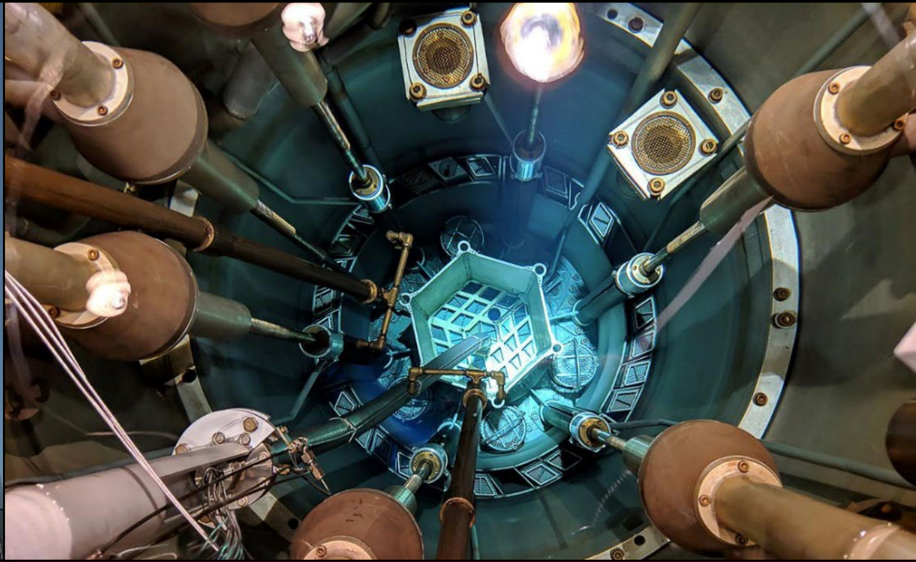
MIT NUCLEAR REACTOR LABORATORY

an MIT Interdepartmental Center

Enhancing Capabilities of Neutron Irradiation Facilities at the MIT Research Reactor to Support Integrated Materials and Instrumentation Testing

David Carpenter, Nesrin Cetiner, Caroline Sears, Lin-wen Hu

Massachusetts Institute of Technology, USA

6/17/2025 – IGORR

Outline

- Introduction to the MIT NRL and the MITR

- NRL Reactor Experiment Activities and Demand

- New and Enhanced Irradiation Facilities
  - Dual pressurized water loops
  - SIGMA dry irradiations
  - Reactive materials
  - New M3 Facility
  - Vertical reflector and pneumatic positions expansion

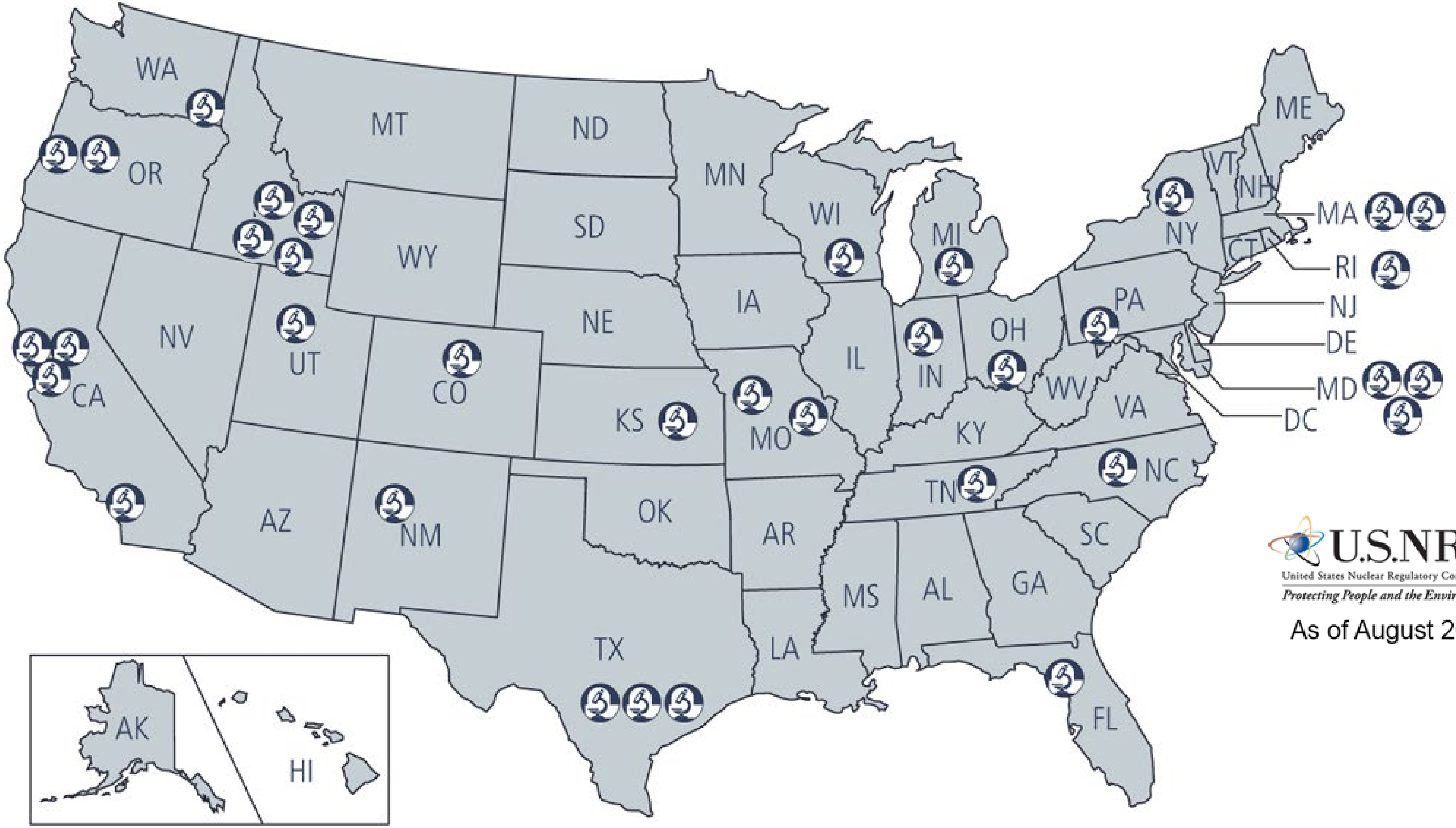
MIT Nuclear Reactor Laboratory

The NRL is an interdepartmental laboratory within the Massachusetts Institute of Technology, with missions in nuclear technology applications, neutron science research, training, and education

- Direct collaborations with academia, government, and industry

- The NRL's primary facility is the MIT Research Reactor (MITR-II), a multi-purpose research reactor owned and operated by MIT
  - MITR is a partner facility of DOE's Nuclear Science User Facilities (NSUF)
  - NRL has many additional capabilities for reactor modeling, neutron physics, and the analysis of radioactive materials

US Research and Test Reactors



U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

As of August 2019

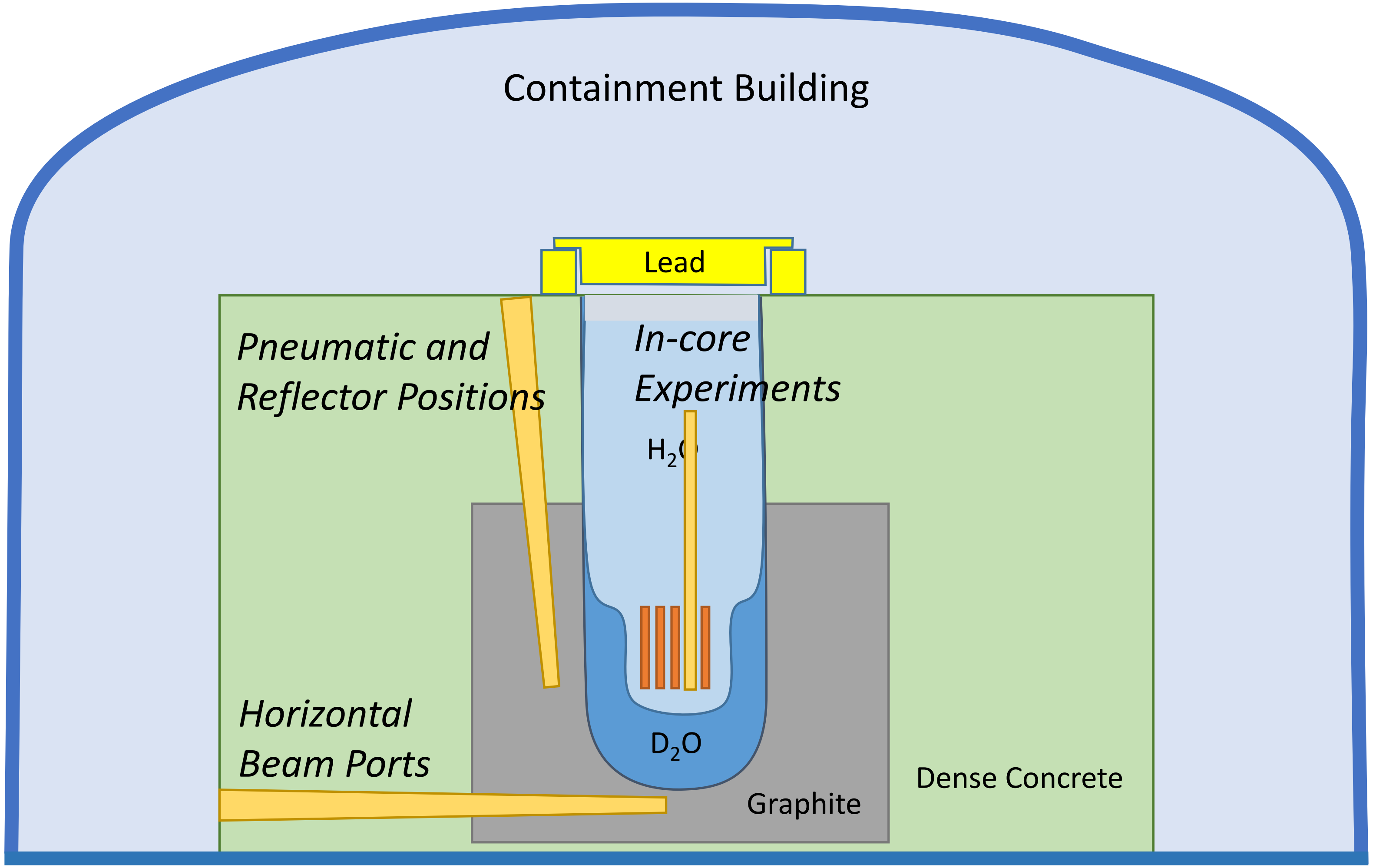
Cambridge and Boston, USA

MIT Research Reactor (MITR)

