May 21, 2024

J. Keith Jewell, Ph.D.

2024 NSUF MSI Relationship Development Workshop

NSUF Irradiation Capabilities



NSUF Nuclear Science User Facilities

NSUF Capabilities Offer Research Opportunities

Neutron Irradiations	Ion Irradiations	Gamma Irradiations	Hot Cells & Shielded Cells	Low Activity Laboratories	Beamlines	High Performance Computing
INL Idaho National Laboratory	Wisconsin University of Wisconsin-Madison	INL Idaho National Laboratory	INL Idaho National Laboratory	INL Idaho National Laboratory	Brookhaven National Laboratory	INL Idaho National Laboratory
Oak Ridge National Laboratory	University of Michigan	Oak Ridge National Laboratory	Oak Ridge National Laboratory	CAES Center for Advanced Energy Studies	Argonne National Laboratory	
Massachusetts Institute of Technology	Argonne National Laboratory	Sandia National Laboratories	PNNL	Oak Ridge National Laboratory	NC State University	
NC State University	Sandia National Laboratories		Los Alamos National Laboratory	Cal	Los Alamos National Laboratory	
Ohio State	Texas A&M University		Westinghouse	PNNL		
Sandia National Laboratories	Lawrence Livermore National Laboratory		University of Michigan	Los Alamos National Laboratory		
SCK•CEN Studiecentrum voor Kernenergie Centre d'Etude de l'Energie Nucleaire			SCK•CEN Studiecentrum voor Kernenergie Centre d'Etude de l'Energie Nucleaire	NC State University; University of Michigan; Purdue University; Wisconsin; University of Florida		
				SCK•CEN Studiecentrum voor Kernenergie Centre d'Etude de l'Energie Nucleaire		

Visit nsuf.inl.gov for details of individual facilities

Traditional In-core Test Reactors

Advanced Test Reactor (ATR)

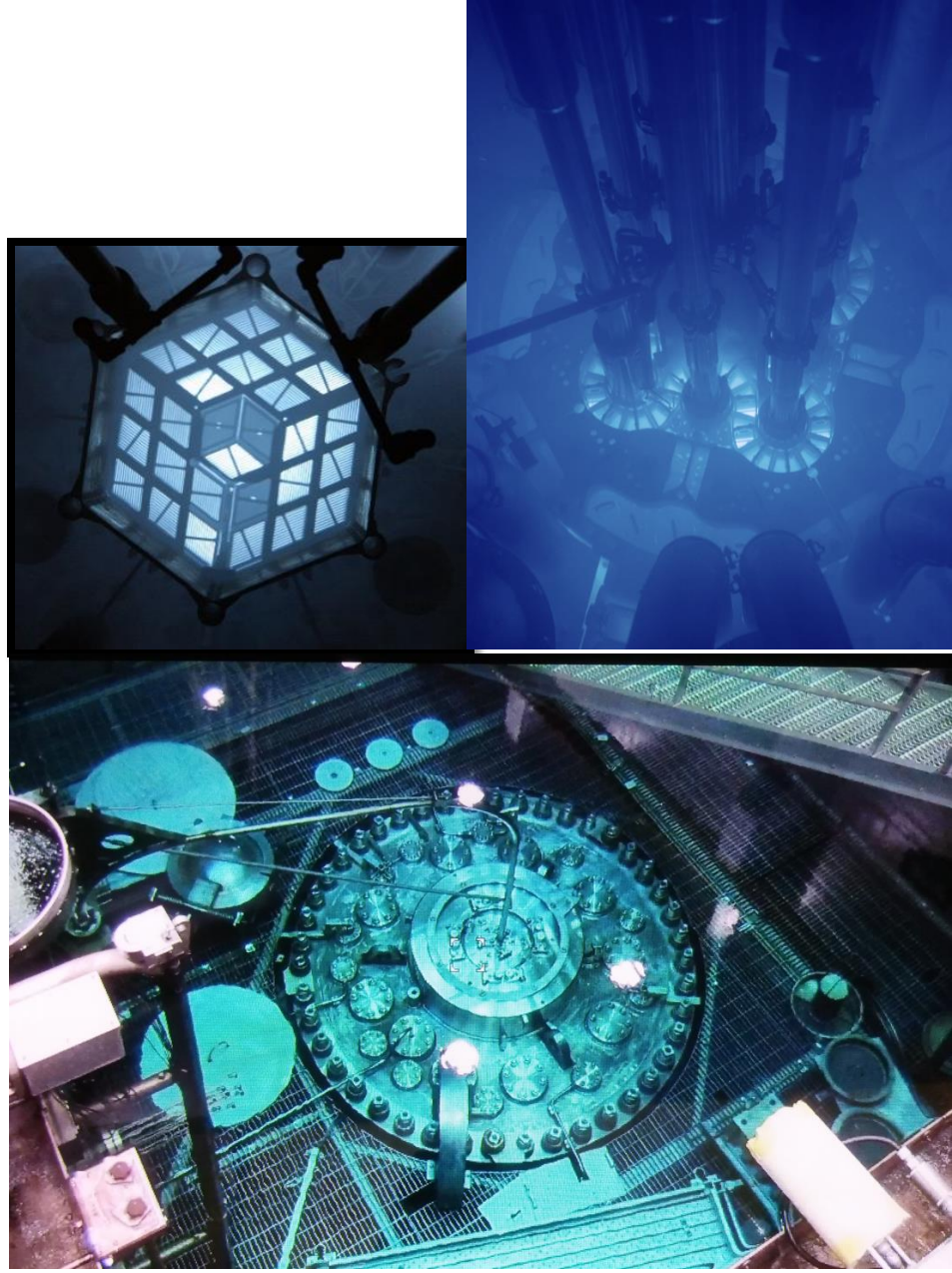
- 48” core height, multiple irradiation positions.
- Suitable for fuels and materials, multiple PWR water loops, standard capsules.

High Flux Isotope Reactor (HFIR)

- Highest thermal and fast flux in US.
- Multiple irradiation positions, reduced sized fuel specimens, standard capsules.

Massachusetts Institute of Technology Reactor (MITR)

- High temperature 1600 C loop, LWR water loop.
- Instrumentation testing, open access.

