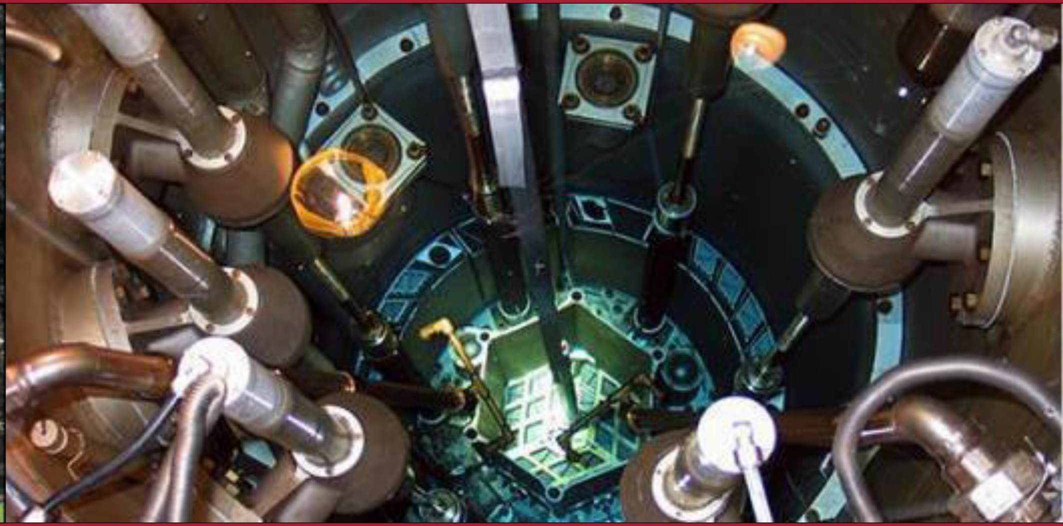
MIT NUCLEAR REACTOR LABORATORY

an MIT Interdepartmental Center



Recent Progress in Advanced Materials and Instrumentation Tests at the MIT Reactor

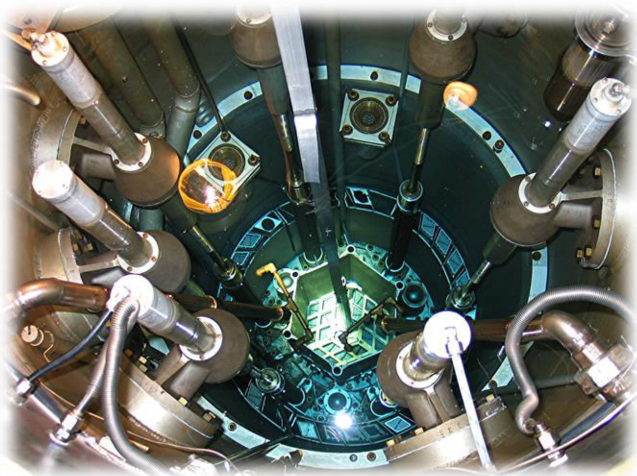
Lin-wen Hu*, Gordon Kohse, David Carpenter