Nuclear Science User Facilities

- Tank-type, light water-cooled
  - D_2O and graphite reflected
- Constructed in 1958 as a heavy-water reactor
  - First criticality July 21^{st}, 1958 (~67 years)
- Upgraded in 1975 (MITR-II) to the current hybrid design
  - Up-rated in 2010 from 5 MW to 6 MW_{th}
  - 2^{nd} largest university reactor in the US
- Operates 24/7, 10-week cycles

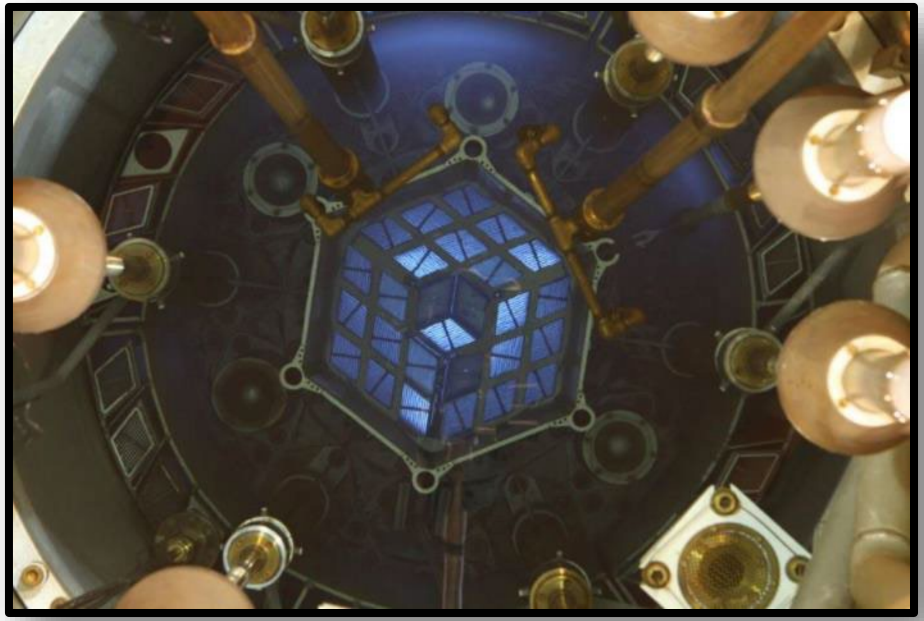
MITR Layout



Containment Building
Lead
Pneumatic and
Reflector Positions
In-core
Experiments
H2O
D2O
Horizontal
Beam Ports
Graphite
Dense Concrete

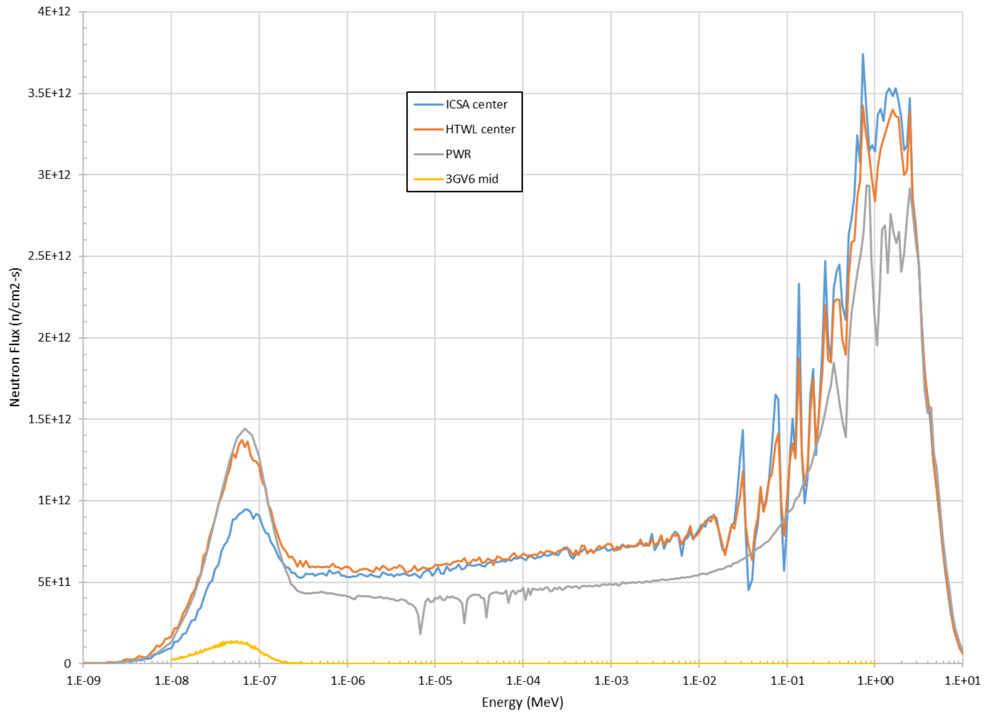
MITR Core Design

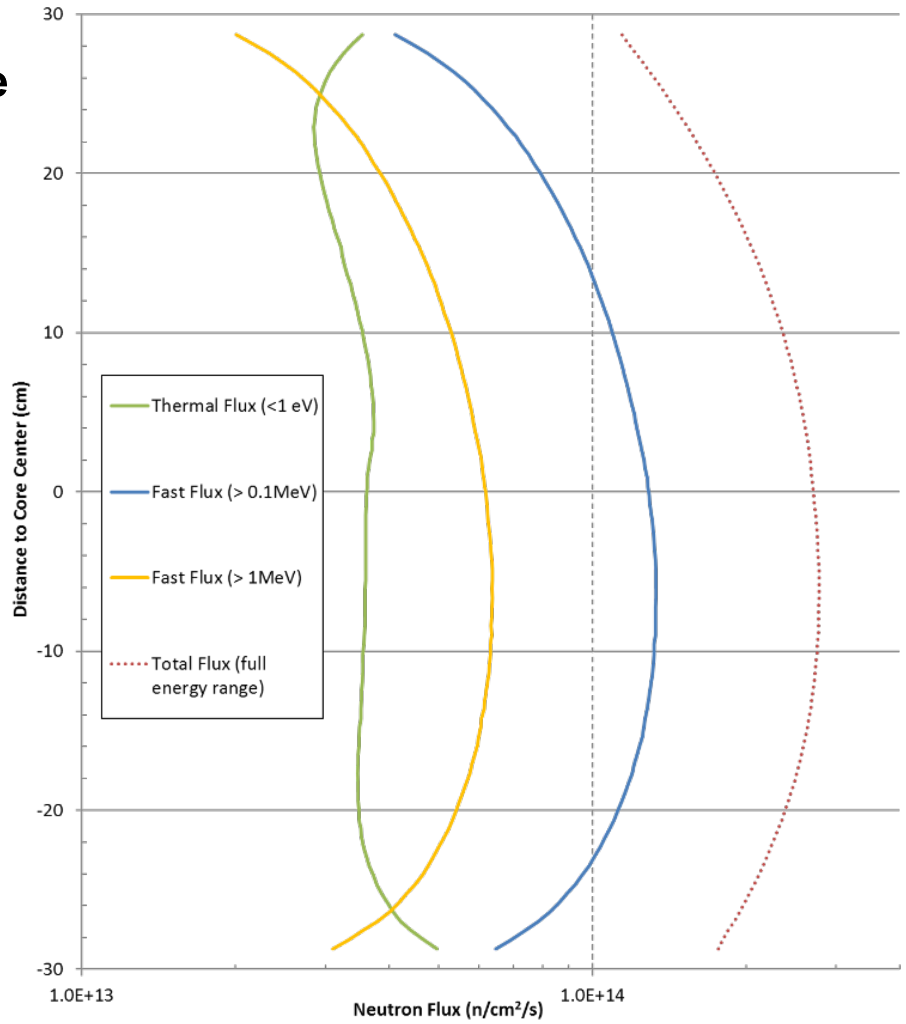
- 24 in (61 cm) tall, 14.5 in (37 cm) across
- 27 positions with 24 fuel elements
  - 15 HEU UAl_x finned fuel plates each
- 6 control blades (B), 1 reg. rod (Cd)
- 3 dedicated in-core experiment positions



Available Fluxes

- In-core flux is similar to LWR
  - Thermal neutron: 3.6×10^{13} n/cm^2-s — **2.7×10^{20} n/cm^2 per cycle**
  - >0.1 MeV neutron: 1.2×10^{14} n/cm^2-s — **5.5×10^{20} n/cm^2 per cycle**
  - Gamma: 2×10^{14} γ/cm^2-s — **Typical heating 2 W/g**
- 3GV are primarily thermal
  - 1.2×10^{13} n/cm^2-s thermal, 2.5×10^{10} n/cm^2-s >1 MeV