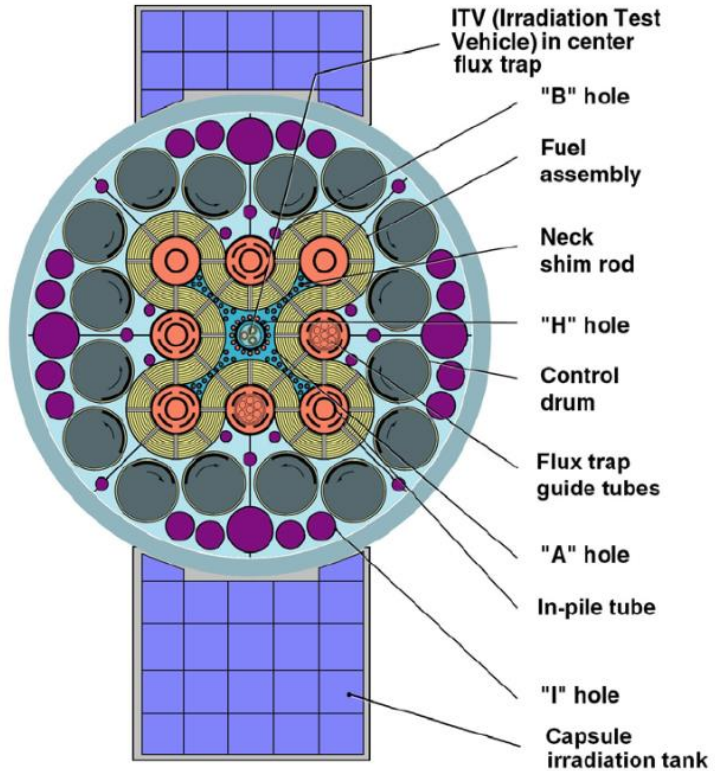


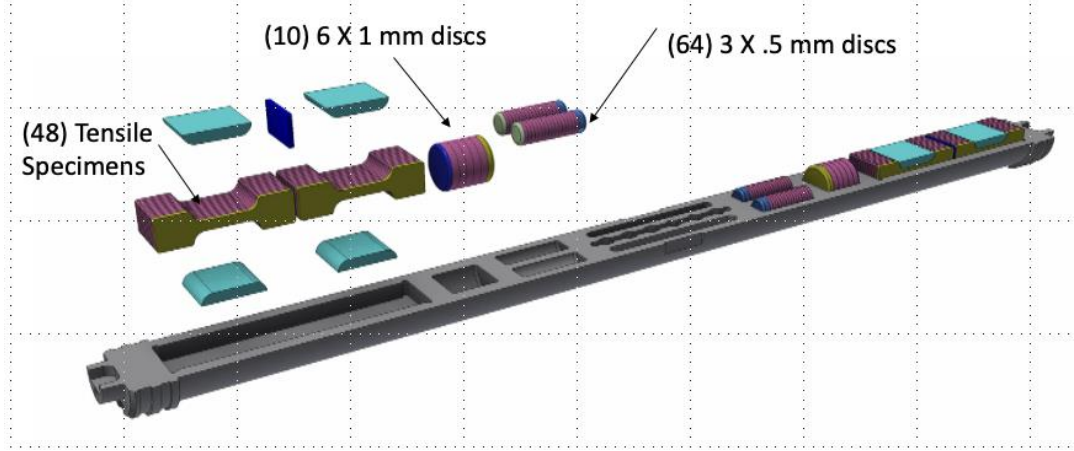
Case Comparison 2 dpa in 316 SS

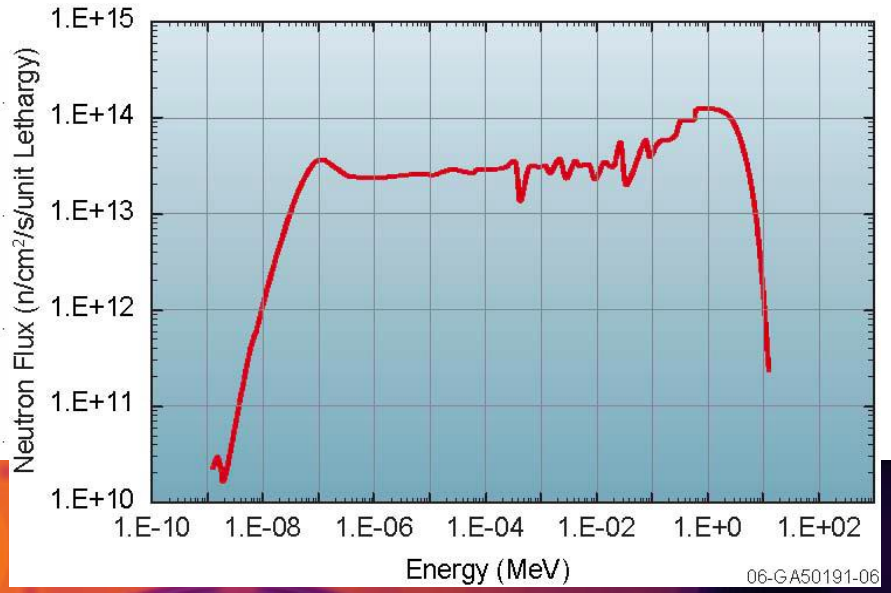
Reactor	Position	Diameter [cm]	DPA	Days	Cycles	Years	Thermal Fluence [n/cm^2]	Fast Fluence [n/cm^2]	Total Fluence [n/cm^2]
ATR	A1	1.6	2	76.2	1.4	0.4	9.91×10^{20}	3×10^{21}	6.74×10^{21}
ATR	A13	1.6	2	86.1	1.6	0.5	1.2×10^{21}	2.95×10^{21}	6.79×10^{21}
ATR	B1	2.2	2	174.3	3.2	1	2.26×10^{21}	3.18×10^{21}	9.53×10^{21}
ATR	B9	3.8	2	583	10.6	3.2	2.91×10^{21}	3.45×10^{21}	1.27×10^{22}
HFIR	PTP	1.1	2	30.9	1.1	0.2	2.85×10^{21}	2.91×10^{21}	8.89×10^{21}
HFIR	RB5B	4.6	2	170.4	6.3	0.9	7.72×10^{21}	3.33×10^{21}	1.7×10^{22}
HFIR	VXF12	4	2	3451.5	127.8	18.3	7.65×10^{22}	2.93×10^{21}	9×10^{22}
MITR	ICSA	4.1	2	408.2	6.5	1.6	7.16×10^{20}	3.09×10^{21}	6.56×10^{21}
MITR	WATF	5.1	2	371.6	5.9	1.5	1.16×10^{21}	3×10^{21}	7.18×10^{21}

Advanced Test Reactor

- 110 MW, 50-60 day cycles typical operation
- $2x10^{14}$ thermal and $2x10^{14}$ n/cm^2-s fast spectrum
- Serpentine core creates nine flux traps and numerous irradiation test positions.
- Multiple experimental positions 1.3 to 12.7 cm diameter

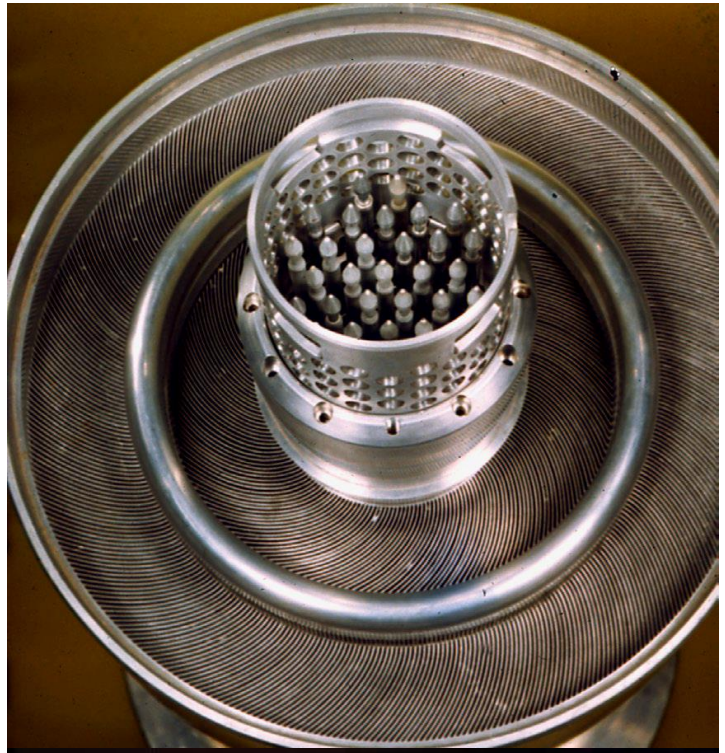


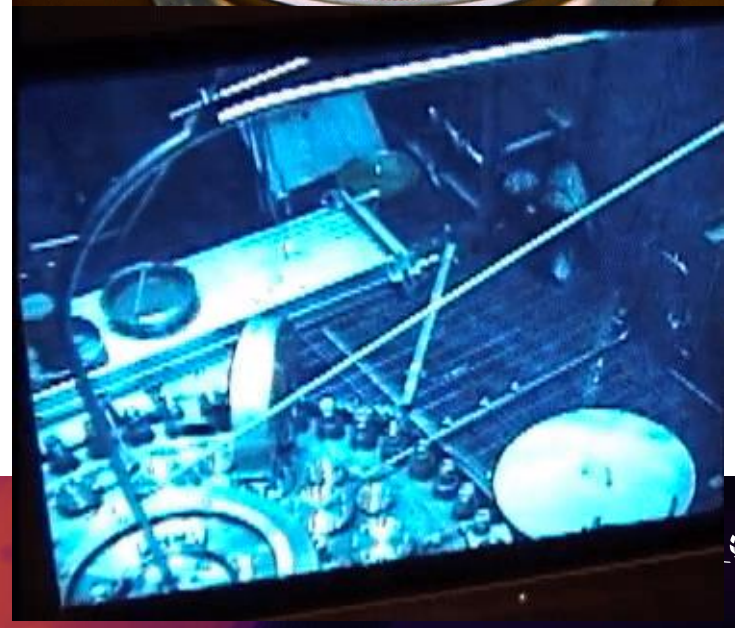




High Flux Isotope Reactor

- Constant 85 MW reactor power.
- 23–25 days/cycle, 6–8 cycles per year.
- Operating 40–50% of calendar year.
- ~50°C, ~3 MPa light water coolant.
- Internal experiment temperatures can range from ~100 to >1000°C (2000°C+, FY23).
- Highest steady-state neutron flux in US.
- Most economical option for many materials irradiations.
- End-of-life light water reactor (LWR) dose (~20 dpa) or fuel burnup (~60 MWd/kg U) achievable in 1–2 calendar years.



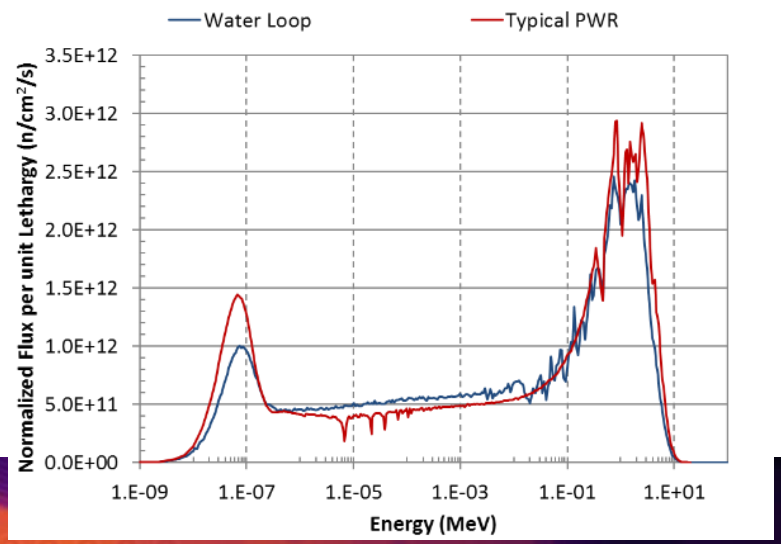


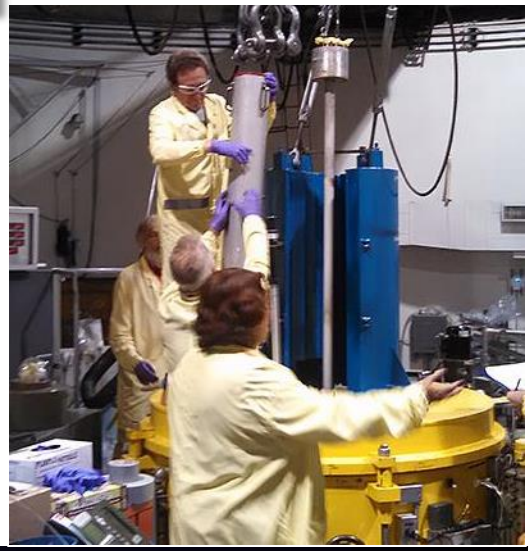


Massachusetts Institute of Technology Reactor

- MITR 6 MW Research Reactor, operating since 1975.
- Light water cooled and moderated with very similar power density to LWR.
- Operates 4 quarterly cycles, 24/7, 8-10 weeks each.
- Cost effective, multiple sensor and instrumentation experiments.
- 3.6x10^{13} n/cm^{2}s thermal, fast flux 1.2x10^{14} n/cm^{2}s.







