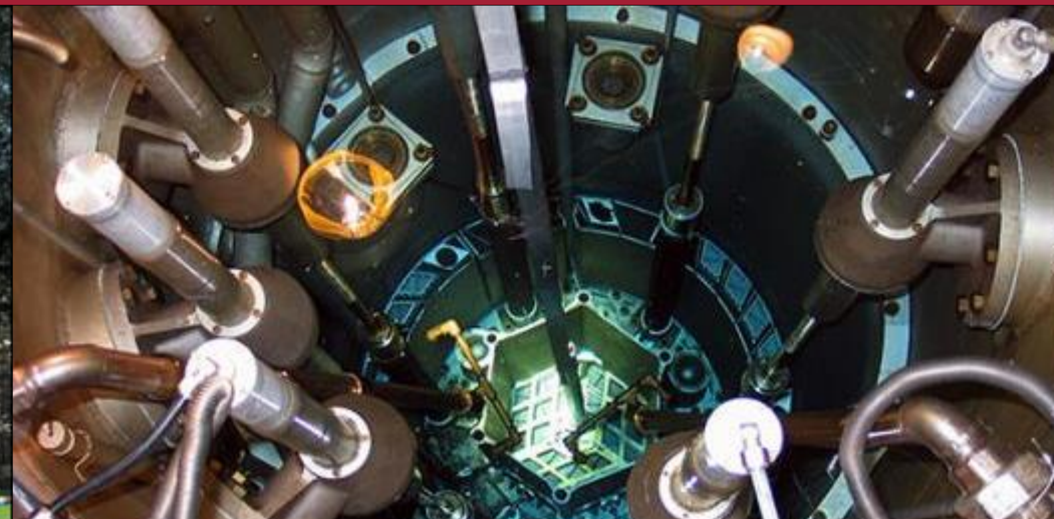
MIT NUCLEAR REACTOR LABORATORY

an MIT Interdepartmental Center



Development of MITR Simulator Digital Twin for LEU Conversion Planning

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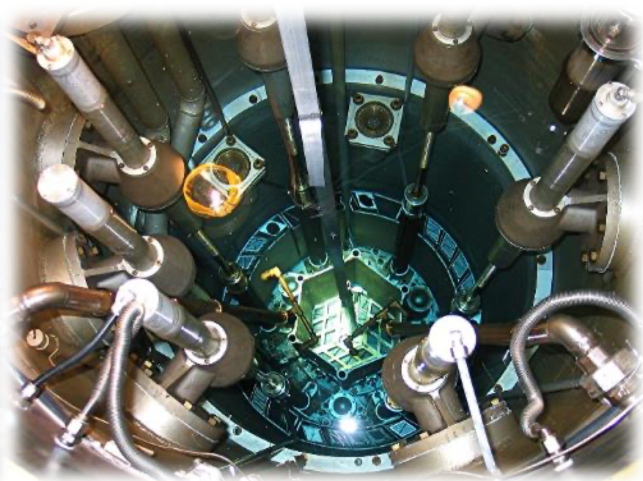
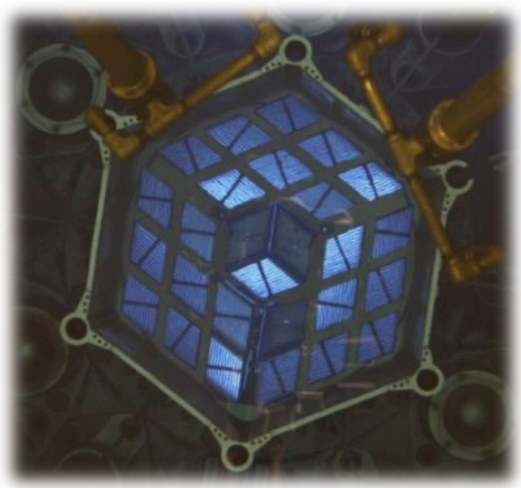
TRTR/IGORR Meeting, University of Maryland, 6/20/2023

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).
- Uprated from 5 MW to $6\ MW_{th}$ in 2010 (2^{nd} 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_2O and graphite reflector.