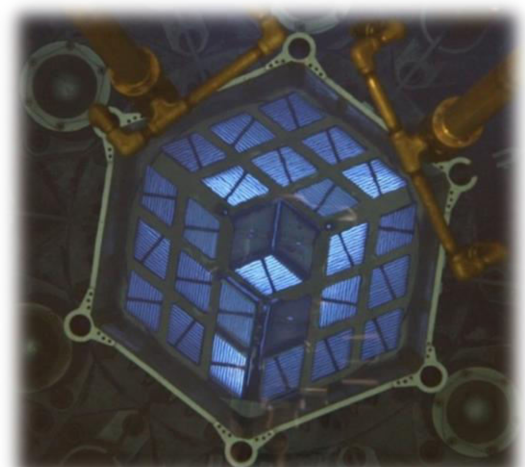
**Director, Research and Services*

TRTR-2018, Newport, RI

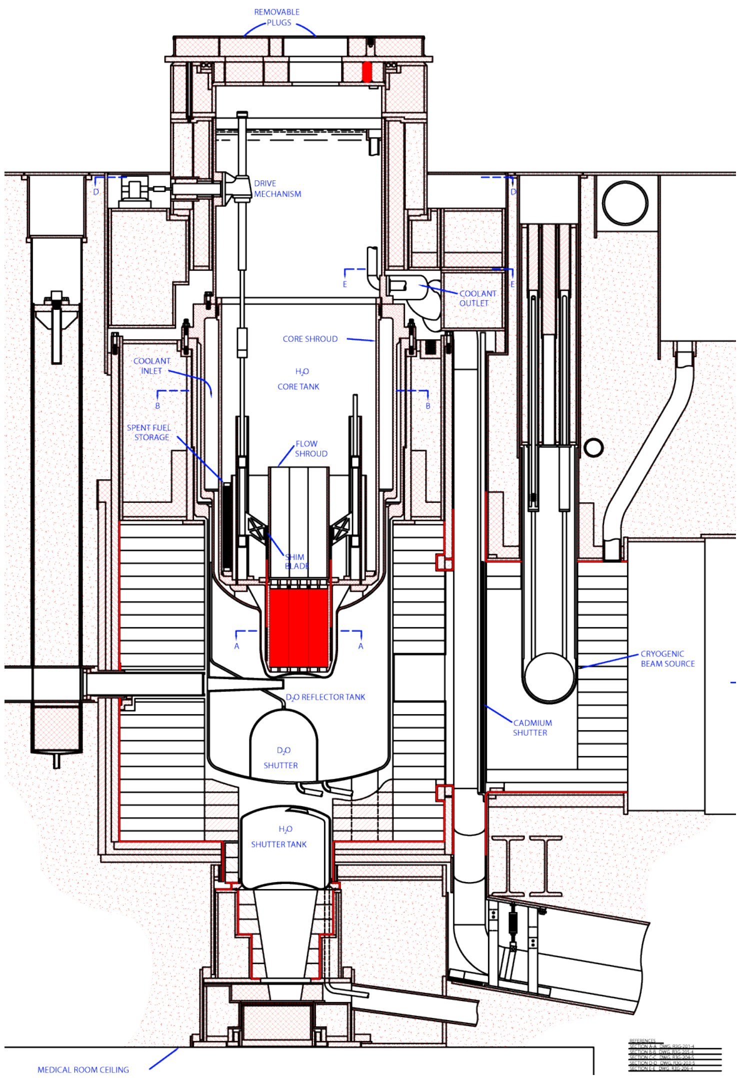
MIT Nuclear Reactor Laboratory

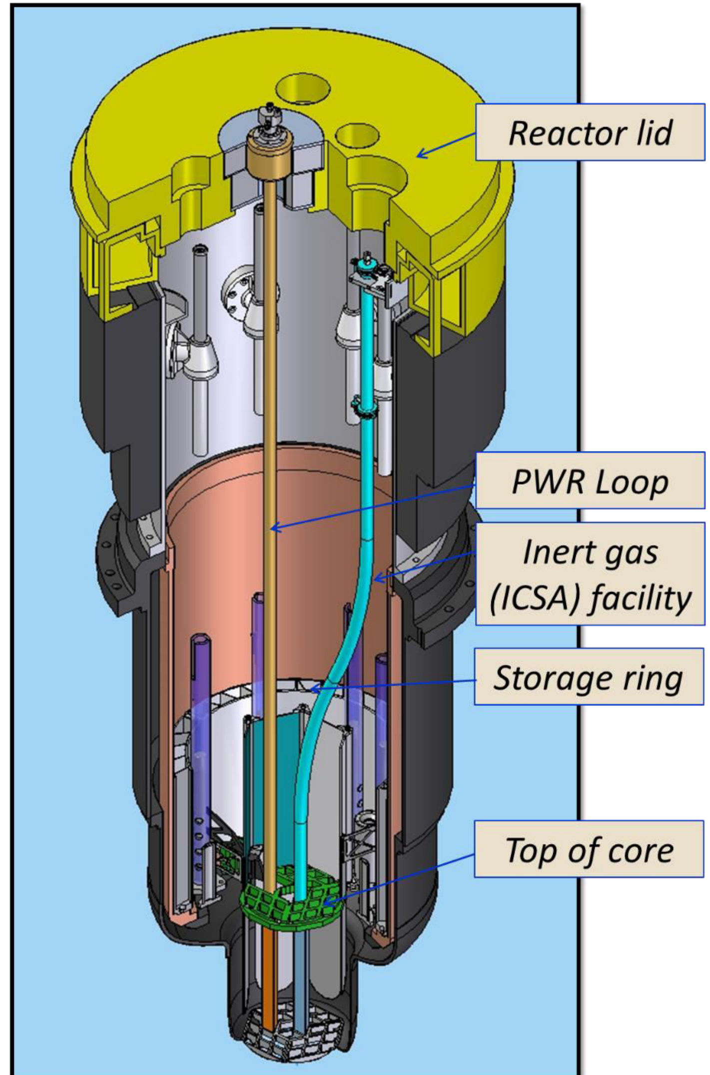
- MIT-NRL is an interdepartmental laboratory with missions in nuclear technology applications, neutron science research, and training/education.
- Primary facility is MIT Reactor (MITR), a multi-purpose research reactor owned and operated by MIT. A partner facility of DOE's *Nuclear Science User Facilities (NSUF)*.
- Constructed in 1958 (MITR-I), upgraded in 1975 (MITR-II) with new core tank and housing
- Uprated from 5 MW to 6 MW_{th} in 2010 (2^{nd} largest university reactor in US).
- Compact core with power density similar to a LWR. *Operates 24/7, 10-week cycles*
- Tank-type, light water cooled and moderated, D_2O and graphite reflector.
- Excellent track record in in-pile irradiation experiments including LWR loop, fuel, high-temperature materials, and advanced instrumentations.





MITR Cross-Section

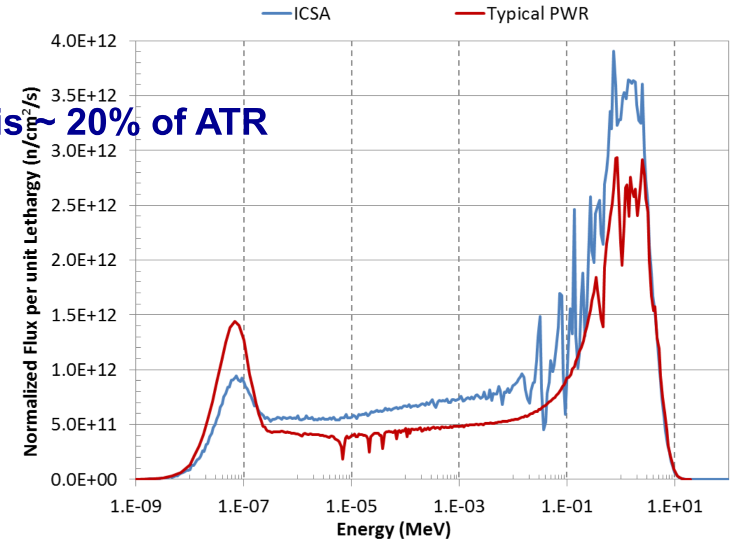


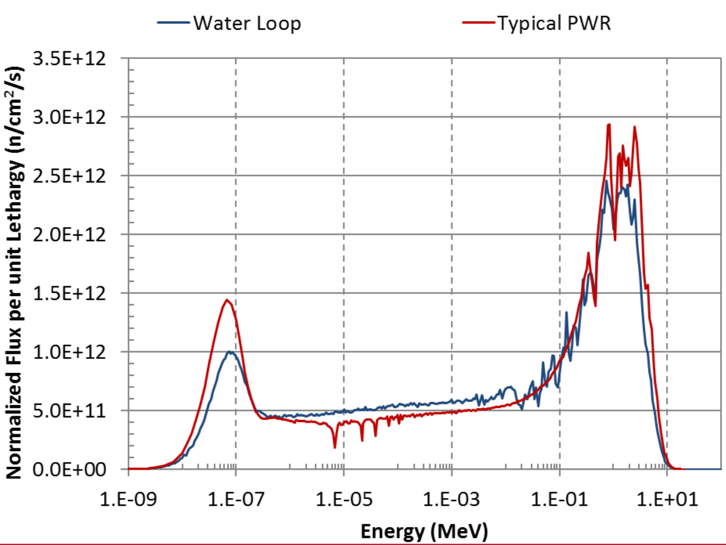


Neutron Flux and Spectrum

Facility	Size	Neutron Flux (n/cm2-s)
In-core	3 available Max in-core volume ~ 1.8” ID x 24” long	Thermal: 3.6×10^{13} Fast: up to 1.2×10^{14} (E>0.1 MeV)
Beam ports	Various radial: 4” to 12” ID	Thermal: 1×10^{10} - 1×10^{13} (source)
Vertical irradiation position	2 vertical (3GV) 3” ID x 24” long	Thermal: 4×10^{12} - 1×10^{13}
Through ports	One 4” port (4TH) One 6” port (6TH).	Avg thermal: 2.5×10^{12} to 5.5×10^{12}
Pneumatic Tubes	One 1” ID tube* (1PH1)	Thermal: up to 8×10^{12}
	One 2” ID tube* (2PH1)	Thermal: up to 5×10^{13}
Fission Converter Beam Facility (FCB)	Beam aperture ~ 6” ID	Epithermal: ~ 5×10^{9}
Thermal Beam Facility (TNB)	Beam aperture ~ 6” ID	Thermal: up to 1×10^{10}