Transient Reactor Experiment and Test Facility (TREAT)

- Transient testing of accident and fuel failure conditions.
- Shaped, high power pulses from 20 GW (80 ms duration) to 120 kW steady state.
- Graphite thermal expansion limits reactivity.
- LOCA and RIA accident testing.
- Module design for PWR and sodium loop
- Highly instrumented, in-situ testing.
- Fast neutron hodoscope for fuel imaging

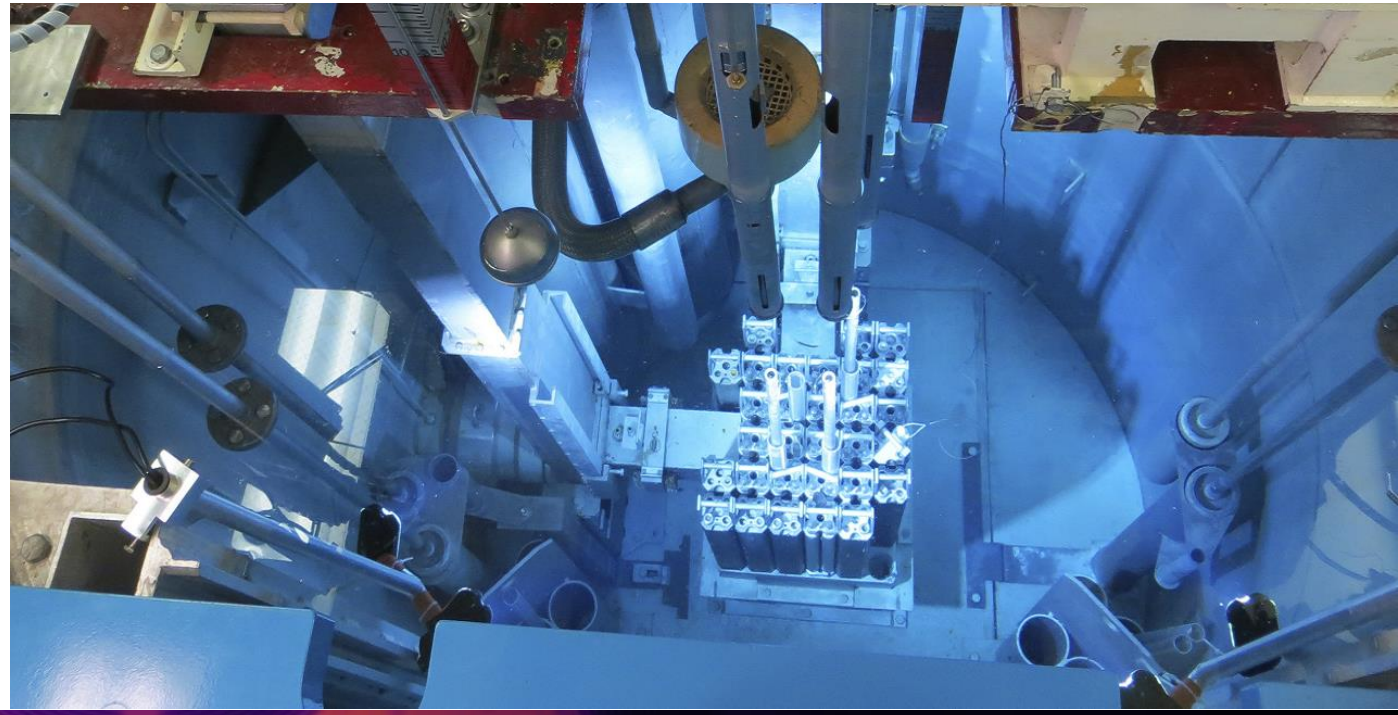




Hodoscope for fission neutron monitoring

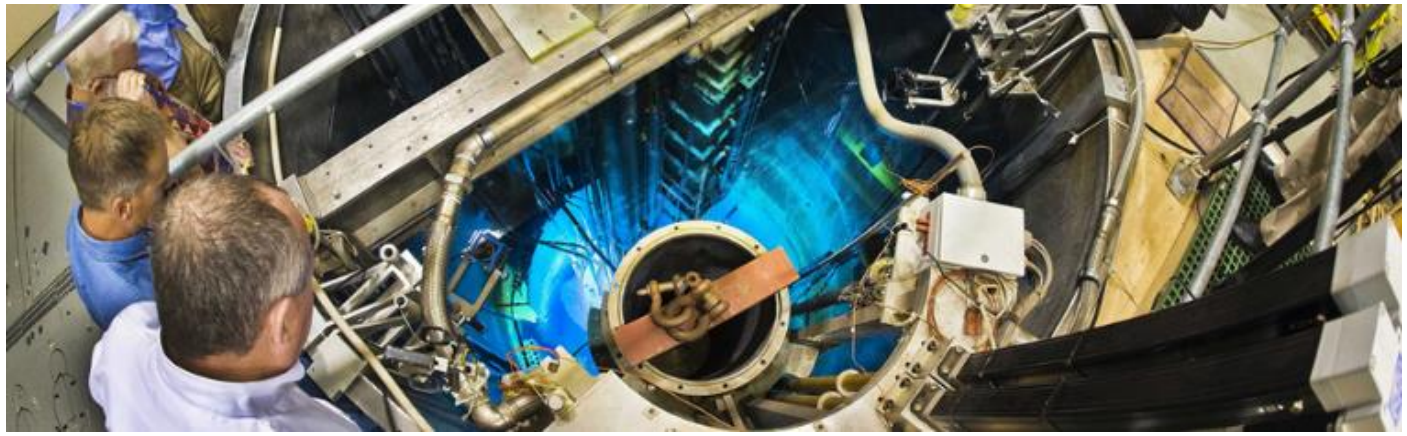
Neutron Radiography Reactor (NRAD)

- 250 kw TRIGA, operating since 1977
- Coupled to the HFEF hot cell facility.
- Non-destructive imaging of fuel pins, fuel migration.
- Low level, thermal neutron instrumentation testing
- In-pile fuel testing (TRISO, molten salts)
- Up to 5.2×10^{12} n/cm^2s flux



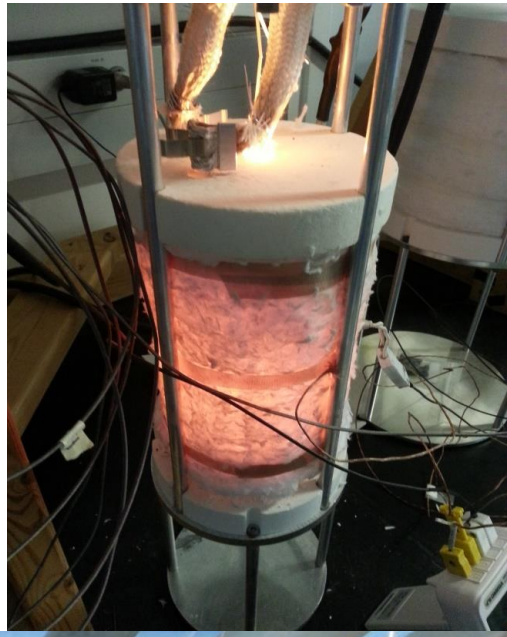
Annular Core Research Reactor (ACRR)

- Annular core with large volume position.
- Very low gradient of neutron flux across position.
- Mixed neutron and photon irradiations.
- Radiography, neutron scattering, non-destructive testing.
- Neutron activation analysis.
- Steady-state 4.4 MW, pulsed up to 60 GW.
- $4x10^{13}n/cm^2s$ flux



The Ohio State University Research Reactor (OSURR)

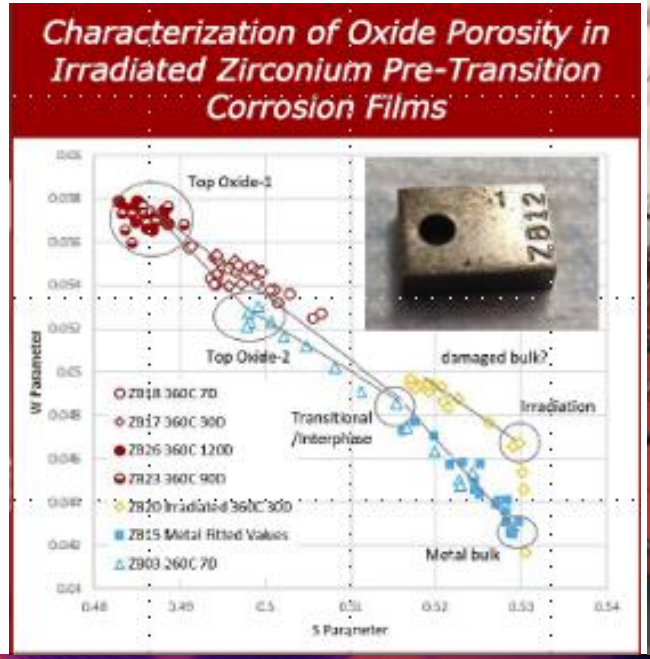
- 500 kW, open pool, MTR, LEU fueled reactor.
- Up to $2.3x10^{13}$ n/cm^2s flux in central dry tube.
- In situ instrumentation capabilities.
- Near core furnaces for heated experiments.
- Thermal and fast neutron beam lines.