NRL Research Areas

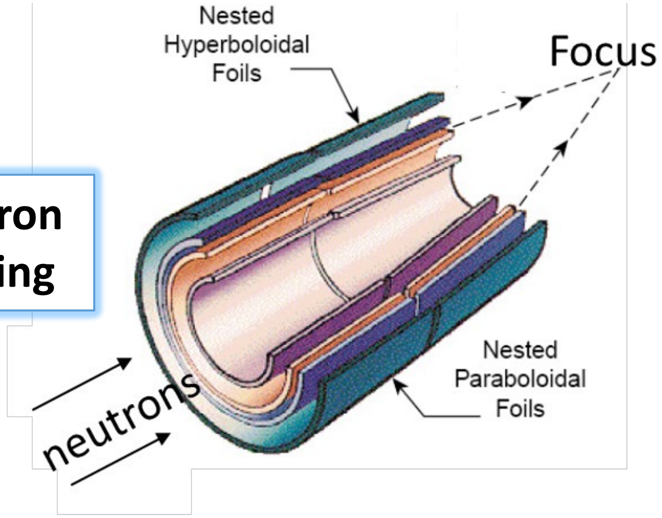
Serving academic, government, and commercial customers through both **Research and Service** agreements

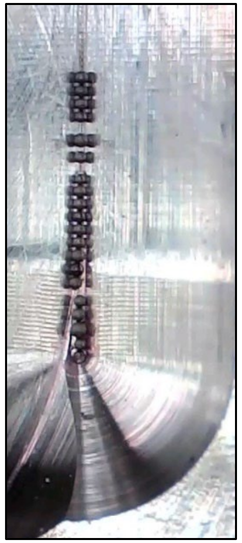
- Novel sensors
  - Fiber-optics, crack-length, ultrasonic, etc.
  - In- and near-core exposure
- Materials
  - Fuels (UZrH, metallic)
  - Ceramics (SiC, CFCs, MAX-phases, hydrides)
  - Metals (3D-printed zircaloy, steels, FeCrAl coatings)
  - Coolants (LWR, molten salt, lead bismuth)
- Neutron interrogation and optics
  - Neutron lensing
  - Radiography
  - Diffraction
- Reactor control, simulation, and dynamics
  - Simulation
  - LEU conversion
  - Autonomous control

LWR Accident Tolerant Fuel

Molten Salts

Neutron Lensing

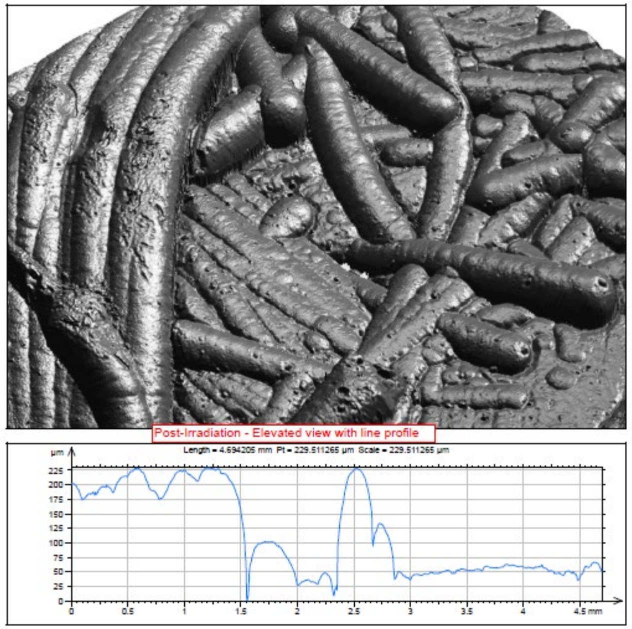


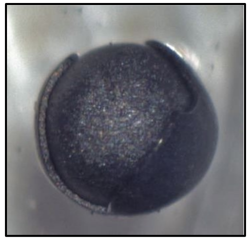


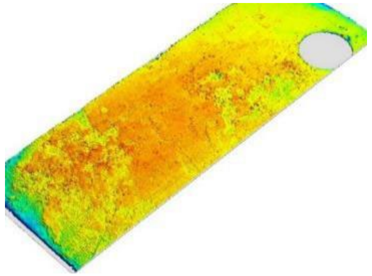
Particle Fuels

Capabilities: Labs

- NTD Silicon production
- Graphite subcritical pile
- Neutron Activation Analysis
- Radioactive sample cutting, mounting, polishing
- Neutron radiography
- Gamma, beta, and x-ray spectroscopy
- Weight and non-contact dimension







- Optical profilometry
- Scanning electron microscopy with EDS
- Laser and Xenon-flash thermal diffusivity
- Dilatometry
- Mechanical test frame with environmental chamber and optical 3D strain tracking
- Vickers hardness testing

Recent In-Core Experiments

Pressurized Water Loop

ACI
SiC LWR cladding in PWR conditions

COATI
ATF SiC coated plates and tubes with ECP

BSiC
BWR SiC channel box and guide tubes

CALOR
Scanning nuclear heating calorimetry

WATF
Accident-tolerant cladding and coatings

ATFB
NSUF-sponsored industry and university ATF cladding

ICCGM
Actively-loaded real-time crack growth monitor

JSiC
JAEA-sponsored BWR SiC cladding

Fuel Tests

HYFI
U-Zr-H LWR fuel rods with liquid metal bonding

AFTR
Internally- and Externally-Cooled Annular Fuel

Advanced Coolants

FS-1, FS-2
FHR coupons in flibe at 700°C with tritium capture

FS-3
FHR and SINAP ceramics with guard heating

WHEP
Sodium thermosiphon for eVinci microreactor

FS-6
Kairos graphite and steel

Inert Gas

ULTRA
Ultrasonic, SPD, and fiber sensors

HYCO
ATF SiC coated plates and tubes at 320°C

TCP
Wire-based thermal conductivity probes

TEGI
Nuclear-heated thermo-electric generators

TREAT
Neutron and gamma transient benchmark

SFX
Sapphire fiber optic temperature sensors

XEN
Ceramic composites for X-energy

NIM
Industrial ceramic and metal composites

HPR
Gold fiber-based photothermal radiometry

HYD
Encapsulated LANL hydrides

NRL Irradiation Research Demands

PWR/BWR materials
- Accident Tolerant Fuel/Cladding

In-core Instrumentation
- Fiber optics
- Miniaturized fission chambers, SPDs
- Ultrasonic emitter/detectors

Advanced Moderators
- Hydrides

Alternative Coolants
- Molten Salts
- Sodium
- Hydrogen

Ongoing Contributions to Accident Tolerant Fuel Development

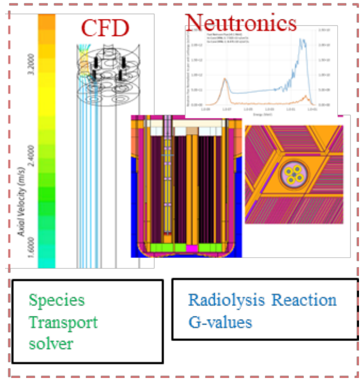
The MITR **High Temperature Water Loop (HTWL)** is one of the primary irradiation test beds for SiC/SiC$_f$, hybrid (composite on metal alloy) and coated clad materials and sealing techniques

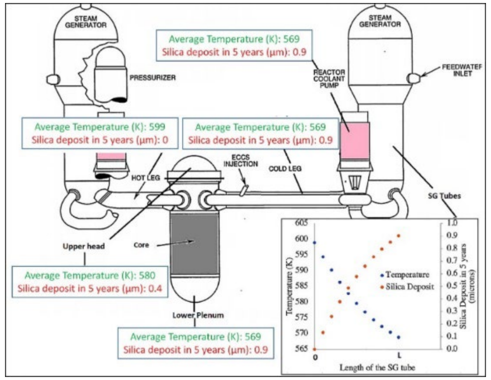
- Many of these materials are being exposed to irradiation in prototypical coolants for the first time

- PWR or BWR conditions with a wide range of B/Li and dissolved gas concentrations , zinc injection, ^{16}N suppression additives

- Collaborations with Westinghouse, CTP, General Atomics, Toshiba, and Oak Ridge National Laboratory, as well as MIT NSED faculty

- Recently-awarded \$5M IRP and MIT VPR support will enable 2nd (HPWL) position for independent simultaneous operation
  - U. of Michigan, Penn. State University, Czech Technical University, INL
  - Framatome, GE/Hitachi, Westinghouse, General Atomics, CTP





IRP will use reactor experiments, lab facilities, and simulation to:

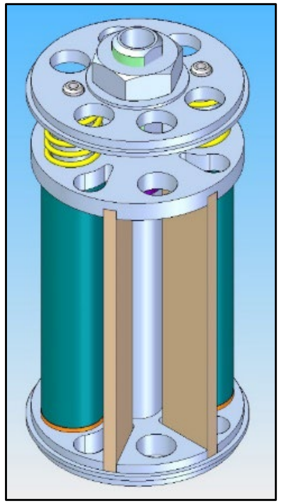
- Study coating performance
- Assess impact of chemistry and CRUD
- Evaluate SiC performance with gradients
- Train new researchers on reactor experiment design and execution