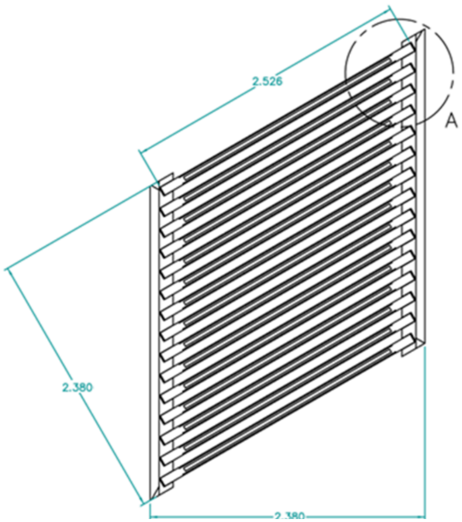




LEU Fuel Conversion Program

- 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.

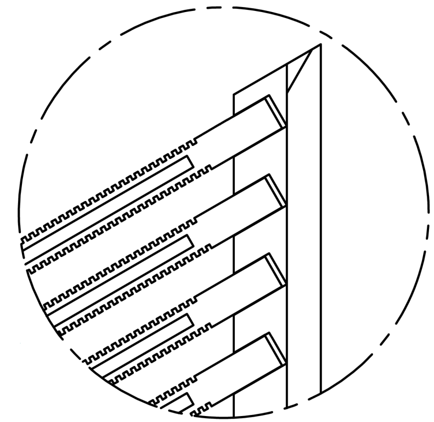
MITR will be the first High-Performance Research Reactor worldwide to be converted using high-density U-10Mo LEU.

HEU and LEU Fuel Element Design

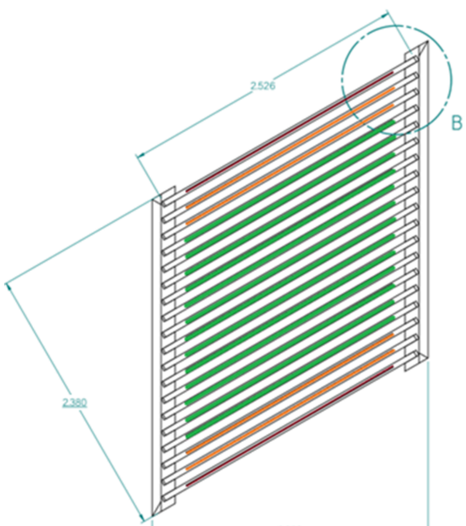


Current HEU Design

- 15-Plate U-Al_x
- Finned plates
- Single fuel thickness

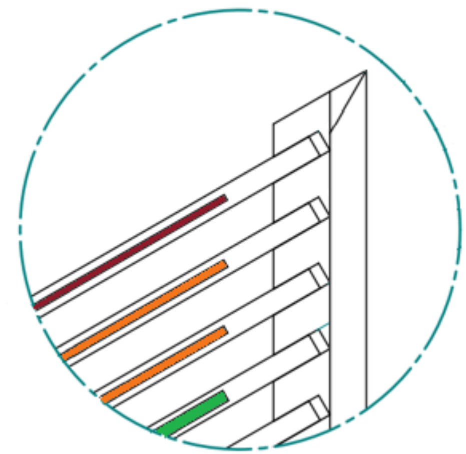


DETAIL A



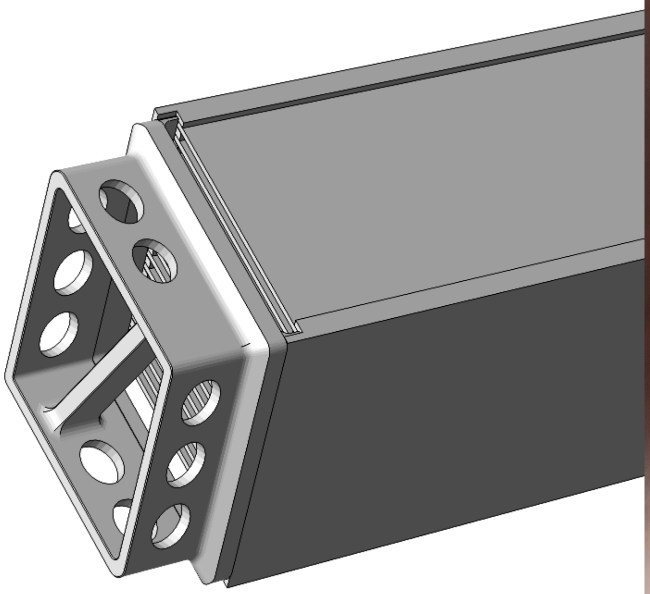
LEU "FYT" Element Design

- 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_x)	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
Fuel Density (gU/cm^3)	**1.54**	**15.3**
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