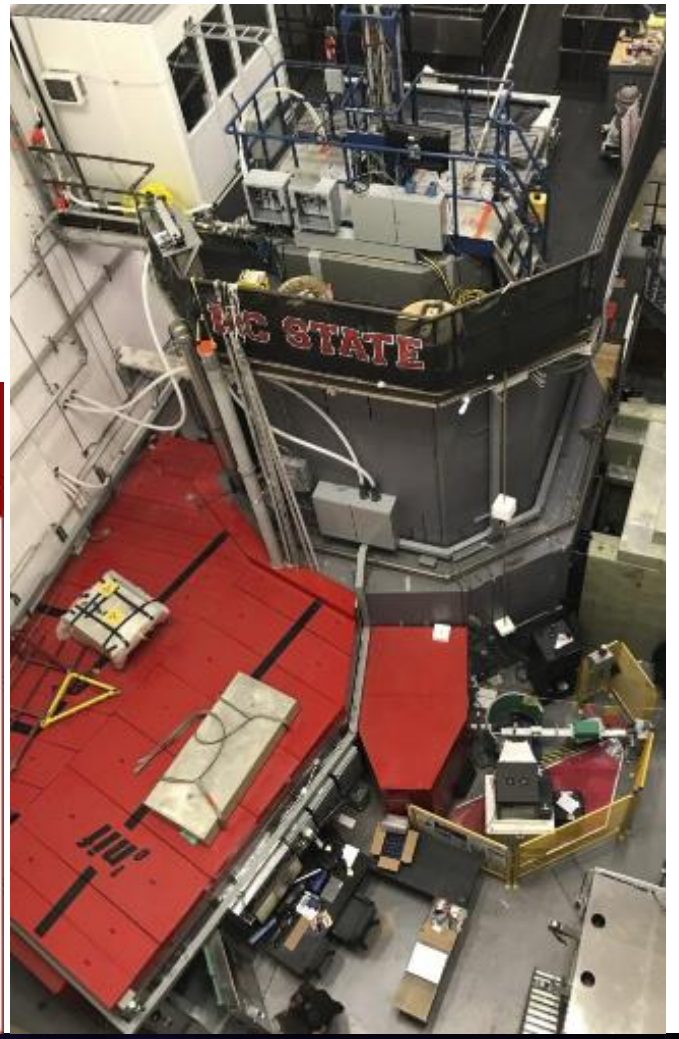




North Carolina State Nuclear Reactor Program (PULSTAR)

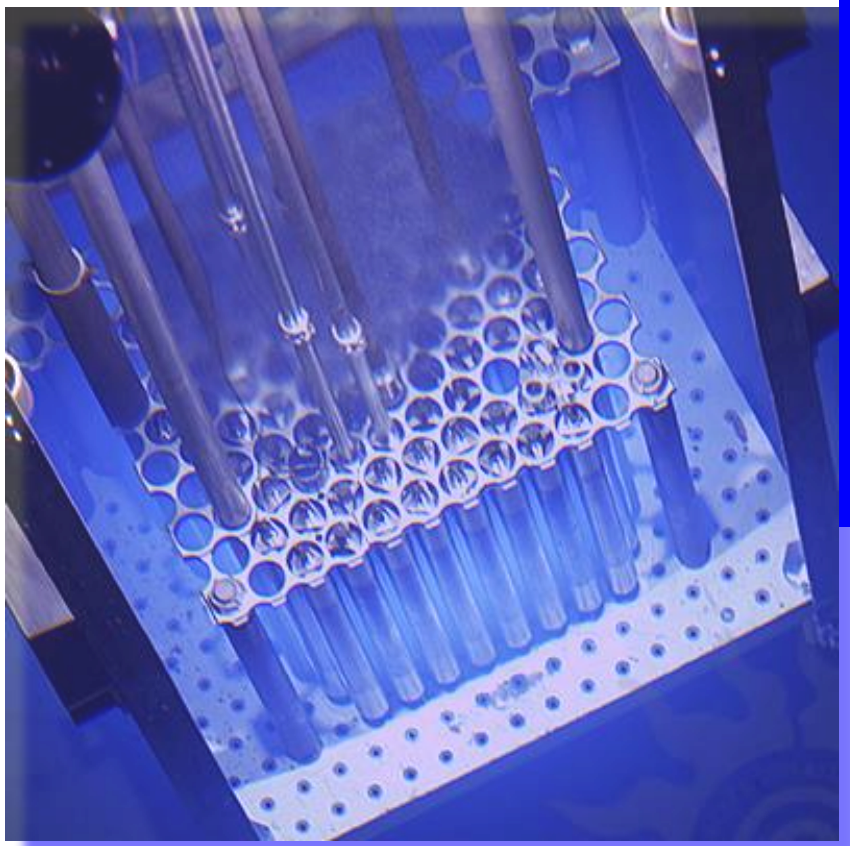
- 1 MW open pool, LEU fuel pins.
- $1x10^{13}$ thermal and $1x10^{12}$ fast n/cm^{2}s flux.
- Multiple beam ports for
  - Neutron powder diffraction
  - Neutron imaging
  - Intense positron source
  - Ultra cold neutron source

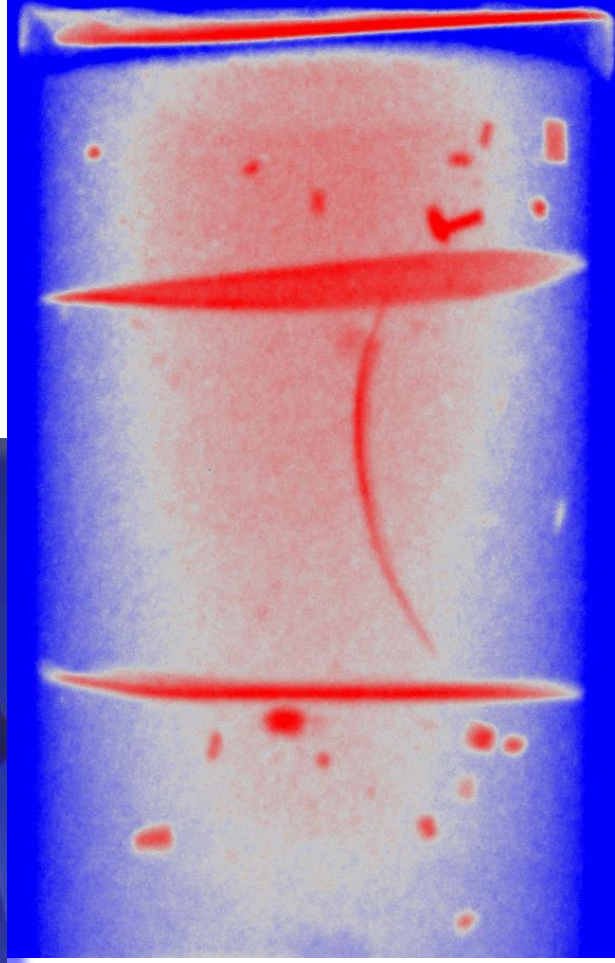




Breazeale Nuclear Research Reactor

- 1 MW TRIGA, open pool
- $3x10^{13}$ n/cm^2s thermal flux
- Newest NSUF partner
- Neutron imaging facility (3-D tomography)
- Gamma irradiation facilities
  - In-pool irradiators
  - Gamma cell dry irradiator (6,000 Ci Co-60, 0.5 Mrad/hr)

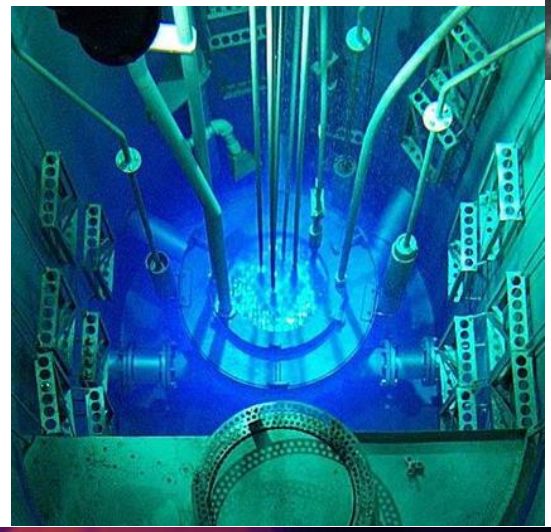




University of Texas NETL Reactor

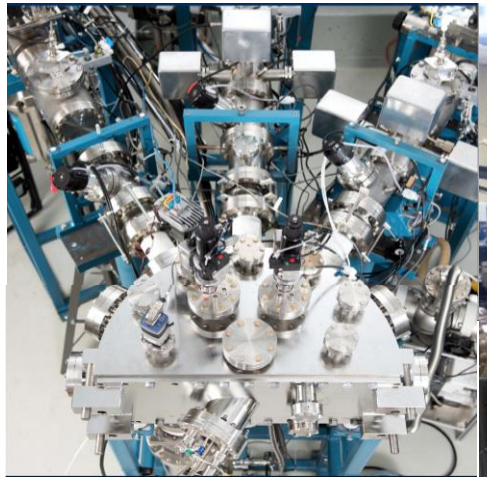
- 1.1 MW Mark II TRIGA, operating since 1992
- Primarily a neutron beam facility
  - Prompt gamma-ray activation analysis (PGAA)
  - Cold neutron source
- New NSUF partner
- Additional radiation sources
  - Thermo 20 KHz neutron generator
  - MultiRad irradiator 20 Gy/min dose



