review for LEU core safety analysis report.



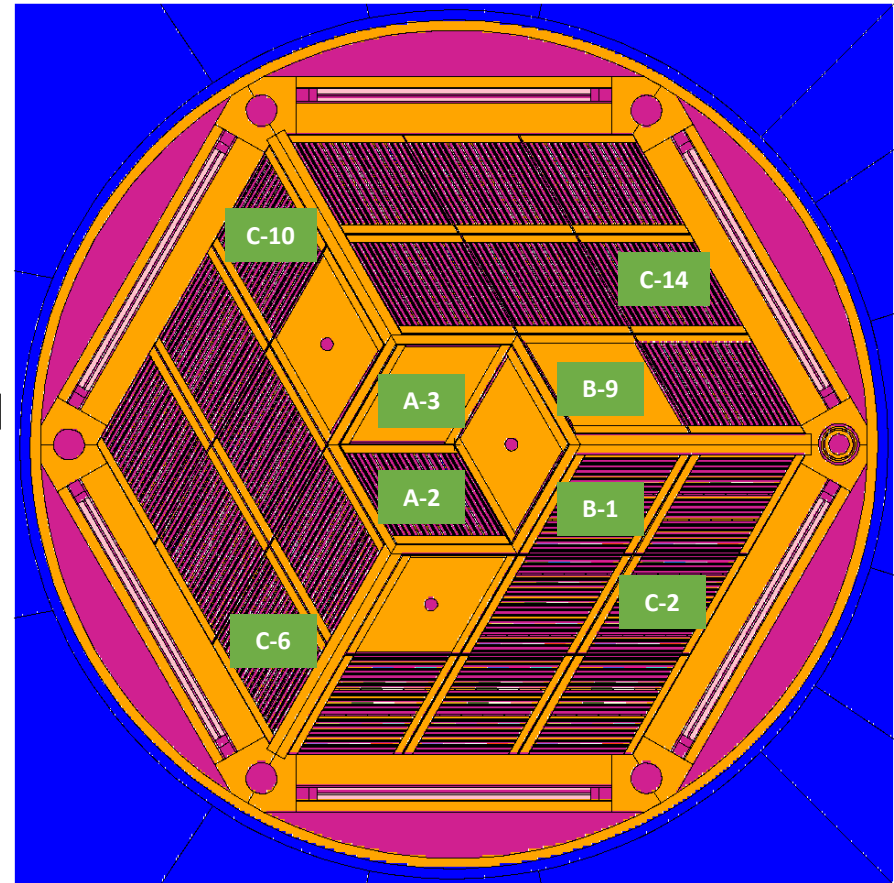
**Many thanks to  
NNSA/M3, ANL and MIT collaborators for  
funding and technical support**



# Startup Plan for Fresh LEU Core



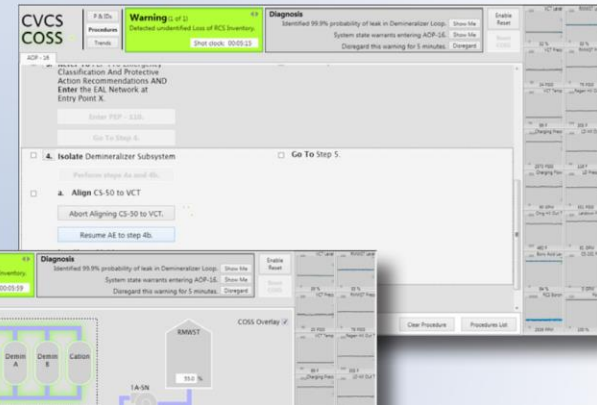
- LEU Core #1 - 22 Fresh LEU Fuel Elements
- Fuel Loading Sequence
- Inverse Count Rate (1/M) Plot
- Approach to Criticality
- Shim blades and reg rod worths, and other reactor physics measurements
- Primary coolant system pre-operational tests at higher flow 2400 gpm
- Stepwise power increase to 7 MW
- Natural convection cooling tests



# INL Human System Simulation Laboratory



*HSSL allows the safe testing of new technologies prior to implementation in the real world*









# MIT Reactor Control Room





# Glass-top Simulator Modules



- 3 Glass-top simulator modules, used for operator training, were transferred to MIT in June 2019 from Pilgrim nuclear power plant after several months of planning. This is a generous donation from Entergy to help expand education training and public outreach at MIT-NRL.
- MITR simulator development started in late 2019 by WSC. HEU model completed acceptance test in July 2021.



# Digital Twins of Nuclear Systems



- Digital Twin (DT) is a virtual/digital representation of a complex component or system.
- Nuclear DT is a new framework being considered to support engineering designs, safety analysis, operator training, and regulatory review/approval.
- DT enabling technology may include capabilities include
  - Information
  - Communication
  - Integration
  - Analysis
  - Control