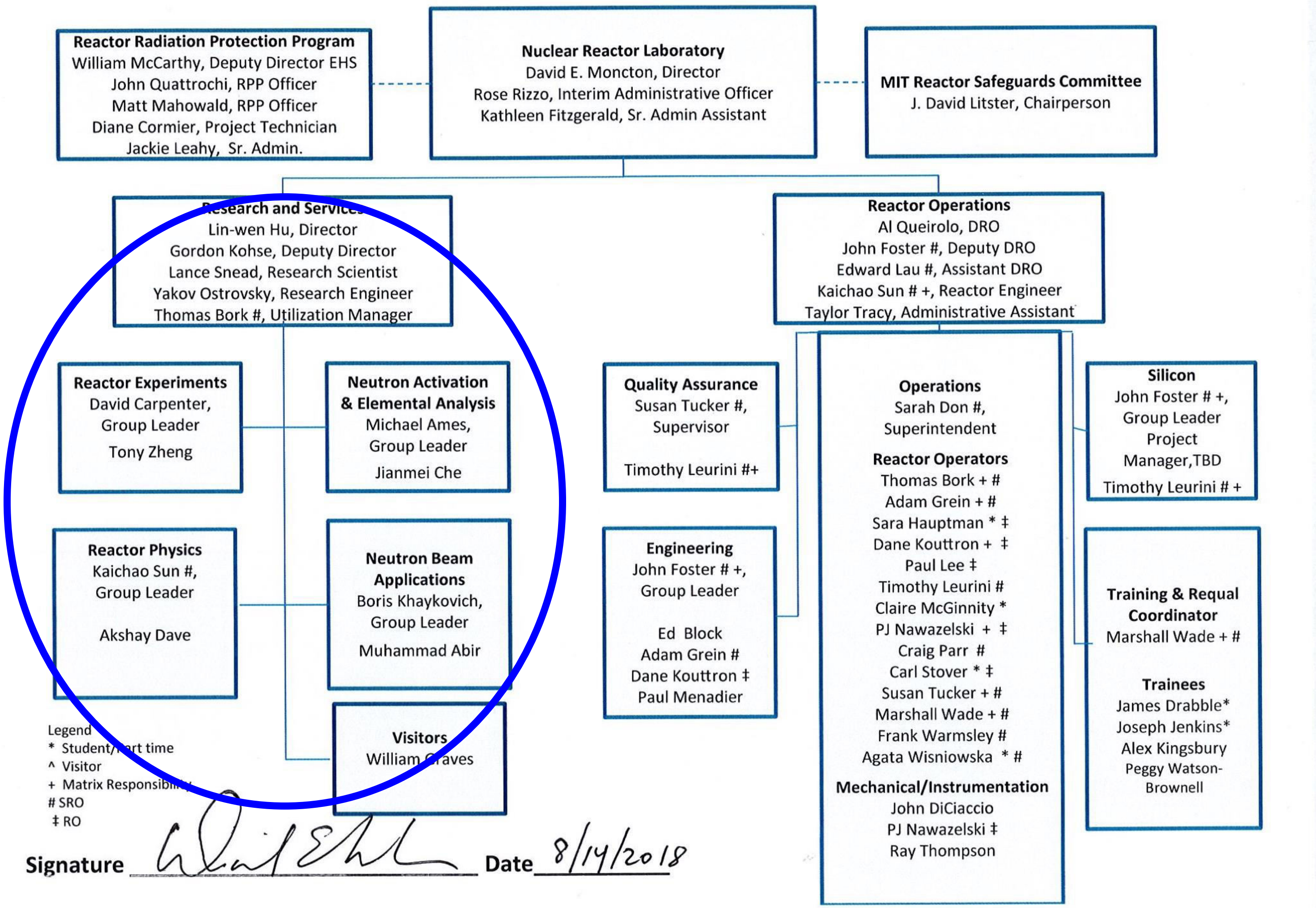
Fast flux is ~ 20% of ATR





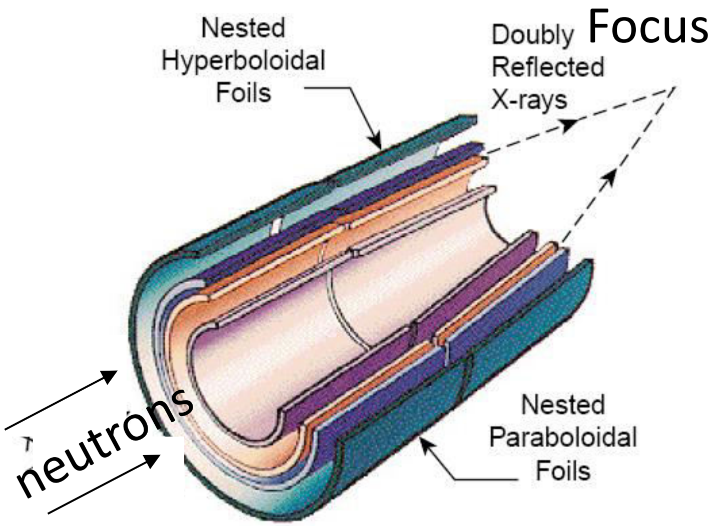
Expanding Research Group

- Since 2006, NRL research and services division has grown to 13 staff (10 PhDs)



NRL Research

- New sensors
  - Fiber-optics
  - Crack-length
  - Ultrasonic
- New materials
  - Fuels (UZrH, metallic)
  - Ceramics (SiC, carbon fiber, MAX-phase)
  - Metals (zirconium, 3D-printed steels)
  - Coolants (liquid flibe salt, lead bismuth)
- Neutron optics
  - Neutron lenses
  - Radiography

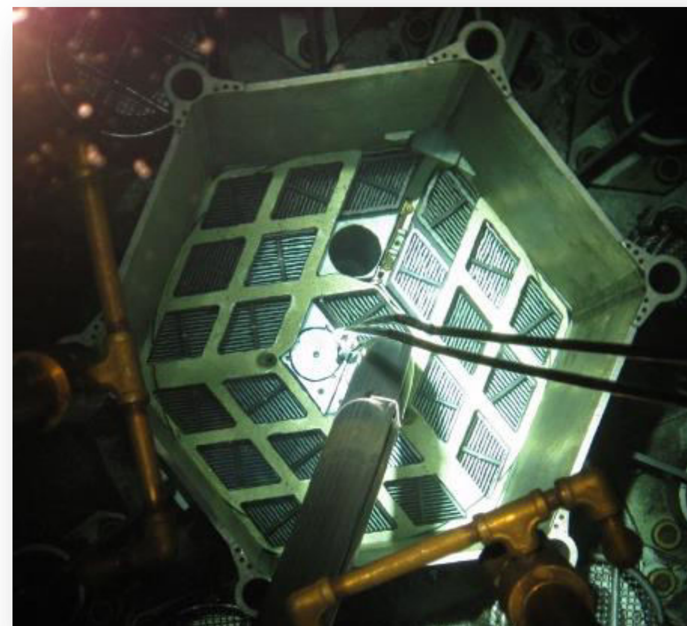


In-Core Materials Irradiation

Materials in Extreme Environments

- ➢ Accident tolerant cladding
- ➢ Advanced fuels
- ➢ Liquid salts
- ➢ Very high temperatures

- ➢ 3 in-core positions dedicated to experiments
- ➢ General facilities for specimen capsules
  - PWR/BWR conditions in water loop
  - Inert gas up to 850°C
- ➢ Customized facilities for high temperatures (>1300°C) and exotic materials (e.g. fluoride salts, fissile materials up to 100 gm U-235)
- ➢ Common measurements: corrosion, swelling, property changes, activation, radiolysis