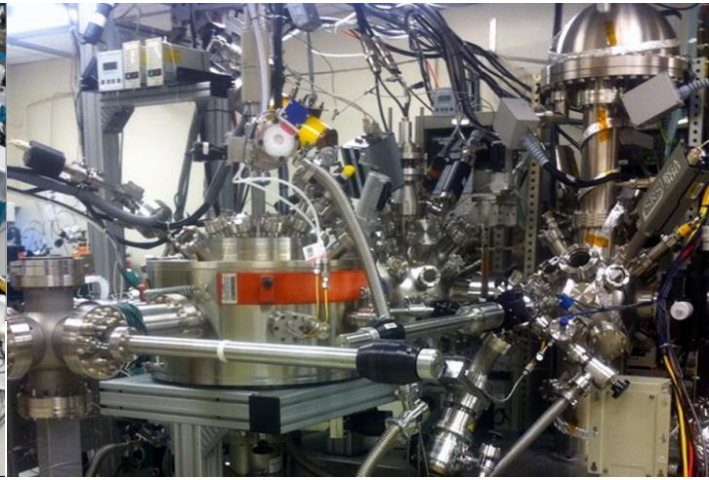


Ion Beam Capabilities

- Michigan Ion Beam Laboratory
  - In situ TEM, triple beam irradiation, in situ creep, corrosion
  - Full talk later today
- Argonne IVEM Tandem Facility
  - In situ TEM, dual beam irradiation
  - Cryogenic, strain testing
- University of Wisconsin
  - 1.7 MV Pelletron accelerator, TORVIS plasma source
  - 3 beamlines with IR laser, IR camera, pyrometer, cryogenic cooling
- Texas A&M Accelerator Laboratory
  - 24/7 operation, wide temperature range (LN to 800 C)
  - Self ion irradiation (Fe in steel, Ni in Inconel, etc.)
- Sandia Ion Beam Facility
  - Light elements H through F, heavy C-Pu
  - Single Event Upset advanced imaging (sub-micron resolution)
- LLNL Center for Advanced Mass Spectroscopy
  - Self-ion irradiation, displacement damage 10^{-3} dpa/s
  - Cryogenic to 800 C
- Purdue University Center for Materials Under Extreme Environment
  - IMPACT Lab, thin film prep, ion beam sputter
  - Ion irradiation 300 eV-2 keV, Auger electron, X-ray Photoelectron, spectroscopy

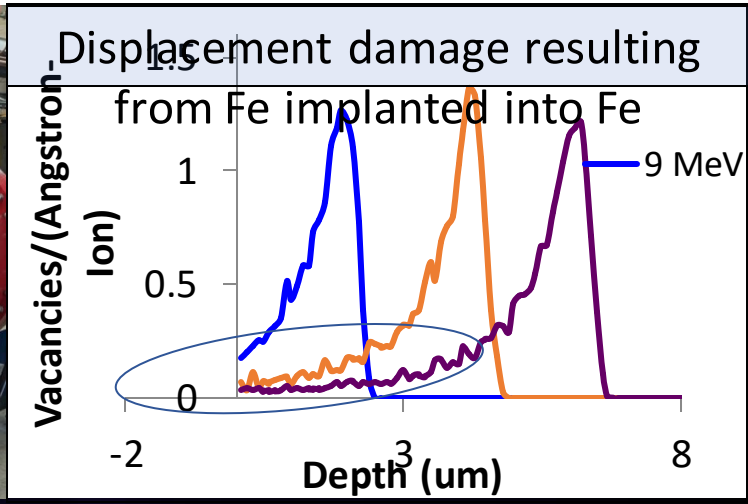


MIBL, triple beam

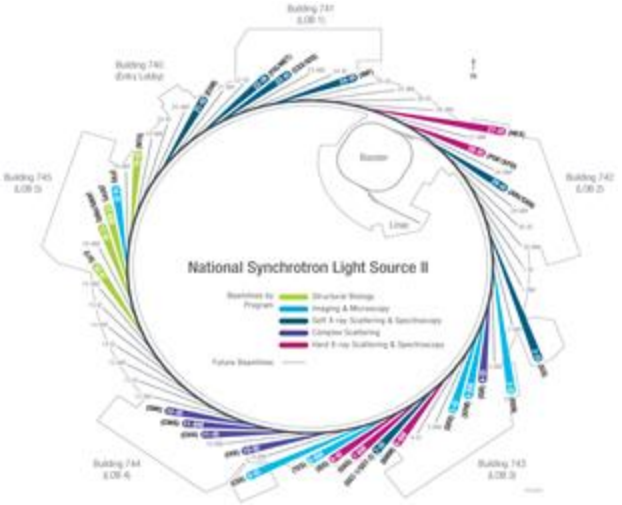


Purdue IMPACT





Beamline Capabilities





- Argonne Advanced Photon Source
  - Ultra-bright high-energy storage ring
  - Activated Materials Laboratory (2024)
- Brookhaven National Synchrotron Light Source
  - New HEX beamline 30-150 keV monochromatic
  - High energy x-ray imaging, 1 um resolution
- Los Alamos LANSCE
  - Advanced neutron imaging, fuels and materials
  - Transmission and scattering spectra




NSUF
Nuclear Science
User Facilities

MIT NUCLEAR REACTOR LABORATORY

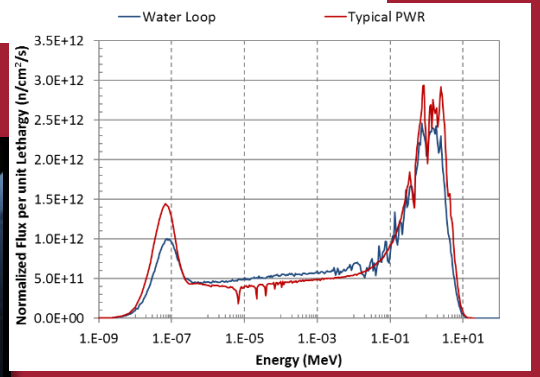
an MIT Interdepartmental Center

Nuclear Science User Facilities

MITR 6 MW Research Reactor

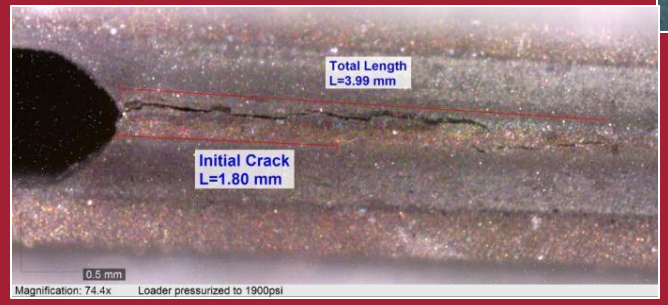
- Current core operating since 1975
- Light water cooled and moderated with very similar power density to LWR
- Operates 4 quarterly cycles, 24/7, 8-10 weeks each



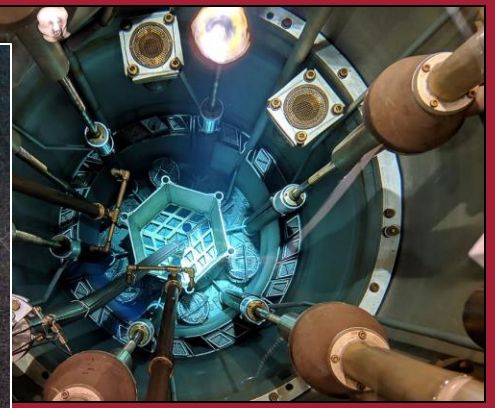


In-Core Real Time Crack Growth Measurement

- Collaboration with INL to adapt a technique from the Halden Reactor Project (Norway).
  - Crack growth is **actively controlled using bellows loader** for cyclic loading
- MITR operating flexibility key to achieving desired test evolution









Nuclear Materials R&D at 3025e (IMET): Handing of HFIR Irradiation Vehicles & Testing

Fundamental radiation effects research and mechanical property measurements in support of material qualification

Nuclear Material Irradiations

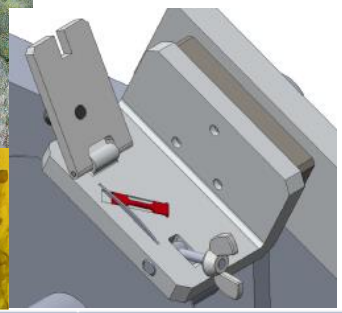


3025e Capabilities









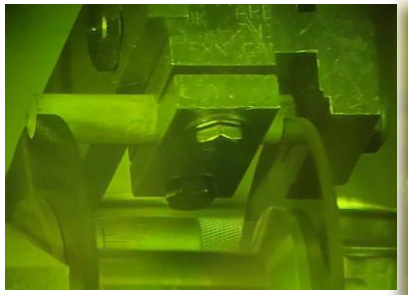
Yearly Nuclear Materials Support:

- 40-80 rabbits
- 60+ on-site/off-site shipments
- 1,000+ material property measurements
- Management and inventory of 1,000s of specimens

Small Sample, Non-Fuel Irradiations → **Receipt of Shipments and Disassembly** → **Sample Identification, Sectioning, and Storage** → **High Dose Material Testing and Characterization**



HFIR and other external reactors (i.e., ATR, MIT, BOR60)





Rabbit Disassembly on Low-Speed Saw and End Mill



High Temp Tensile Testing



In-cell JEOL SEM 6010LA

Creep, Hardness, Fracture Toughness, Charpy Impact, Fractography, Swelling

Impact

International Significance: Critical to HFIR irradiation testing workflow offering the highest fast flux in the world

Scientific Contribution: Allows ORNL researchers to publish impactful research on radiation effects of materials

Deployment: Next generation nuclear reactors (ARDP) are reliant on 3025e to support material qualification efforts