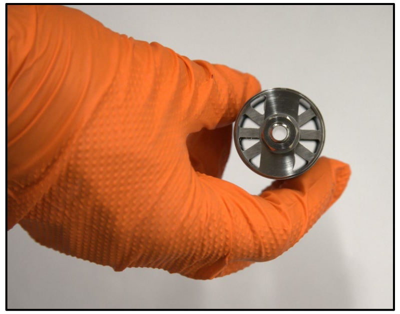
JAEA-NRL Cladding Research Program

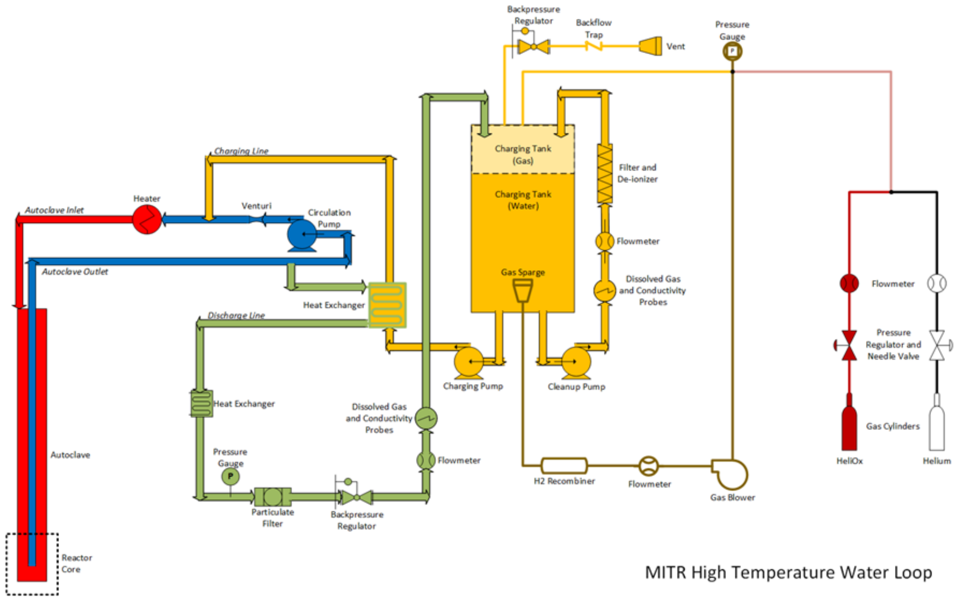
- Started December 2022 and sponsored by the Japan Atomic Energy Agency in collaboration with:
  - Toshiba Energy Systems & Solutions Corporation
  - Hitachi GE Vernova Nuclear Energy

Japan Atomic Energy Agency
Oarai Research & Development Institute

- Irradiation of non-fueled SiC-composite specimens in the MITR water loop
  - BWR (NWC) loop conditions
  - 4 cycles with intermediate sample change-outs
  - Over 50 plate and rodlet specimens irradiated so far
- Post-irradiation examinations conducted in the NRL hot labs



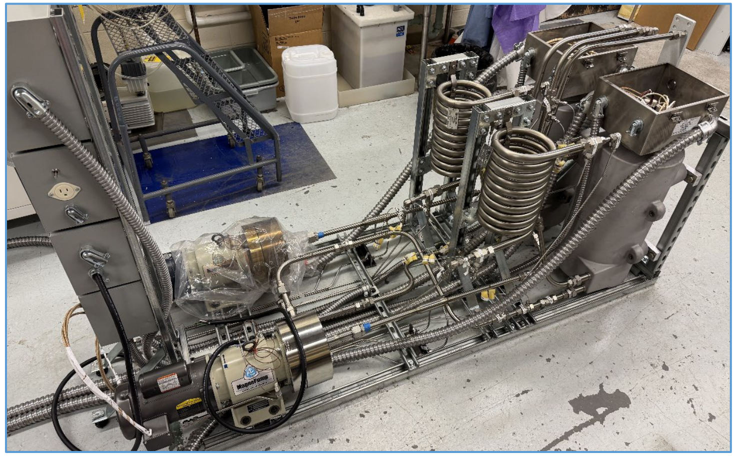


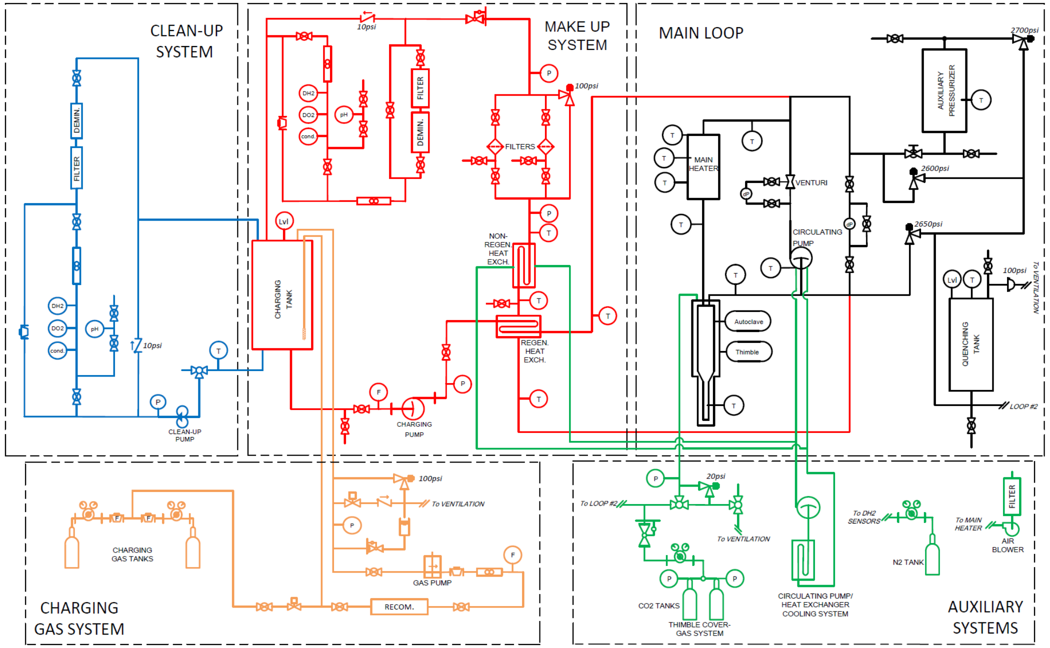


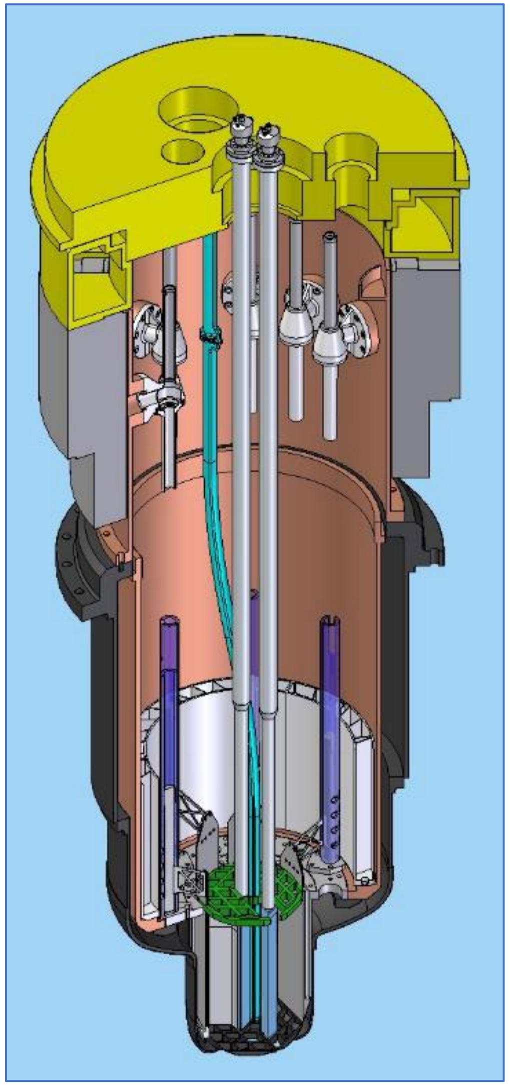
MITR High Temperature Water Loop

Dual Water Loops

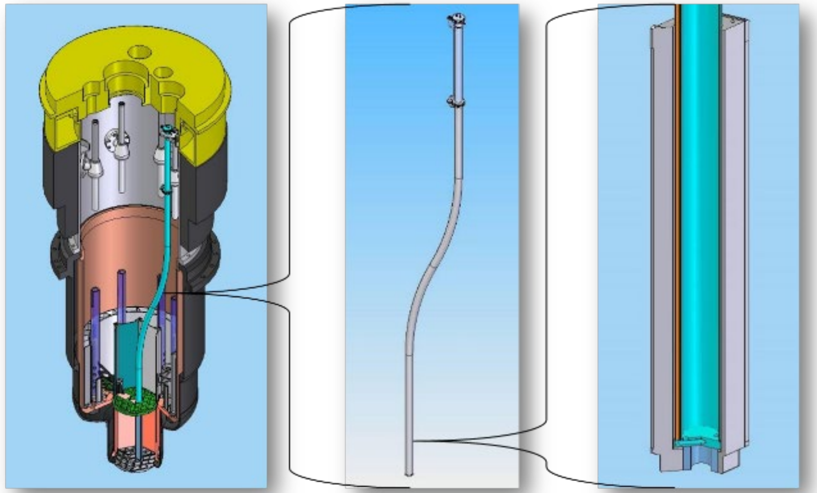
- Establishing capability for two simultaneous but independent in-core pressurized water loops:
  - One loop will operate at existing HTWL (BWR/PWR) conditions
    - **10.3 MPa, 300°C**
  - Second loop (HPWL) to operate at PWR hot-channel conditions
    - **17.2 MPa, 350°C**
  - May operate core A3 position as either a water loop or a dry experiment
- Planning first operation of new loops in 25Q3