Recent In-Core Experiments

Pressurized Water Loop

ACI
SiC LWR cladding in PWR conditions

BSiC
SiC channel box and guide tubes

WATF
Accident-tolerant cladding and coatings

ICCGM
Actively-loaded real-time crack growth monitor

COATI
ATF SiC coated plates and tubes with ECP

Fuel Tests

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

AFTR
Internally- and Externally-Cooled Annular Fuel

Fluoride Salt

FS-1
FHR coupons in flibe at 700°C and tritium capture

FS-2
Additional coupons, salt, and activation sampling

FS-3
FHR and SINAP ceramics, guard heating

Inert Gas

HTIF
Ceramics and TRISO >1400

Drexel
MAX-phase materials at 300-700°C in inert gas

LUNA
Fiber optics at 700°C

ULTRA
Ultrasonic transducer and self-powered detector test

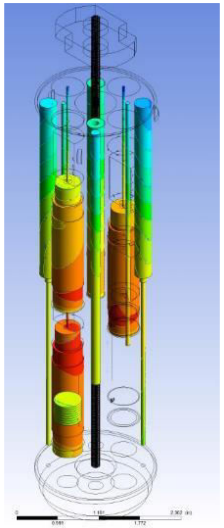
ULTRA 2
Ultrasonic and fiber optic sensors at 800°C

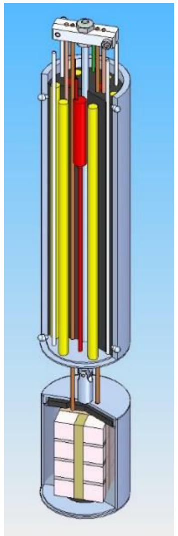
HYCO
ATF SiC coated plates and tubes at 320°C

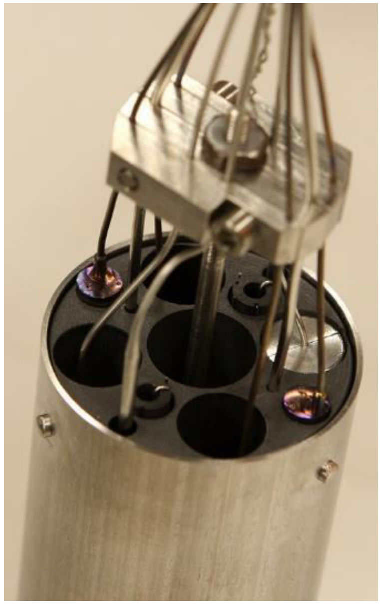
TREAT
Neutron and gamma transient benchmark

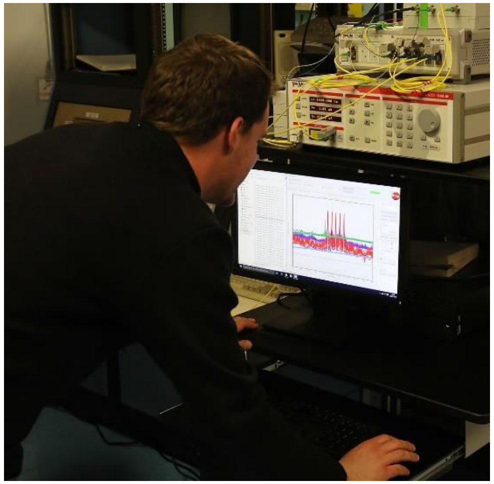
Radiation-Hardened Ultrasonic Sensors

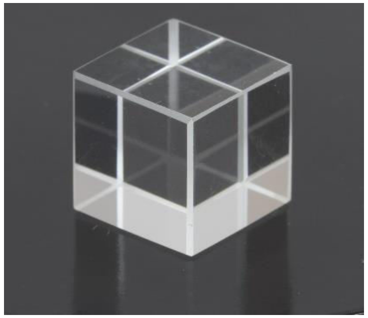
- Collaboration with INL and Pennsylvania State University,
  - Six different ultrasonic transducers
  - Real-time response as a function of flux, temperature, fluence
- Miniaturized neutron and gamma detectors also successfully tested
- Follow-up collaboration with INL, CEA, University of Pittsburgh, and AFO Research
  - Includes optical glasses and radiation-hardened fiber optics





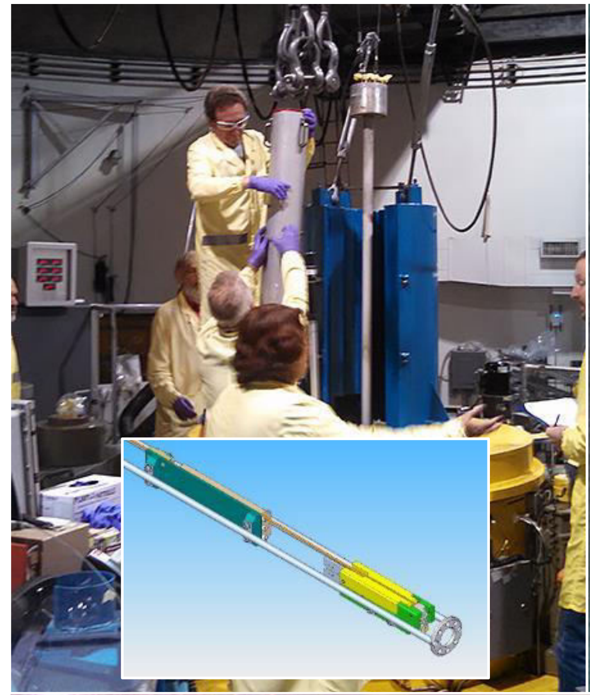


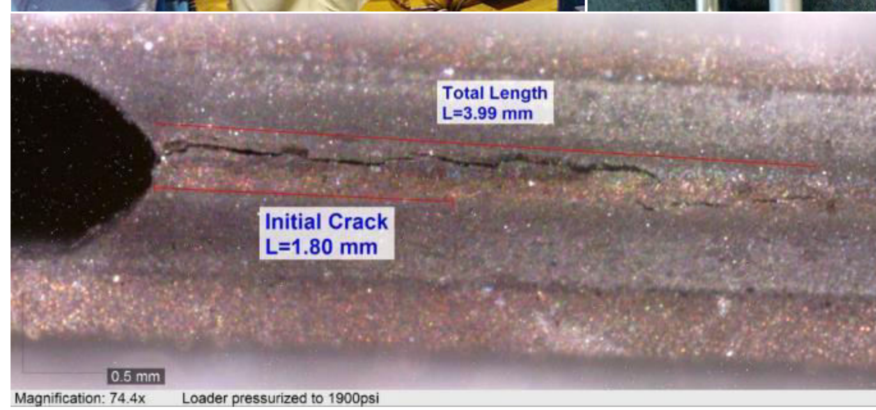




In-Core Crack Growth Monitors

- Collaboration with INL to adapt an in-core crack growth measurement technique from the Halden Reactor Project (Norway).
  - Crack growth is **actively controlled**, and the crack length measured **in real-time**
- Successful demonstration provides a path forward to deployment in US test reactors.
  - High-pressure miniature bellows development (3000 psi in-core)
  - Establishing new test protocols
  - Observation and mitigation of significant radiation-induced signal noise (including new saturation phenomena)
- MITR operating flexibility key to achieving desired test evolution