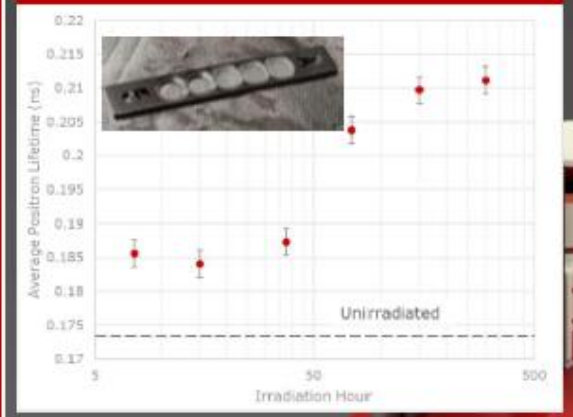
LAMDA: Enables Low Dose Advanced Characterization (TEM, FIB/SEM, Thermophysical Properties)

DOE-Office of Science: Fusion Materials Program
DOE-Office of Nuclear Energy: – Accident Tolerant Fuels (**ATF**), Nuclear Science User Facilities (**NSUF**), Advanced Materials and Manufacturing Technologies (**AMMT**), Advanced Reactor Demonstration Projects (**ARDP**)
Other: Fluor Marine Propulsion and U.S. Nuclear Industry **International Sponsors:** JAEA, UKAEA, CEA

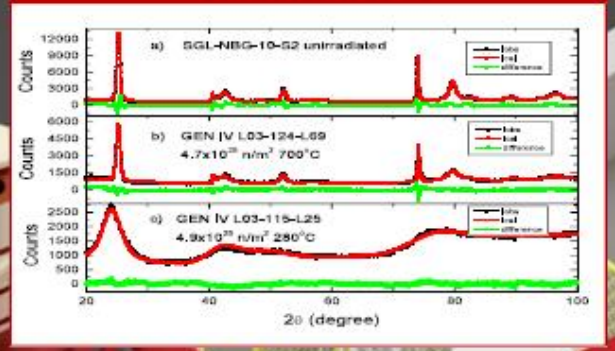
NSUF Nuclear Science User Facilities

NC STATE UNIVERSITY

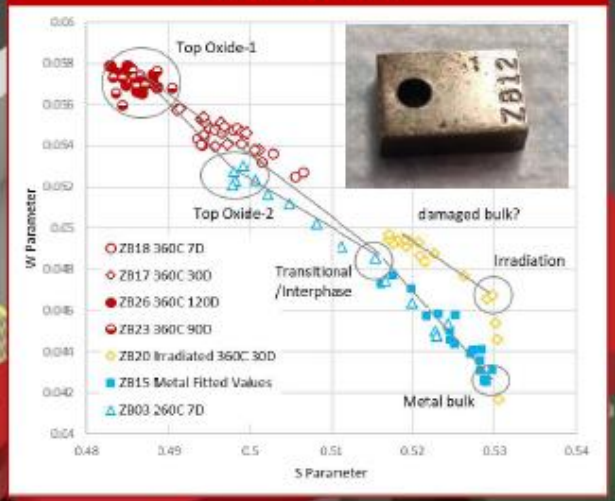
Average positron lifetime of of Ga2O3 before and after irradiation as a function of irradiation hours



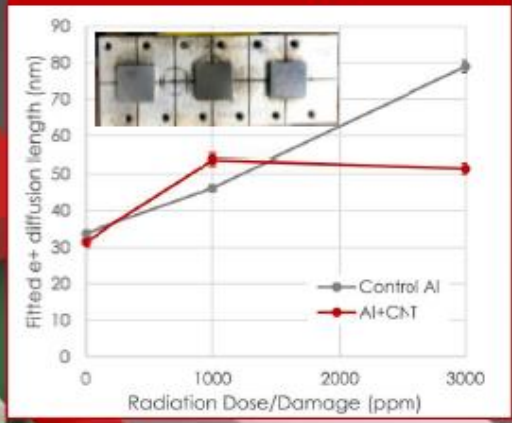
Neutron powder diffraction and transmission in graphite to assess impact of microstructure on neutron thermalization



Characterization of Oxide Porosity in Irradiated Zirconium Pre-Transition Corrosion Films



Quantification of porosity evolution in ion irradiated metal-1D/2D nanocomposites and gas-embrittled steels via Positron Annihilation Spectroscopy



Irradiation of Sensors and Adhesive Couplants for Application in LWR Primary Loop Piping and Components



Neutron Irradiation of a radiation resistant digitizer at PULSTAR



Our Collaborators in Various NSUF Projects

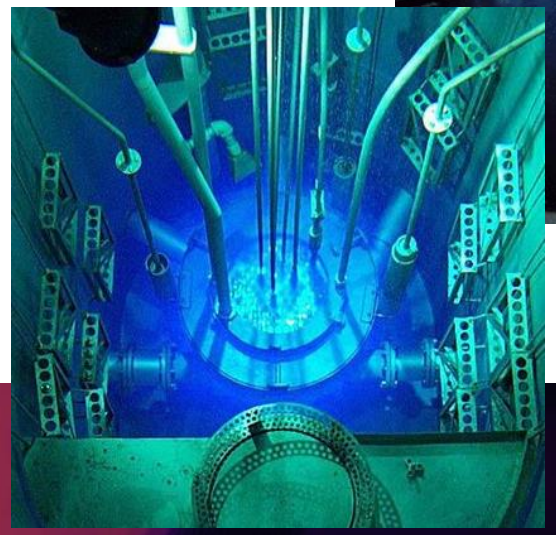
EPRI · MIT Massachusetts Institute of Technology · University of Notre Dame · University of Wisconsin-Madison · Oak Ridge National Laboratory · University of Illinois Urbana-Champaign

NRP NUCLEAR REACTOR PROGRAM

UT-NETL Reactor

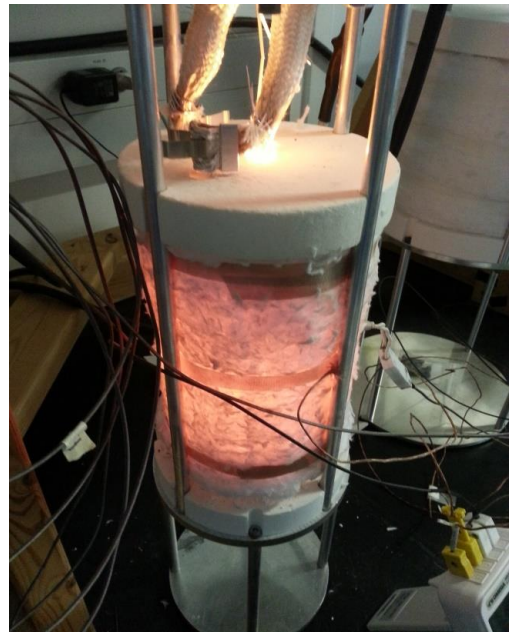
- The University of Texas at Austin - NETL is home to a 1.1 MW TRIGA Mark II reactor with initial criticality in 1992
  - reactor is principally designed as a neutron beam facility and includes a Prompt Gamma-ray Activation Analysis (PGAA) system with a cold neutron source
- NETL includes numerous additional radiation sources:
  - Thermo MP320 14-MeV Neutron Generator ($1x10^8$ n/s with a pulse rate up to 20 kHz)
  - Pu(Be) and Cf-252 Neutron Sources
  - Calibrated α, β, and γ Radiation Sources
    - Including a MultiRad 350 irradiator at 20 Gy/min dose rate



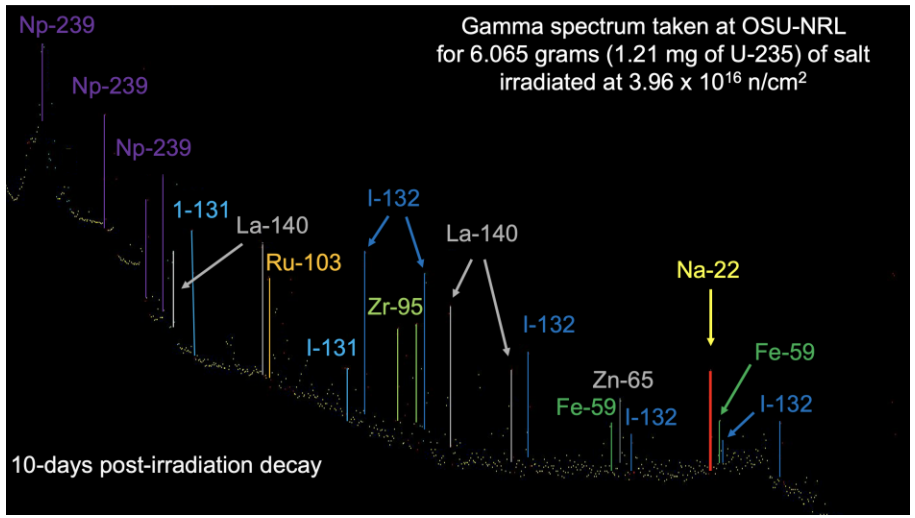


The Ohio State University Nuclear Reactor Laboratory

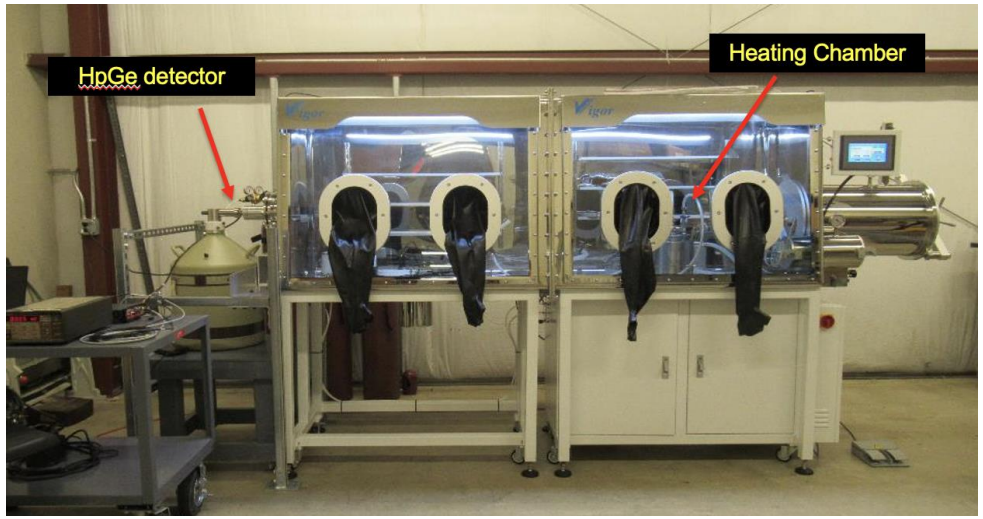
- 500 kW; 2.3 x 10^{13} $cm^{-2}s^{-1}$,LEU fuel; open pool; natural convection cooling
- On-demand operation with in-situ measurement capabilities
- In-core and near-core irradiation under high temperature and high flux
- Thermal and fast neutron beam for neutron CT, neutron depth profile
- Wide user base (e.g., NASA, AFIT, INL, ORNL, LLNL, GE, Apple, etc..)
- Active in RTE (reviewed 12 proposals in 2022, 8 so far in 2023), NSUF 1.2