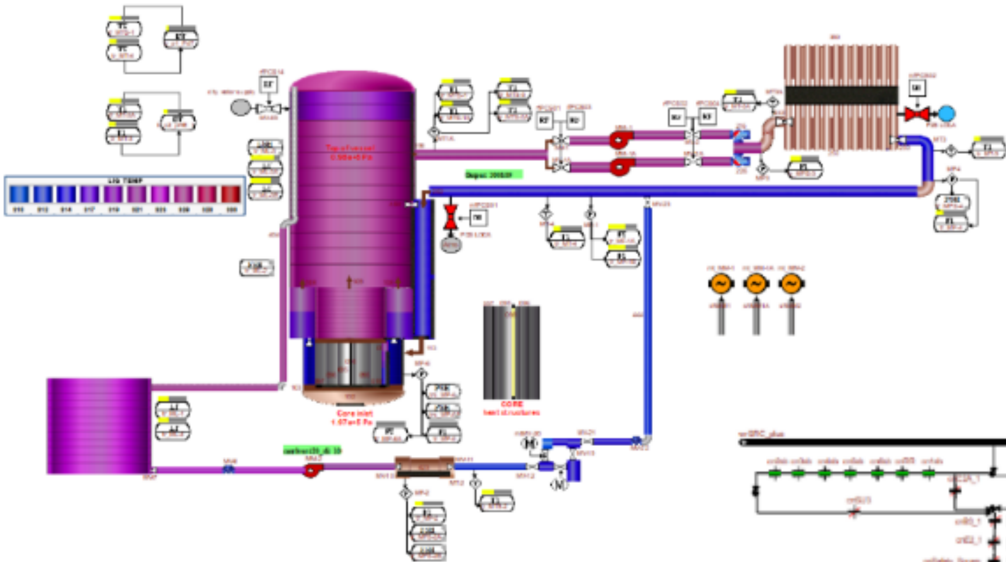
Three 5x5 fuel storage racks were fabricated by MIT central machine shop. The rack design was modified based on the HEU spent fuel storage rack design. One fuel rack will be used for fresh LEU fuel elements.

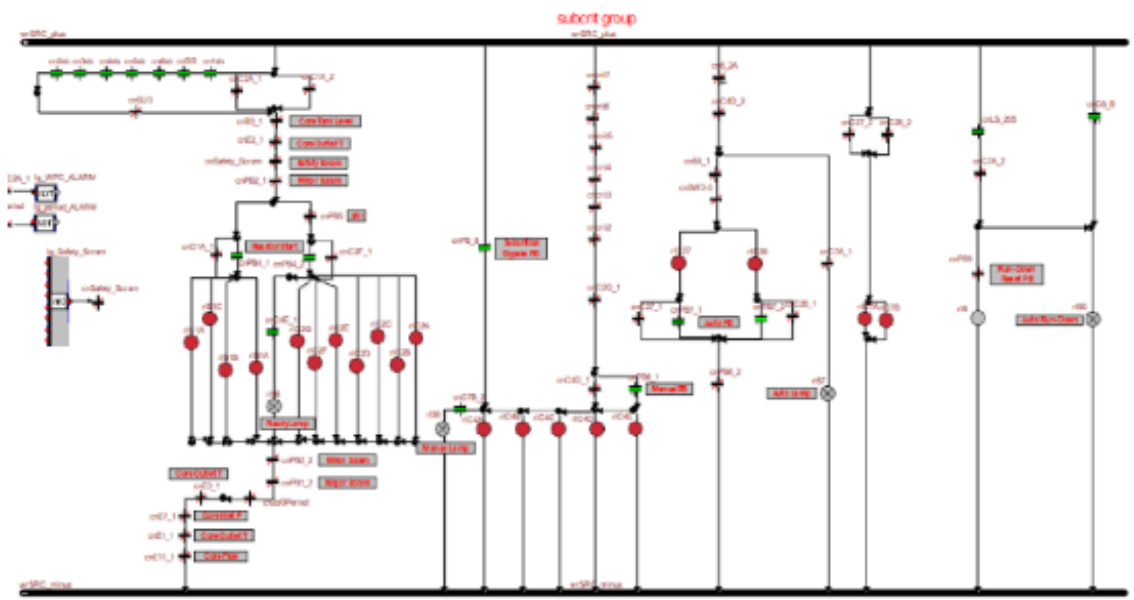
MITR Simulator Overview

- 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.