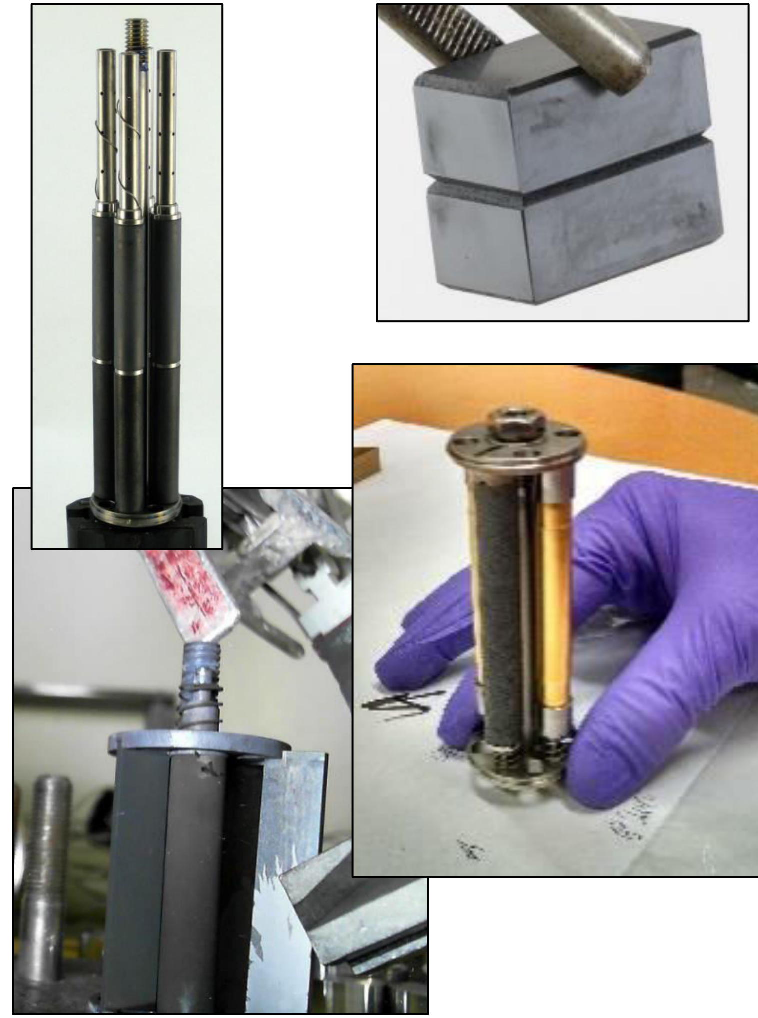


LWR In-Core Electrochemical Potential

- COATI contains 3 ECP probes
  - Real-time measurement of the electrical potential between a passive electrode and the structure of the loop
- Probes are located near the core to capture the local corrosion environment (radiolysis)
- Experimental probes able to withstand high temperature, pressure, PWR chemistry

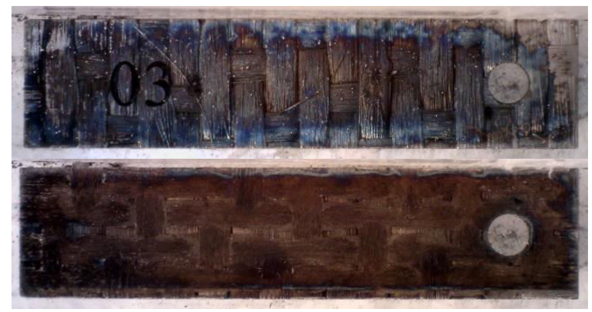
Ongoing Contributions to Accident Tolerant Fuel Development

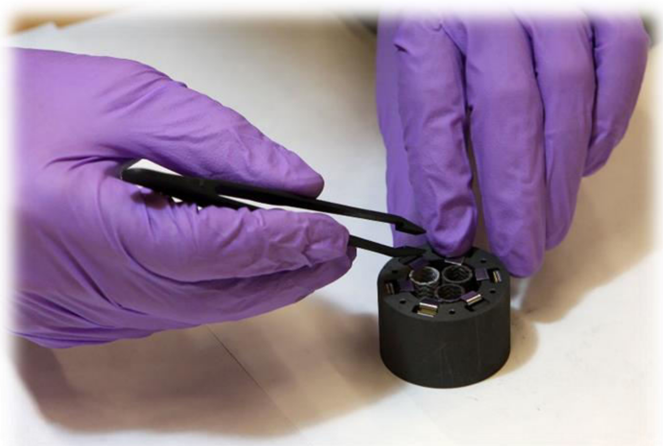
- The MITR water loop is one of the primary irradiation test beds for SiC/SiC$_f$, hybrid (composite on metal alloy) and coated clad materials and sealing techniques
  - Many of these materials have been exposed to irradiation in prototypical coolants for the first time
- PWR or BWR conditions with a wide range of B/Li and dissolved gas concentrations , zinc injection, ^{16}N suppression additives
- Collaboration with Westinghouse, CTP, General Atomics, and Oak Ridge National Laboratory, as well as MIT NSED faculty and staff (Mike Short, Ju Li, Koroush Shirvan)

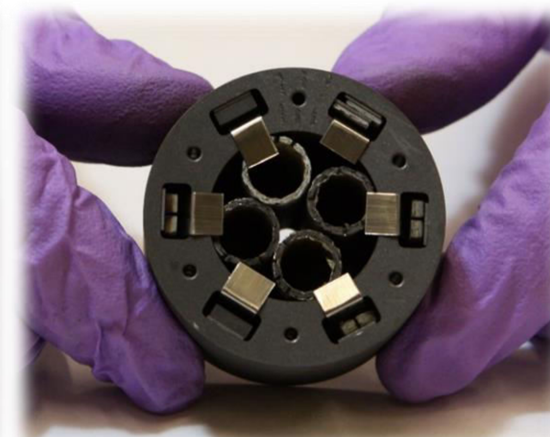


HYCO – Hybrid Composites

- Collaboration with Oak Ridge National Laboratory for Accident Tolerant Fuel materials development
- 60 metal and ceramic specimens irradiated at 320°C in the ICSA (helium)
- Undergoing PIE in NRL hot cells prior to shipment to ORNL