New capability: Fuel salt irradiation and processing



Fission products spectrum of fuel salt [1.3 mg U-235]



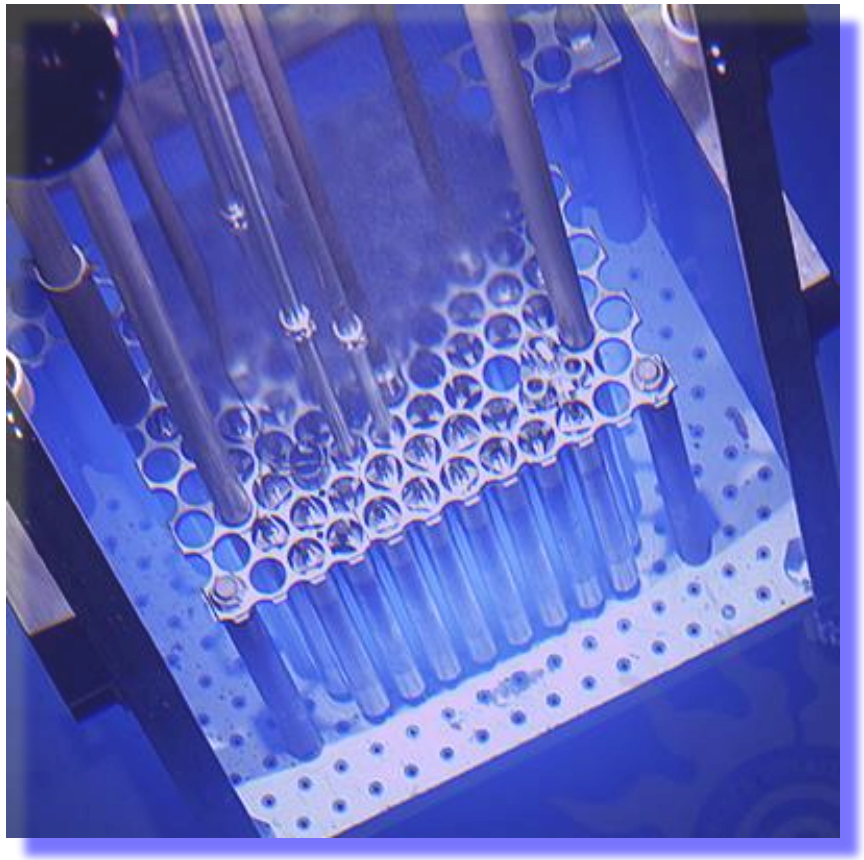
Fuel Salt Processing and Gamma Counting Facility

5 generations of furnaces for near-core heated experiments:

- Fiber optics,
- High-temperature fission chamber
- Nuclear thermal proportional

Radiation Science & Engineering Center

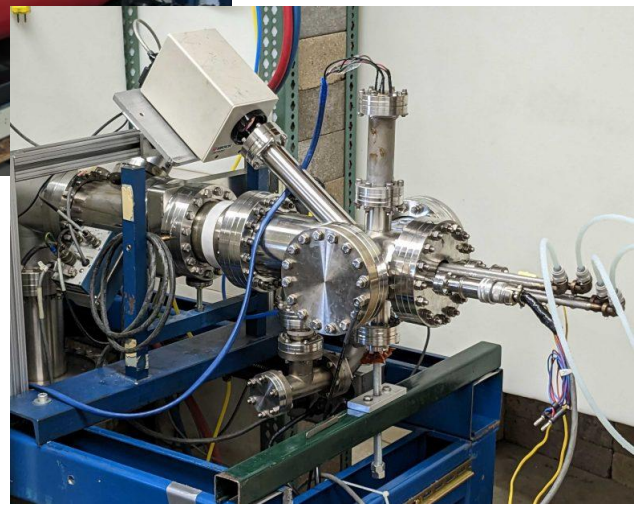
- Breazeale Nuclear Research Reactor
  - 1 MW TRIGA
  - 3 x10^{13} n/cm^2 sec thermal neutron flux at core center
- Gamma Irradiation Facilities
  - In-Pool irradiators
  - Gamma Cell 220 Dry Irradiator (6,000 Curie Co-60, 0.5 MRads/hour)
- Hot Cells
- Radiation Detection & Measurement Labs
- Neutron Beam Laboratory
- Radionuclear Applications Laboratory
- Radiochemistry Laboratory
- Nuclear Security Education Laboratory
- Subcritical Graphite Reactor Facility



University of Wisconsin – Madison Ion Beam Lab: Overview

- 1.7 megavolt NEC Pelletron electrostatic tandem accelerator
  - Ion energies 1 – 5 MeV
  - Toroidal volume plasma ion source (TORVIS): Hydrogen or Helium, 5 – 30 microamps
  - Cesium sputter ion source (SNICS): C, Si, V, Fe, Ni, Zr, W, et. al., 1 – 15 microamps, varies by ion
  - Three target beamlines with IR laser, IR camera, pyrometer, liquid nitrogen & propylene glycol cooling

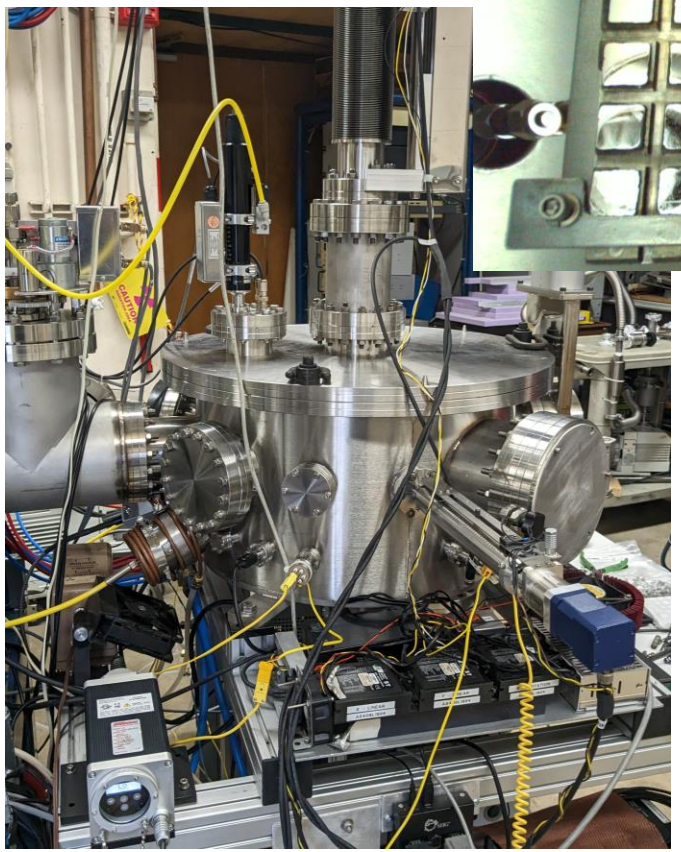




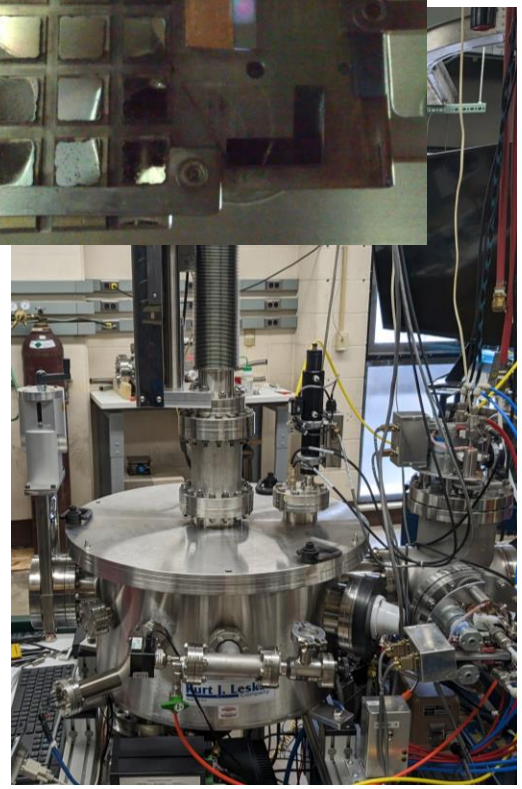


Recent Development: High Throughput Irradiation Beamline

- Motivation: Quickly collect data across the compositional space of additively printed HEAs
- Large chamber (60 L) w/ large (15 cm X 15 cm) stage attached to linear actuators
- Sequential irradiation of many samples without breaking vacuum or waiting for cool down
- IR laser heats sample surface locally & directly
- Dual-wavelength pyrometer measures surface temperature locally (400-900 ºC)