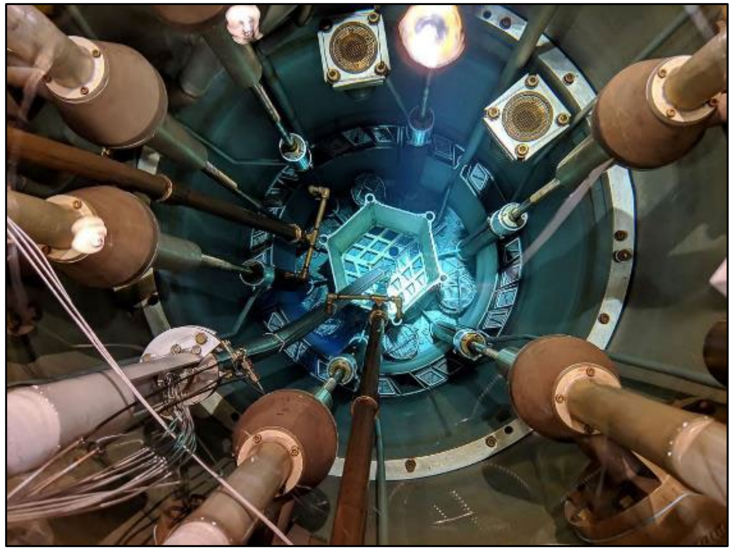




In-core Dry Irradiations



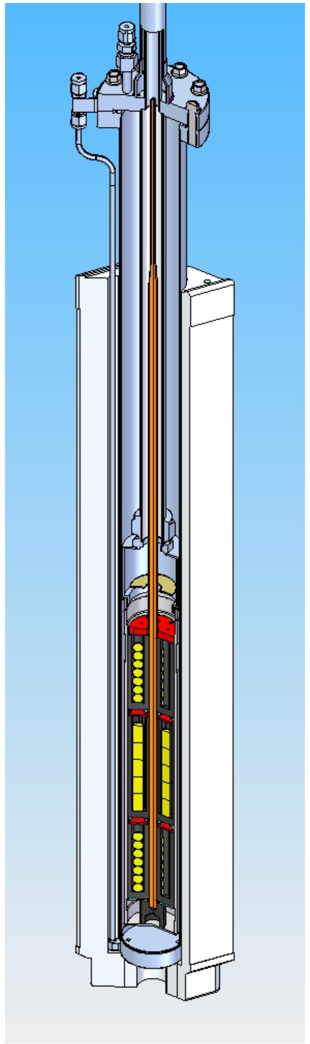
Reactor core tank ICSA thimble In-core region



For projects in inert gas environments, MITR currently has two <u>helium/neon</u> sweep gas-controlled facilities.

- Originally used access tube design with an “S-bend” jog to block direct radiation streaming
  - Capsules lowered on pneumatic snake and stacked
- 450-850°C typical with nuclear heating only
  - Additional multi-zone electrical heating available
- Nominal operation single-zone gas control with ±2°C stability over a cycle
- Lead-out capacity 12 x 1/16-inch lines

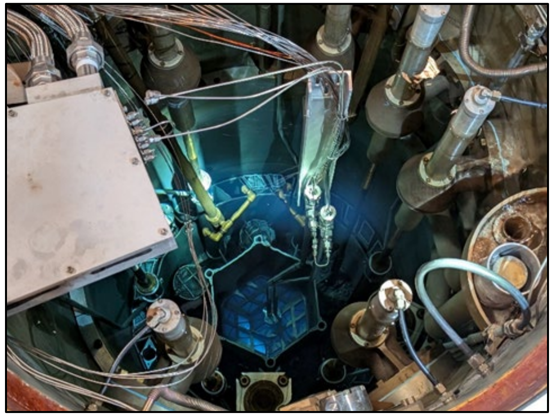
SIGMA Dry Irradiation Design

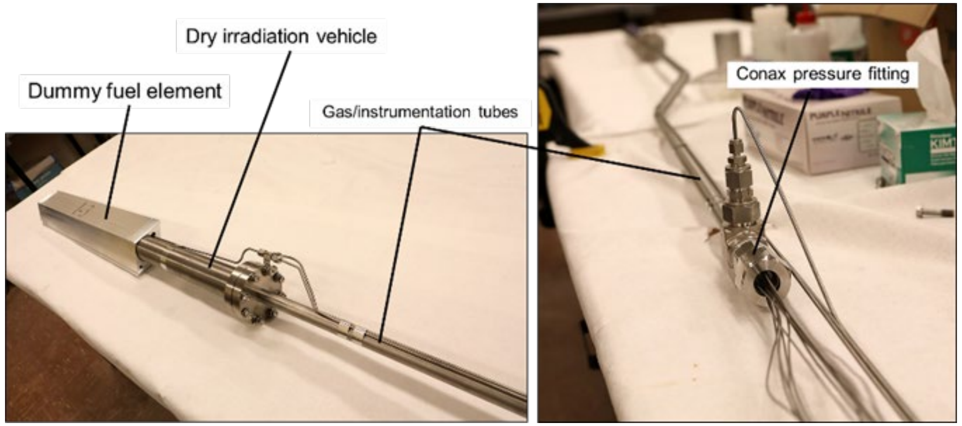


Small Inert-Gas Multipurpose Assembly

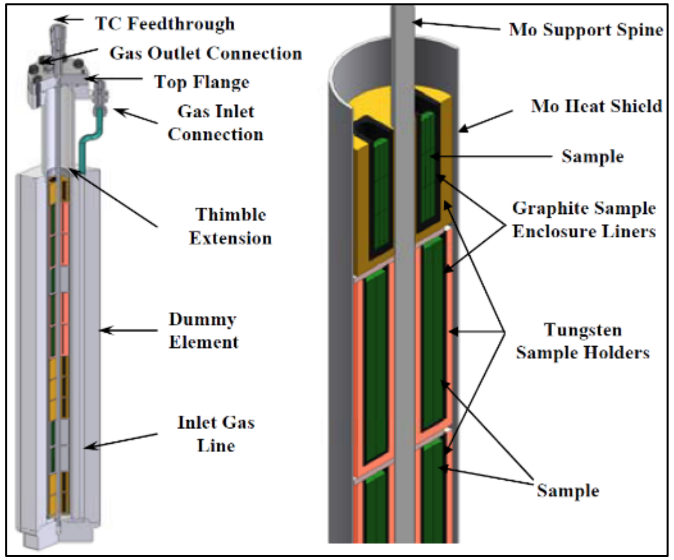
- Outer irradiation vehicle (safety boundary) rated for 900°C
- Simpler geometry gives more flexibility in target design
- Better thermal contact = lower minimum temperature

- Operating envelope permits different experiments using the same pre-reviewed design
  - Established temperature, pressure, and chemical compatibility specifications
  - Compatible with MITR ECCS spray requirements
  - Supports versatile lead-out arrangements

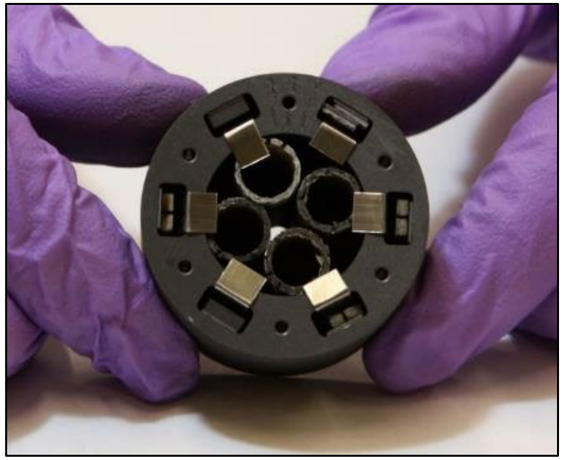


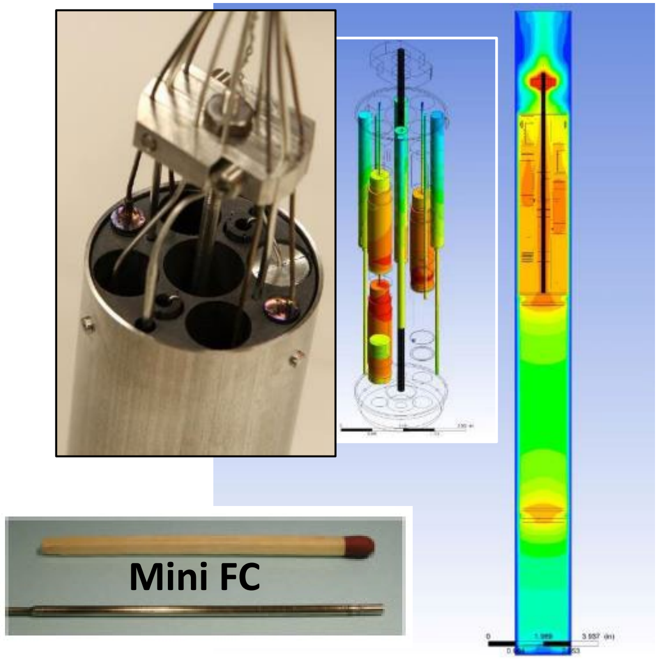


Materials and Sensors in Gas

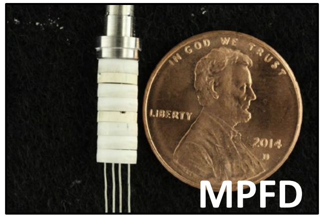


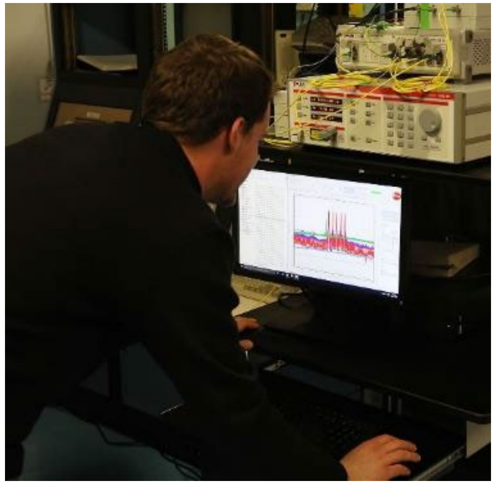
Metals and ceramics at high temperature



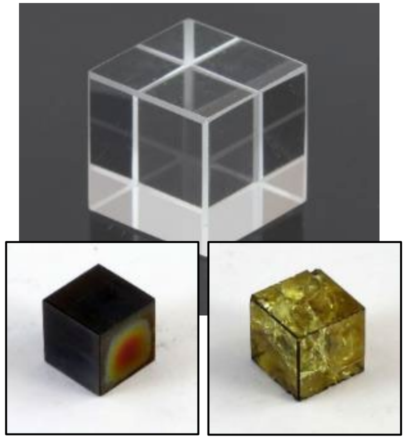


Miniaturized sensors





Fiber optics



Flibe Salt and FHR Materials Irradiations

- Initially a multi-university project (from 2012, six years, $12.5M)
  - Included joint graphite testing project with the Chinese Academy of Sciences
  - Three in-core and one reflector irradiation of static flibe focusing on corrosion, salt permeation, and tritium transport