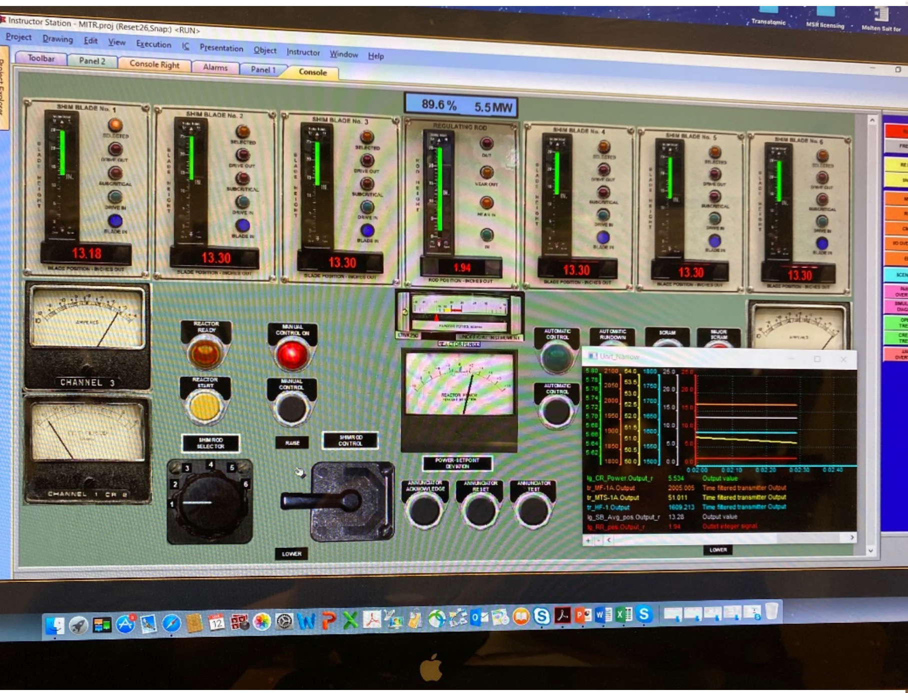
MITR simulator is the first replica simulator and “Digital Twin” of a University Research Reactor

Industry Standard, Validated Software





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


Project Drawing Edit View Execution IC Presentation Object Instructor Window Help
Toolbar
Panel 2
Console Right
Alarms
Panel 1
Console
89.6 % 5.5 MW
13.18
13.30
13.30
1.94
13.30
13.30
13.30
CHANNEL 3