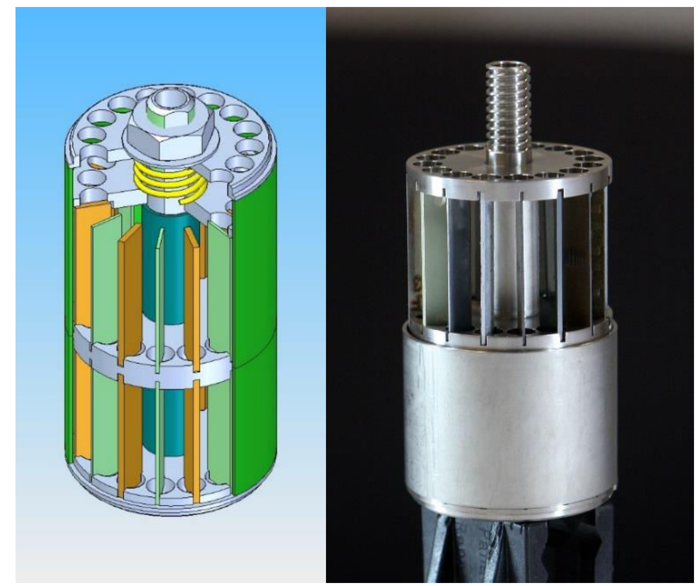






COATI

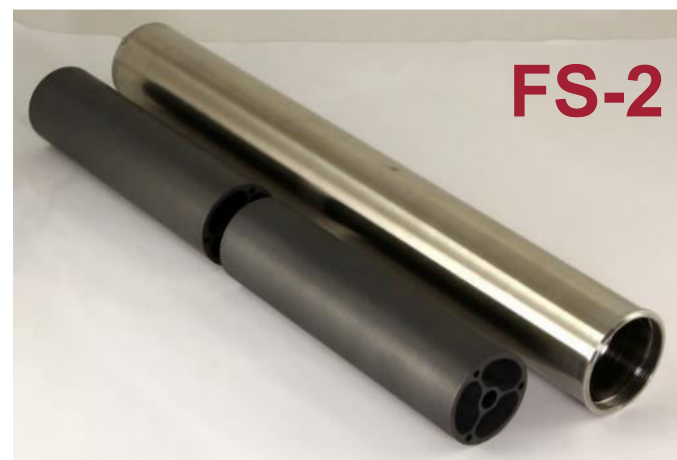
- CTP and ORNL Accident Tolerant Clad Irradiation
- New silicon carbide metal-coated materials at 290°C and 1500 psi in the water loop
- Follow-on to HYCO ICSA irradiation of similar materials



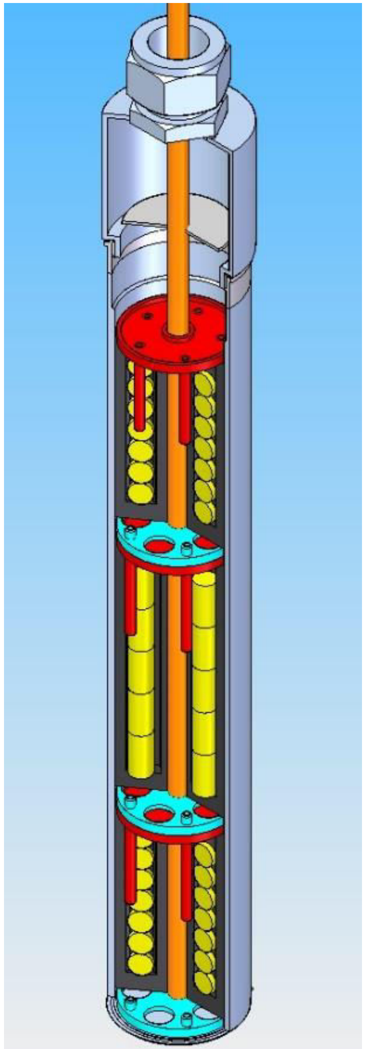
First-of its-Kind Molten Salt Irradiations Completed at MIT

- First in-core irradiation of MSRE flibe in 60 years
- 1000 hours at 700°C
- TRISO, Hastelloy, SS316, and SiC corrosion specimens
- Flibe is 99.995% ^{7}Li; still substantial tritium release

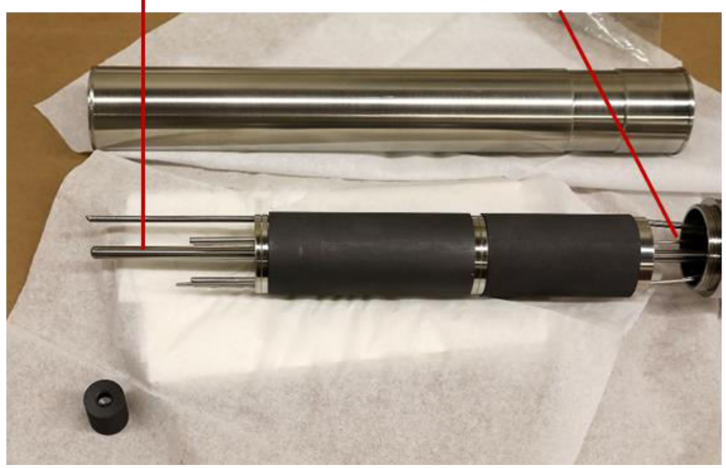
- 2 fluoride redox potentials
- Added graphite and C/C coupons
- Tritium and salt interaction with fuel compact graphite
- Cracking performance of TRISO particles
- 300 hours at 700°C



Fluoride Salt Irradiation #3 (FS-3)