- Currently in final year of a $4.8M project to *design, build, and test an instrumented salt loop at the MITR*
  - Loop outside the reactor tank that partly decouples reactor neutronics from loop
  - Provides an experimental test bed for chemistry control, salt cleanup, tritium control and instrumentation

- Recently completed an in-core NSUF-sponsored irradiation led Kairos Power with graphite and steel samples

Nuclear Energy University Program
U.S. Department of Energy

Massachusetts Institute of Technology

NC STATE UNIVERSITY

Berkeley UNIVERSITY OF CALIFORNIA

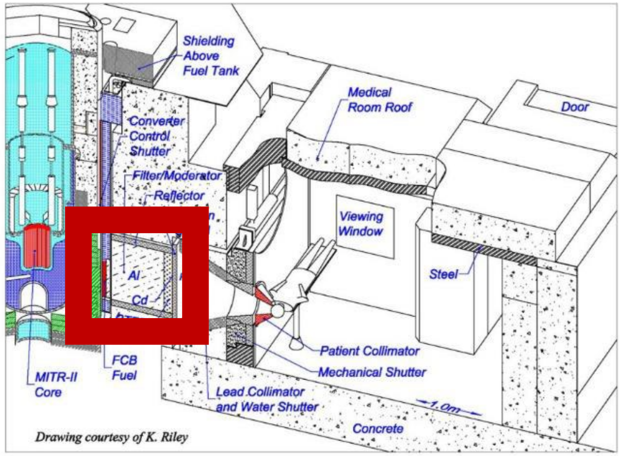
OAK RIDGE National Laboratory

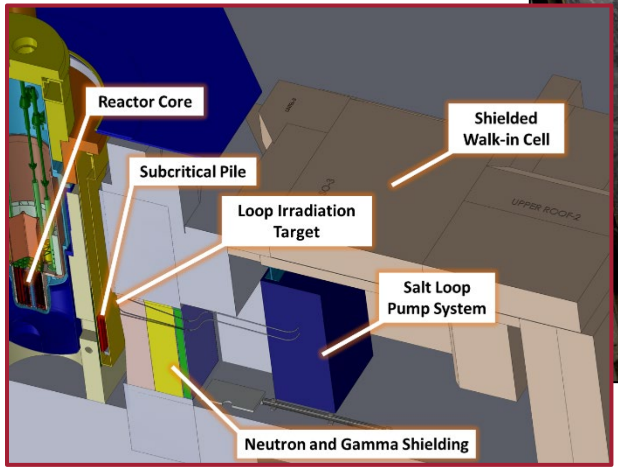
M³ Facility Conversion

Conversion of <u>reactor-driven subcritical facility</u>, the Fission Converter (FC), from medical therapy (epithermal) to flexible materials testing (full spectrum).

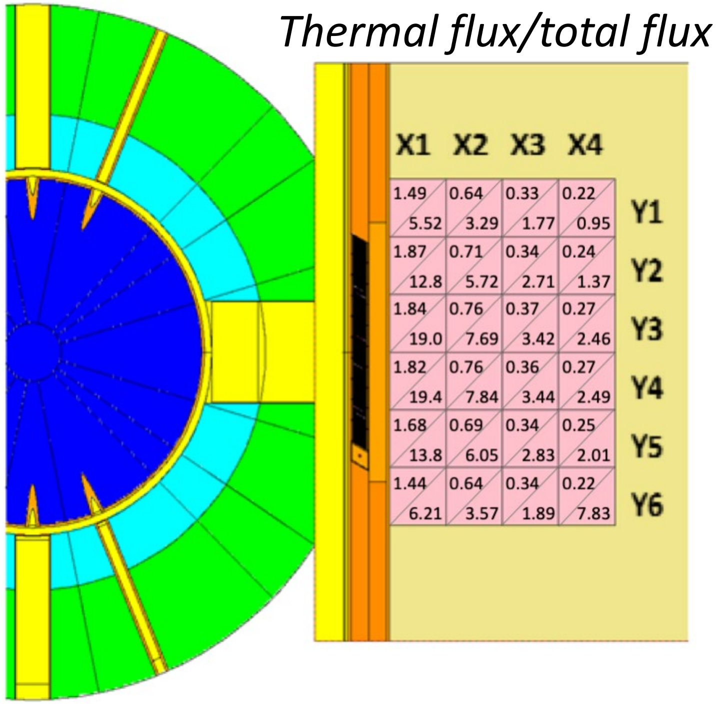
- Removal of $1m^3$ neutron filter to access highest flux region for experiments
- Installation of forced-flow flibe salt loop (MSR IRP), fusion magnet (PSFC) irradiations

Peak total flux:
$1.9x10^{12}$ n/cm²-s





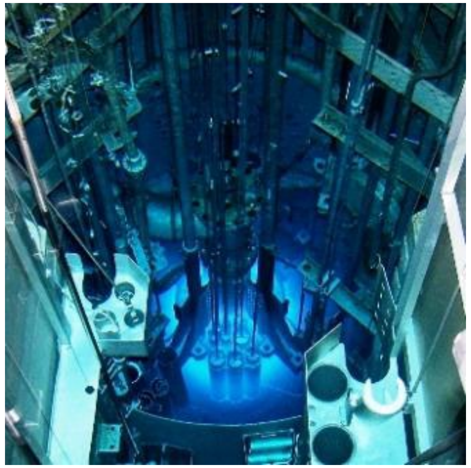
Thermal flux/total flux



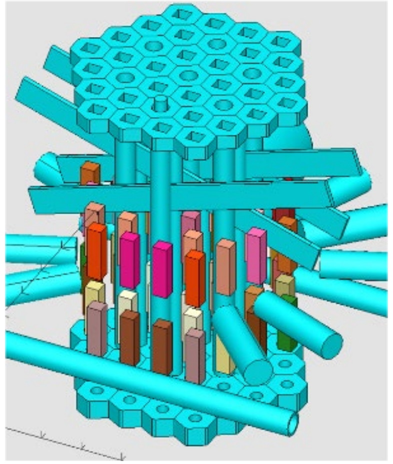
U.S. High Performance Research Reactors

MITR, 22-27 Elements

MURR, 8 Elements



NBSR, 30 Elements

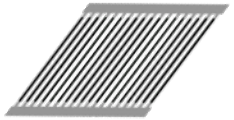
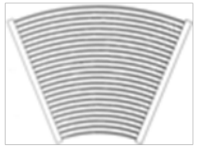
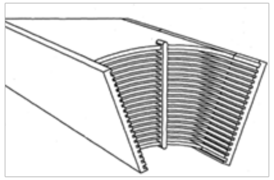
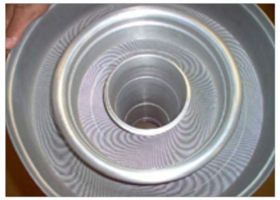


ATR
40 Elements

HFIR
Annular
Element Pair
(540 plates)

MATERIAL MANAGEMENT AND MINIMIZATION
CONVERT, REMOVE, DISPOSE

LEU Fuel Conversion

Reactor	
MITR	
NBSR	
MURR	
ATR/ ATRC	
HFIR	

- MITR currently uses >93% enriched UAl_x fuel
- Plan 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.
- The fuel matrix, high-density monolithic U-10Mo, was selected for all U.S. High-Performance Research Reactors (ATR, HFIR, NBSR, MURR, MITR).
- MITR will be the next U.S. reactor and first HPRR to be converted to LEU.