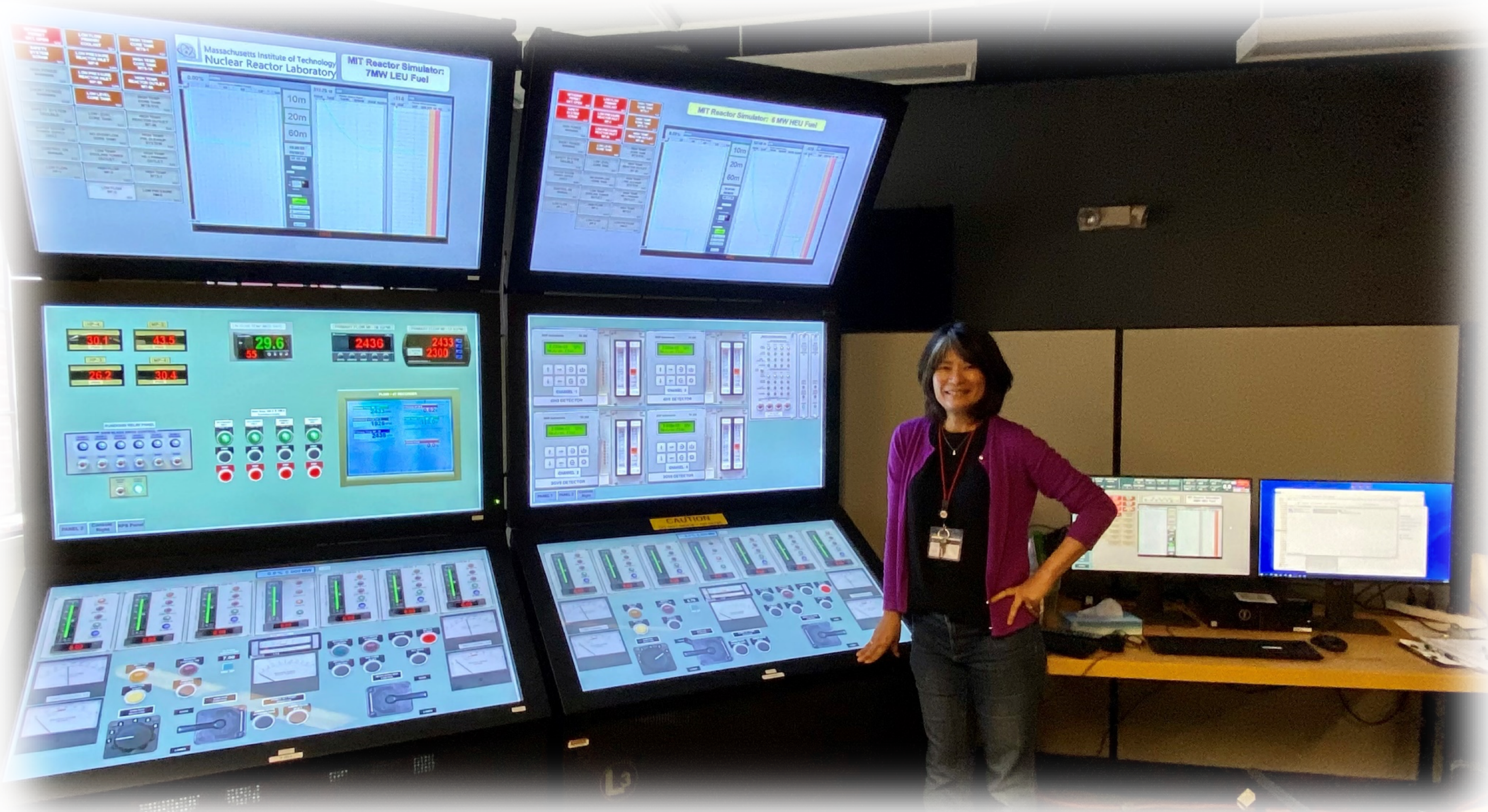

CENTER CONSOLE ALARM
LEFT ALARM
RIGHT ALARM
WITHDRAW PERMIT CKT. OPEN
LOW FLOW PRIMARY COOLANT
HIGH TEMP. CORE TANK MTS-1
LOW LEVEL CORE TANK
LOW TEMP. COOLING TOWER OUTLET
LOW LEVEL CORE TANK
SAFETY SYSTEM SCRAM
LOW PRESSURE REACTOR INLET MP-6
HIGH TEMP. CORE TANK MTS-1A
NO OVERFLOW CORE TANK
HIGH FLOW MF-2
HIGH TEMP. MTS-1
PERIOD CHANNEL LEVEL SIGNAL OFF-SCALE
LOW PRESSURE REACTOR INLET MP-6A
HIGH TEMP. REACTOR OUTLET MT-5A
LOW FLOW HF-1
LOW FLOW MF-2
LOW PRESSURE HM-C
HIGH TEMP. CORE TANK MTS-1/1A
CONTROL ON MANUAL
HIGH TEMP. REACTOR OUTLET MT-5A
HIGH TEMP. PRI. CLEANUP SYSTEM
HIGH TEMP. HE-1 PRIMARY OUTLET
Back To Overview
33.2
2016
1900
2019
27.7
37.3
22.8
24.3
PANEL 2
Console Right
CAUTION
DO NOT MODIFY OR MOVE
0.0 % 0.002 MW