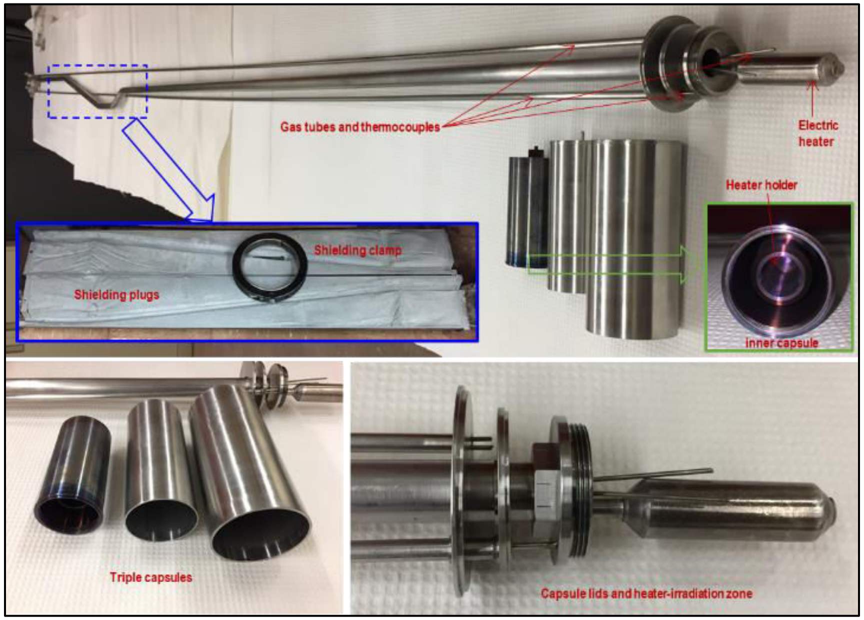


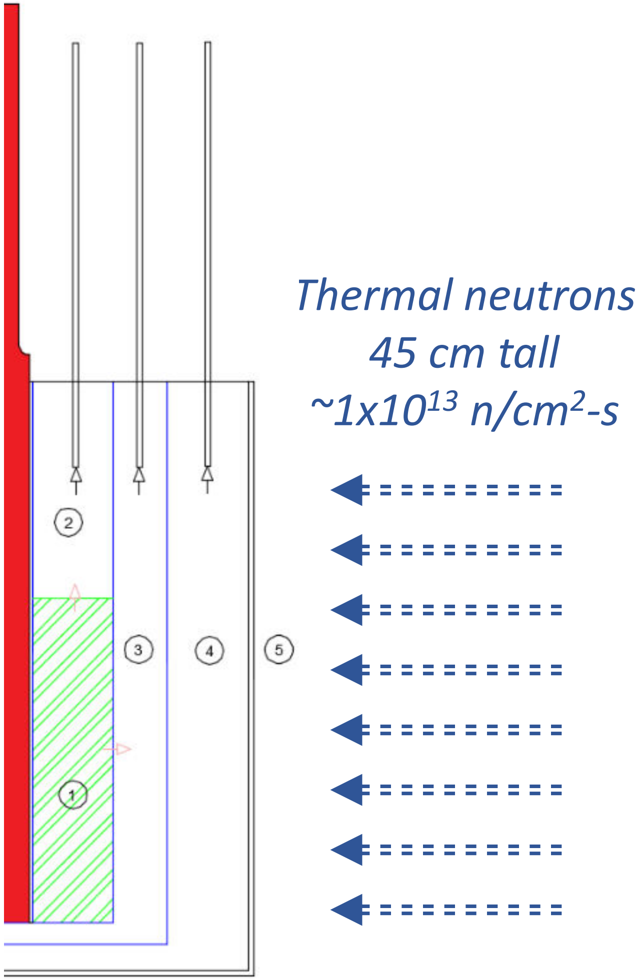
- Large matrix of graphite and C/C specimens (95)
- Applying lessons learned
  - More fluoride capture options/protect instrumentation
  - Electrical guard heating
  - Hydrogen injection system
- MSRE enriched flibe cleaned at UW-Madison, analyzed at MIT via NAA
- Flibe and specimens loaded into graphite crucibles at UW
- Dried in furnace at MIT, then assembled into nickel capsule under helium



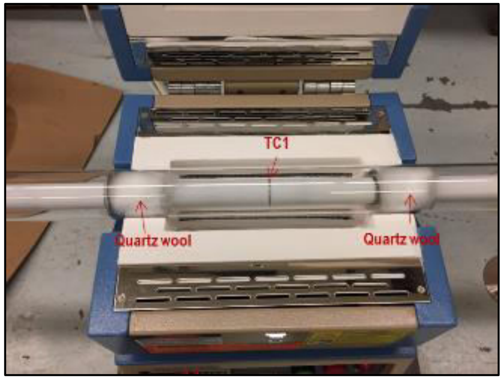
Fluoride Salt Tritium Permeation (FS-4)

- Use MITR thermal neutron beam (3GV) to continuously generate tritium in flibe salt at 600-700C
  - Vertical position for improved access, flux
  - Electrical heating complemented with nuclear
- Investigate **steady-state** tritium diffusion through metals, barrier coatings
  - Salt contact on inside surface





Fluoride Salt Tritium Permeation (FS-4)

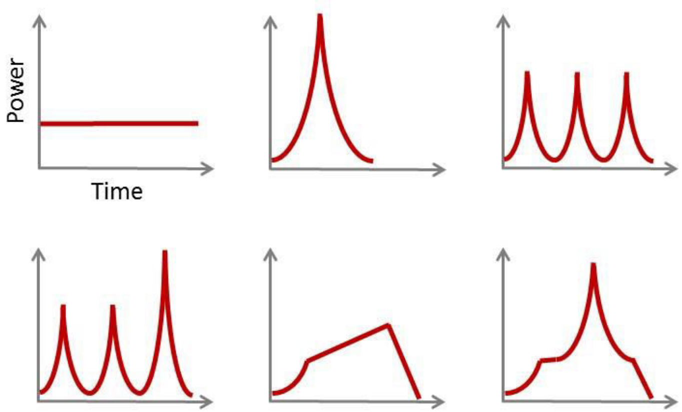


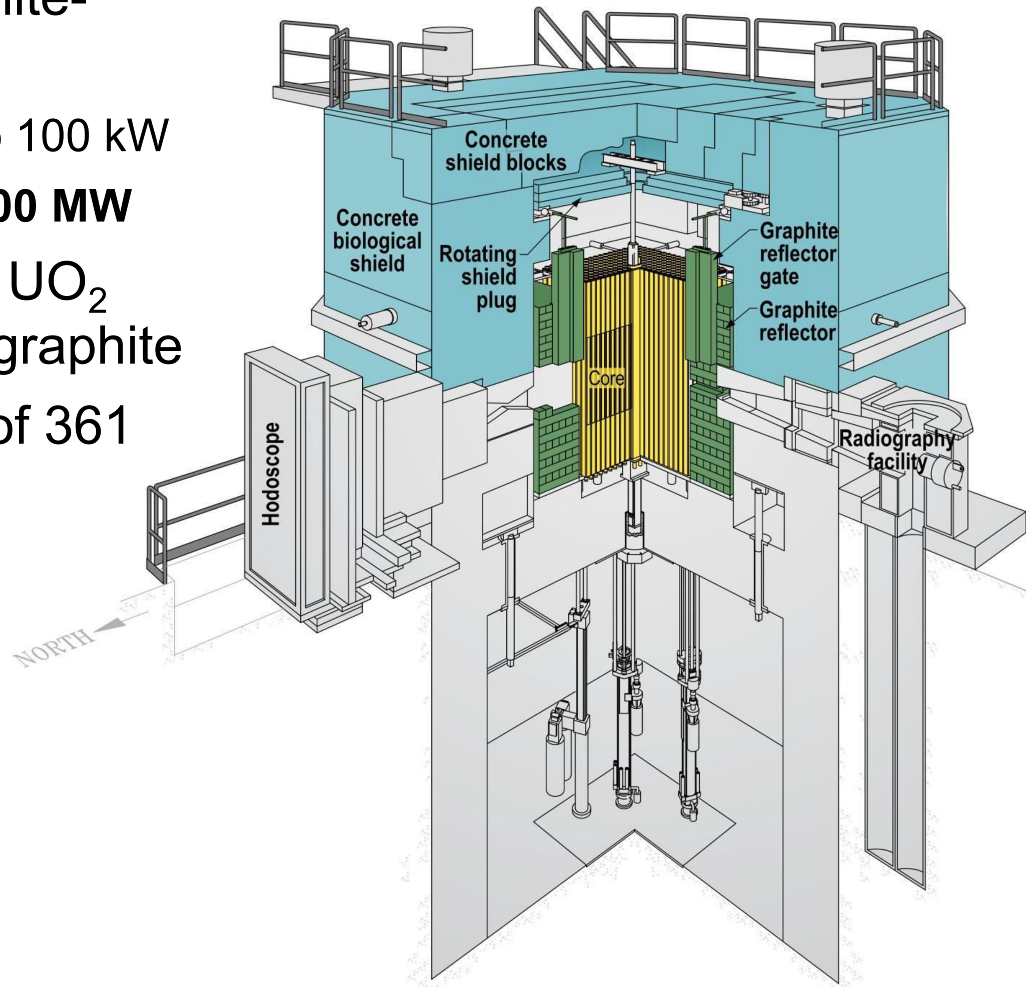
- External tube furnace allows tritium diffusion testing in the absence of neutron or gamma irradiation
- Quartz barrier prevents tritium release at high temperature
- Multiple test sections can be quickly installed
  - Bare 316SS
  - Alumina coated (with intermediate coatings) 316SS