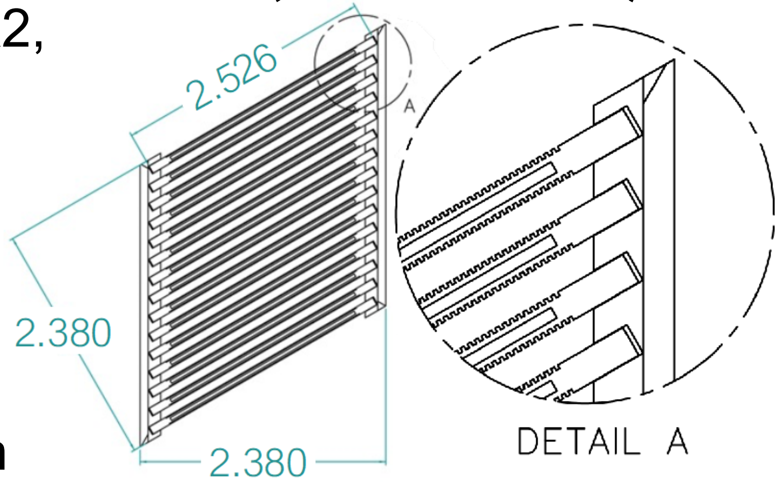
Fission Converter Lead Element LEU Test

While test irradiations of new MITR LEU element are planned for BR2, we could perform the first on-site irradiation in the Fission Converter

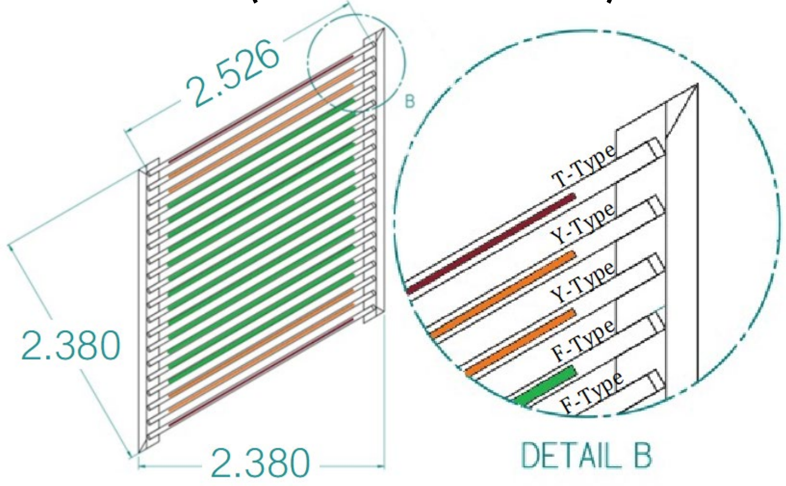
- Current study by led by Dr. Lin-wen Hu and doctoral candidate Caroline Sears to assess feasibility of using the FC with LEU elements

- Neutron transport with **MCNP5** (LANL) and thermal hydraulics with **STAT7** (ANL)
  - FC Assembly k_{eff} → must be under 0.9
  - FC Assembly Power → must be under 300 kW
  - P_{ONB} (onset of nucleate boiling) → must be 300 kW or greater

HEU (93.15 wt% ^{235}U)



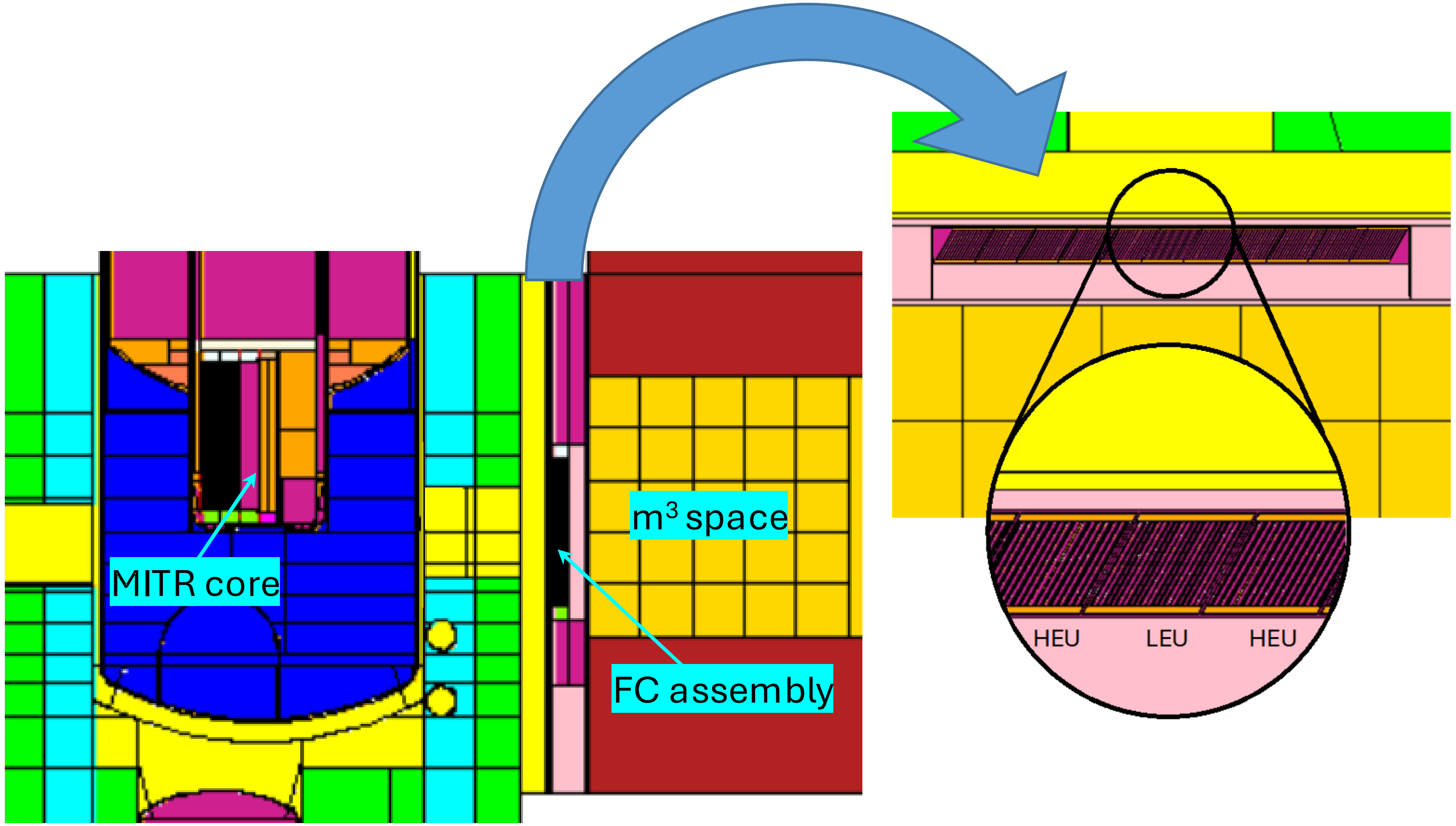
LEU (19.75 wt% ^{235}U)

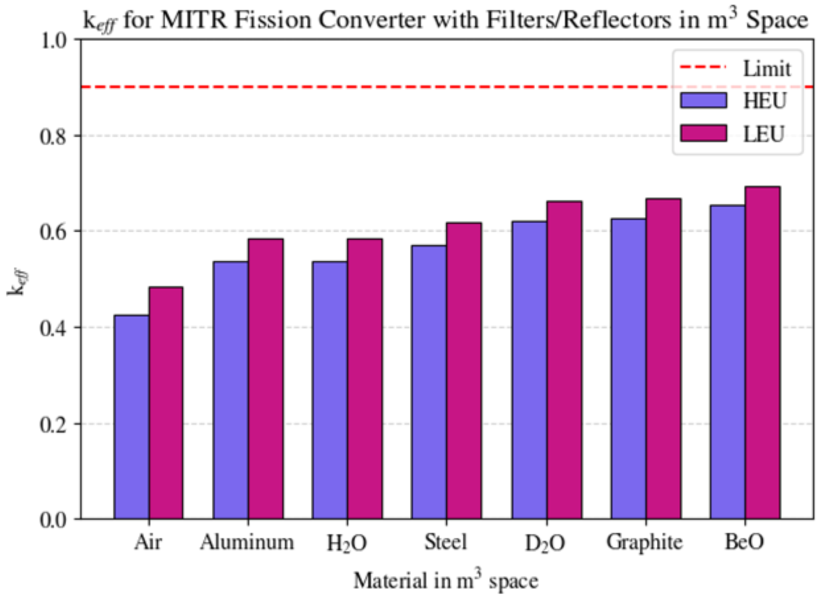


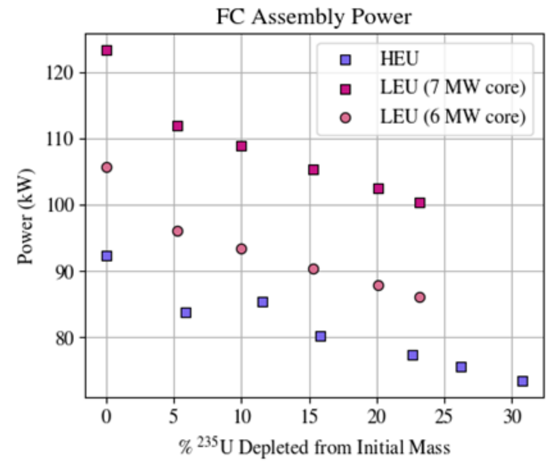
The MIT Reactor Fission Converter LEU low power testing research is sponsored by the U.S. Department of Energy, National Nuclear Security Administration Office of Material Management and Minimization Reactor Conversion Program under contract 2J-30101 with Argonne National Laboratory

FC HEU-LEU Modeling

Using pre-existing MITR/FC system models, but swapped center HEU element with an LEU element