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

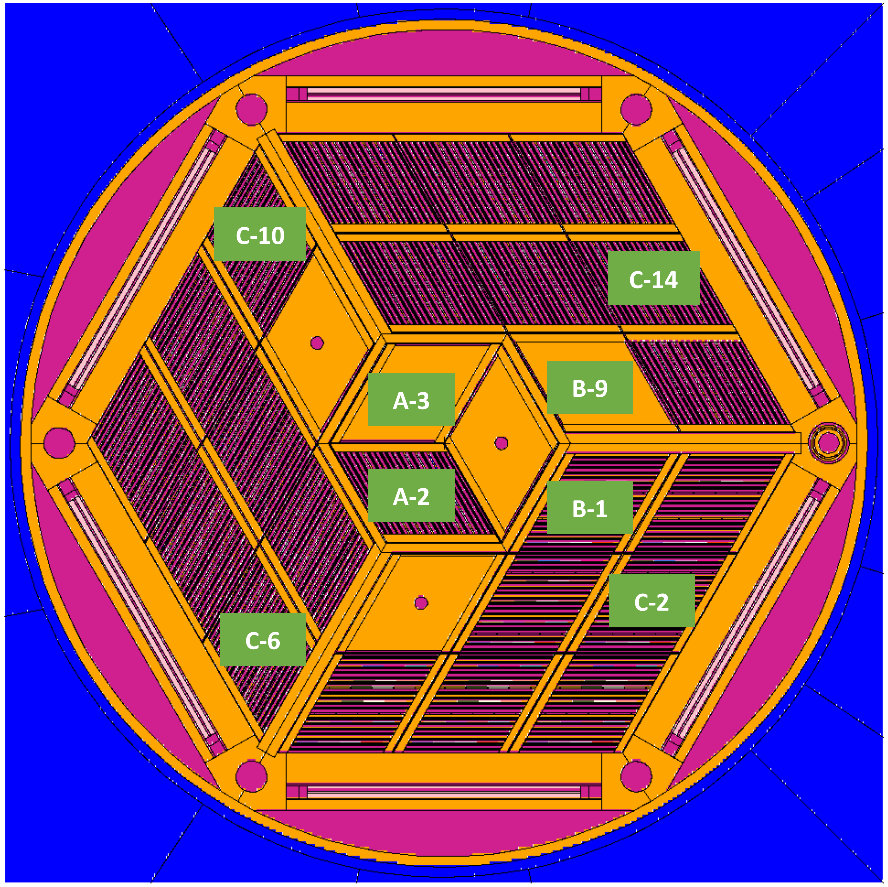
- Significant progress has been made in LEU fuel design/specifications, safety analysis, startup plan, facility modifications, and fuel development for the MITR LEU fuel conversion.
- The MITR LEU simulator is developed and models the LEU core with higher flow and upgraded heat exchanger to support engineering 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

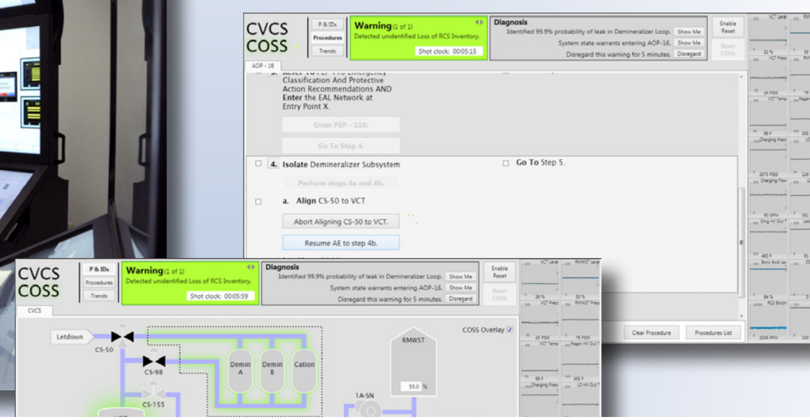
- LEU Core #1 - 22 Fresh LEU Fuel Elements
- Fuel Loading Sequence
- Inverse Count Rate (1/M) Plot
- Approach to Criticality
- Shim blades and reg rod worths, and other reactor physics measurements
- Primary coolant system pre-operational tests at higher flow 2400 gpm
- Stepwise power increase to 7 MW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



INL Human System Simulation Laboratory

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

Idaho National Laboratory




SYNCHRONIZING DISPLAY
FEEDWATER PUMP SWITCH
SPEED CONTROL
CONTROL ROD

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