- Three days of operation at low power
  - 100-200kW with natural flibe produces sufficient tritium
  - 620°C flibe temperature
  - He/H2 purge gas in four independent flow systems
- Order of magnitude reduction in tritium permeation with “first-effort” alumina coating

TREAT – INL Transient Test Reactor

- A graphite-moderated, graphite-reflected, air-cooled reactor
  - Steady-state operation up to 100 kW
  - Pulsed operation up to **18,000 MW**
- Fueled with 93.1% enriched UO_2 particles finely dispersed in graphite
- TREAT core has maximum of 361 fuel assemblies (19 x 19)





TREAT Instrumentation Tests

- Collaboration with Oregon State University, University of Michigan, and INL on **instrumentation and benchmarking** in support of the **TREAT restart**
- Irradiations in the MITR test sensors and produce data to support code benchmarking
  - TREAT steady-state equivalent <100 kW
  - Positive and negative reactivity insertion transients
- Follow-on irradiation with identical setup in TREAT (M8CAL test position)

First university-led experiment completed in June 2018.

Fission wire

Natural uranium, U/Cd

Activation wires/foils

Al-Co, Fe, Fe-Ni-Cr, Nb, Ti, Cu-Au

Self-Powered Detectors

Gamma (platinum), Neutron (vanadium)

Miniature Fission Chambers

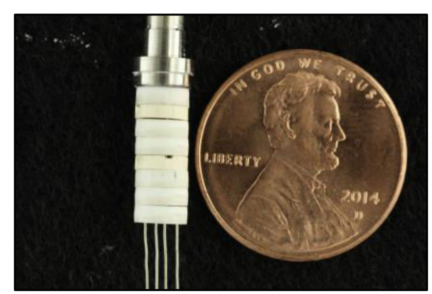
Enriched uranium in metal rods

Micro-Pocket Fission Detectors

Uranium and thorium in a metal rod

Mini FC

MPFD



Shipment to INL-TREAT

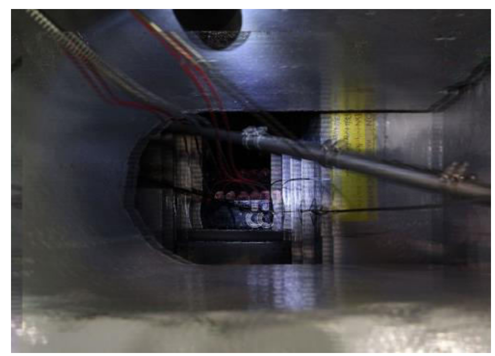
Irradiated Experiment Test Assembly (from MIT to INL)

Irradiated Activation Wires (from TREAT to INL Counting Lab)

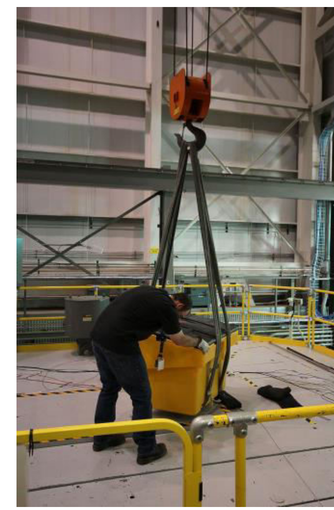
Installations

Loading Instrumentation Assembly into TREAT M8CAL Core

Arranging Cables

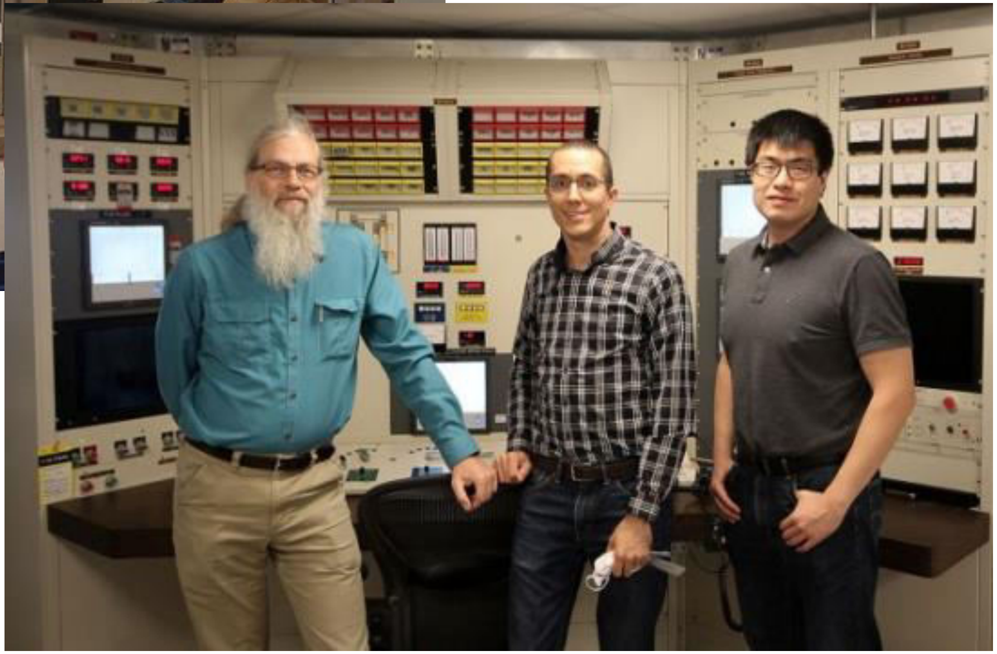


Experiment Top View



Complete Shielding

TREAT Experiment



Supporting and PIE Capabilities

- Beam ports/neutron radiography
- Pneumatic tubes/rabbits
- Neutron activation analysis - High-efficiency gamma spectroscopy and scintillation lab
- Hot cell and hot box facilities
  - Optical profilometry - 1.6µm x 12nm resolution
  - Scanning electron microscopy with EDS
  - Xenon-flash thermal diffusivity analyzer
  - New PIE lab in restricted area (SEM, instron machine etc.)

Summary

- MITR offers complementary capability to DOE test reactors (ATR, TREAT, HFIR) and plays an important role in national programs such as Nuclear Science User Facilities (NSUF), Accident Tolerant Fuel, advanced sensors/instrumentations.
- MIT-NRL research team is specialized in new reactor experiment demonstration such as crack growth monitor, and high-temperature salt and materials irradiation to support FHR/MSR program.
- Demand has increased from DOE programs (through NEUP/NSUF/GAIN programs, national labs) and industry (TerraPower, KairosPower, Westinghouse)
  - Advanced reactors, materials and sensors development program
  - MITR's ease-of-access to university and industry researchers
  - Track-record in project execution.


Thank you!