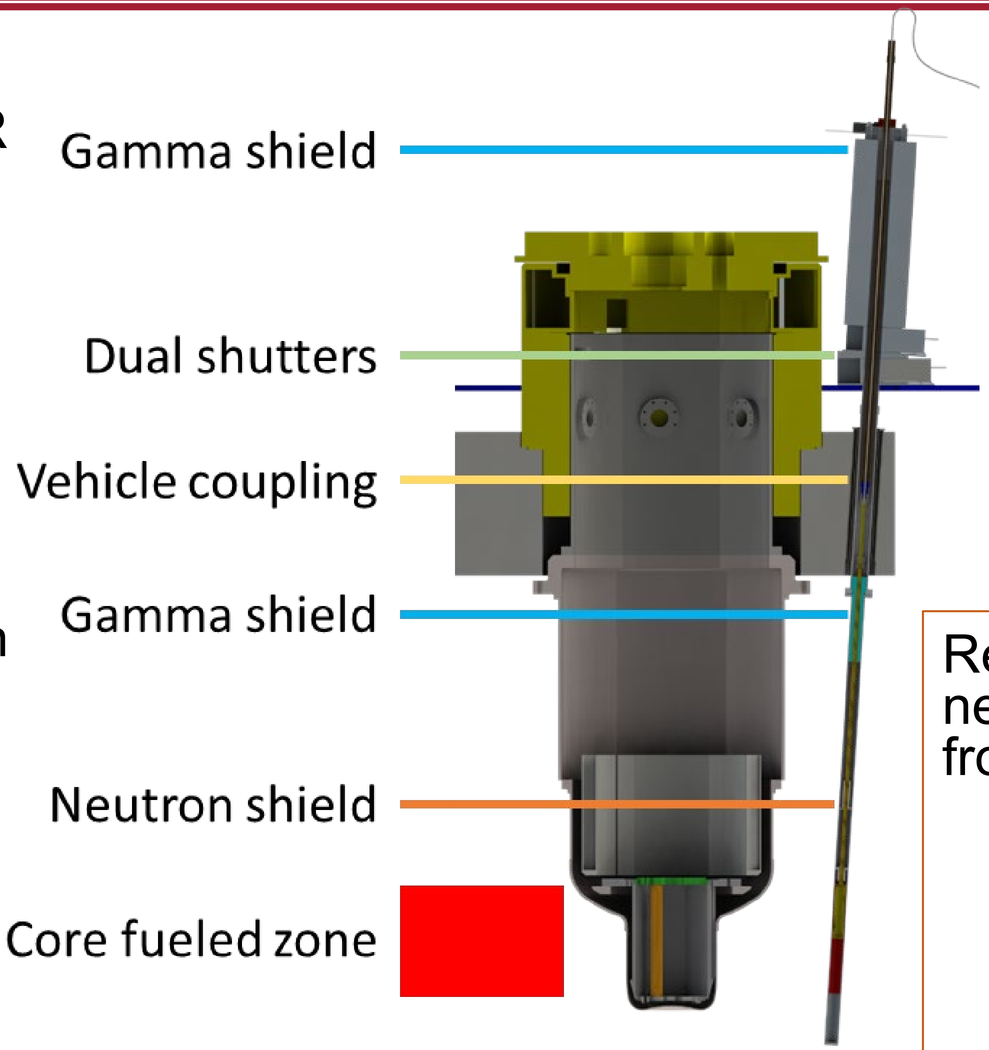


MITR Graphite Reflector

The **3GV** positions are six near-vertical dry locations in the MITR graphite reflector

- Extend to 17 in (43 cm) below core, 151 in (3.8 m) total length
- 3.37 in (85 mm) ID in the in-core zone
- Normally requires 2.65 in (67 mm) ID water-cooled jacket at ~35°C

- ➢ Have shutter/cask available on one position currently, two more are under development.
- ➢ Operating outside the core allows flexible development:
  - H2 flow loops
  - Boosted fissile tests
  - Rapid actuation



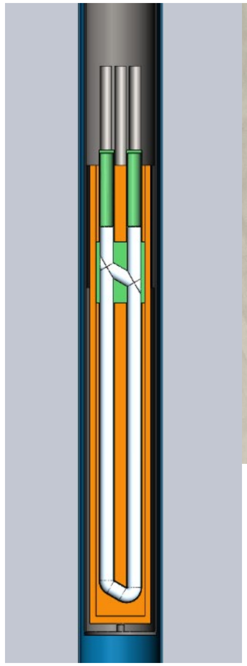
Reflector locations are neutronically-decoupled from the reactor

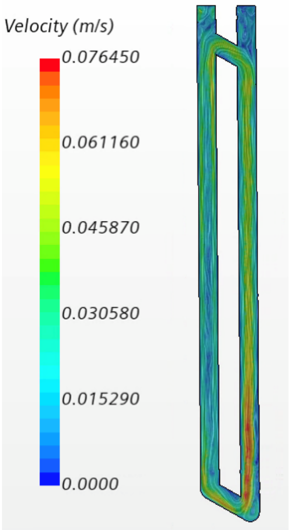
- Thermal flux similar to in-core ~1×10^{13} n/cm^2/s,
- Fast flux ~1×10^{10} n/cm^2/s
- Larger volume than in-core

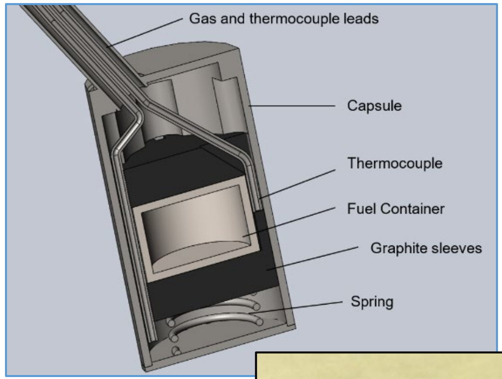
Recent 3GV Irradiations

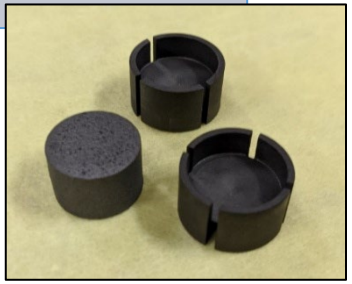
ARPA-e GEMINA Project

- First modern reactor irradiation of molten salt with natural-convection flow
- Two electrically-heated capsules
- FLiNaK and FLiBe salts with dopants
- Post-irradiation NDE



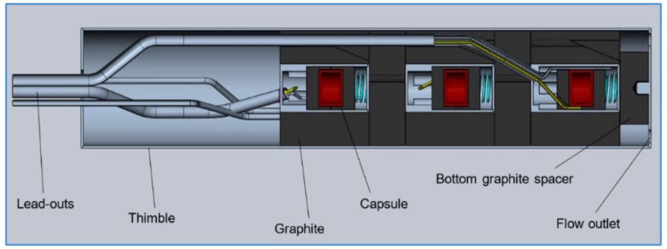






Advanced Manufactured Fuel Irradiation

- Evaluate performance of 3D-printed fuel compacts
- Supporting the ORNL Transformational Challenge Reactor
- UN and UCO kernels, TRISO, and TRISO compacts at 5-50 W/cc
- Measured fission gas release

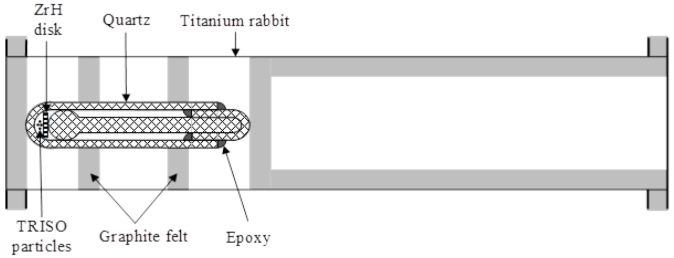


NRAMP Nuclear Thermal Propulsion

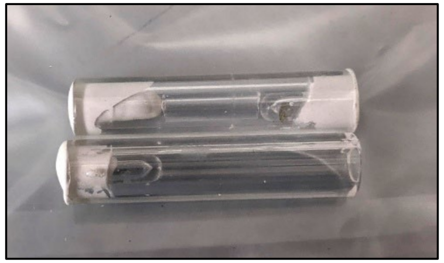
- Joint projects with NASA, INL, and Little Prairie Services
- Building capability to test NTP fuels and moderators
- Nuclear-heated ceramic with H_2 flow
- Mechanically-actuated through a neutron shield to simulate SNP reactor operation

Pneumatic Irradiation Facilities

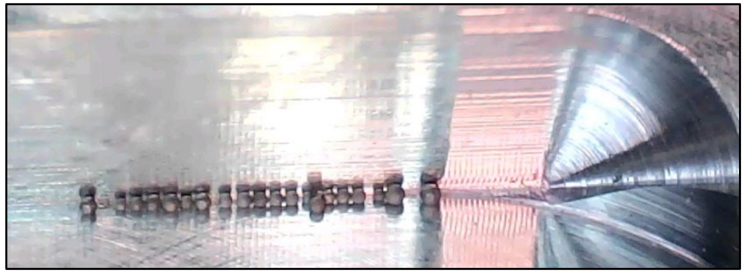
- Actively expanding utilization of MITR pneumatic access positions
  - Only air cooling with 50g max sample mass
  - **1PH1** rabbits are 1” dia., 3.24” long
    - Located in graphite reflector
    - $8x10^{12}$ n/cm^2-s thermal
  - **2PH1** rabbits are 1.375” dia., 6.25” long
    - Located in heavy water reflector
    - $5x10^{13}$ n/cm^2-s thermal
    - $3x10^{12}$ n/cm^2-s >1 MeV
- Testing fuel under H_2, molten salts
- Adding instrumentation, increasing cooling and payloads



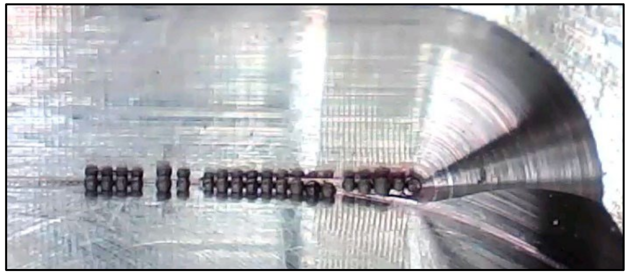
H2 sealing test vials



W-coated UN kernels



Uncoated UN kernels



AGR UCO TRISO

Summary

The MIT Nuclear Reactor Laboratory is transforming the **MITR** into a materials and instrumentation irradiation test facility

- Reduced emphasis on medical (esp. BNCT), beamline, NTD silicon
- Increasing facilities for instrumented experiments at a wide range of conditions
- Changing our facilities to meet the community's demands
  - Doubling LWR water loop capacity, additional near-core exposure
  - Higher density of irradiation vehicle lead-outs
  - Molten salts, advanced manufactured fuels, reactive gas environments
  - More flexible irradiation spaces – denser instrumentation, neutronic decoupling, larger size, more extreme conditions