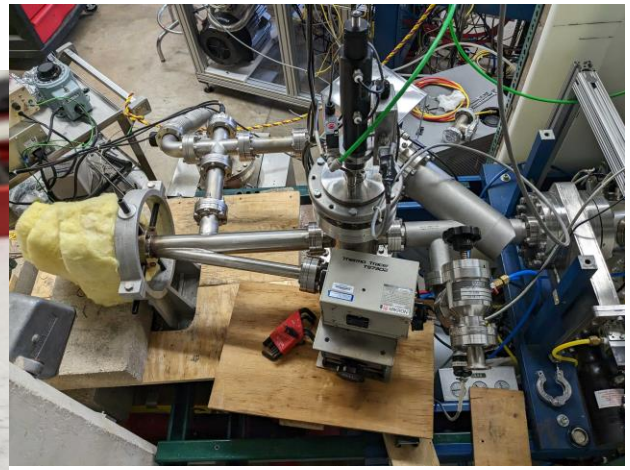


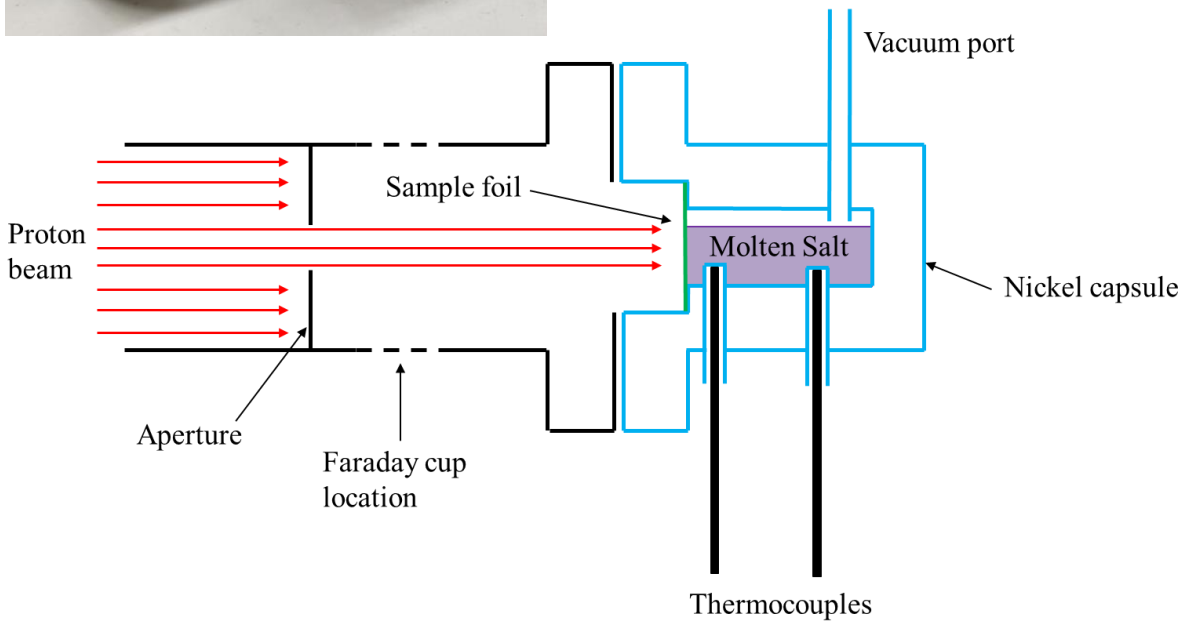
Nathan Curtis, Michael Moorehead, et al. NEUP/NSUF project 20-19128, Machine Learning on High-Throughput Databases of Irradiation Responses and Corrosion Properties of Selected Compositionally Complex Alloys for Structural Nuclear Materials, Federal Gran/Cooperative Agreement Number: DE-NE0009001

Recent Development: In-Situ Molten Salt Corrosio

- Motivation: Understand performance of structural alloys for molten salt reactors under simultaneous corrosion and irradiation
- Heated Ni capsule holds molten FLiNaK behind thin foil target
- 2.8 MeV protons range > thickness of foil target; back side of foil experiences simultaneous corrosion and radiation damage
- 1st successful run to 0.015 dpa this year! A new run to higher dpa is planned this Fall



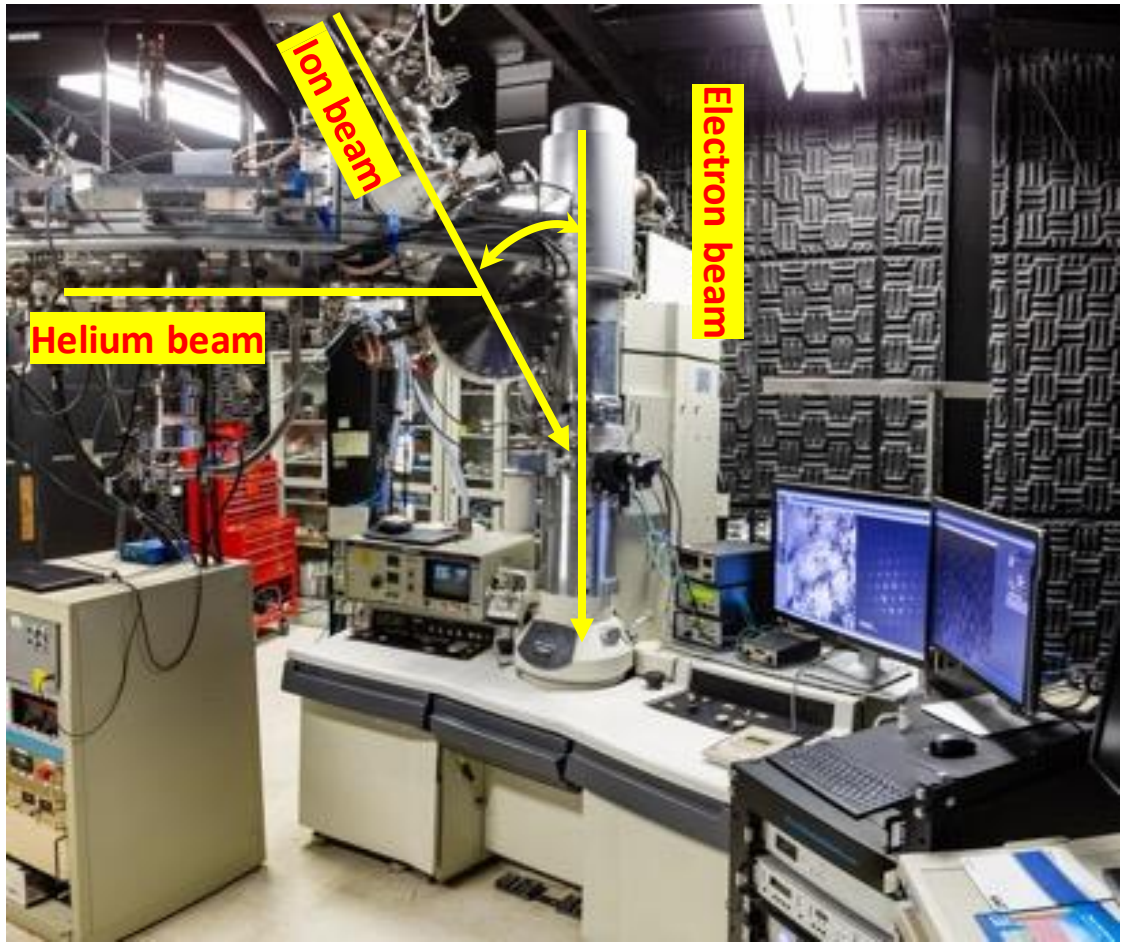




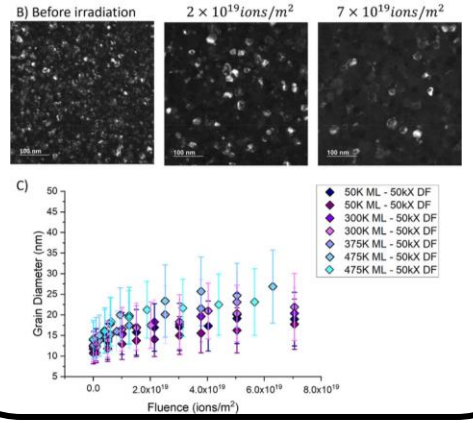
Cole Evered, et al. NEUP Project 21-24195: Enhancing Yellowjacket for Modeling the impact of Radiation and Stress on the Corrosion of Molten-Salt-Facing Structural Components, Federal Grant/Cooperative Agreement Number: DE-NE0009163

IVEM-Tandem Facility at Argonne NATIONAL LABORATORY

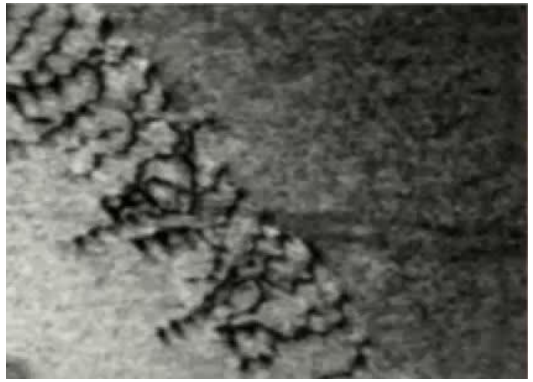
IVEM is a dual-ion beam facility for in situ TEM studies of defect structures in materials under ion irradiation



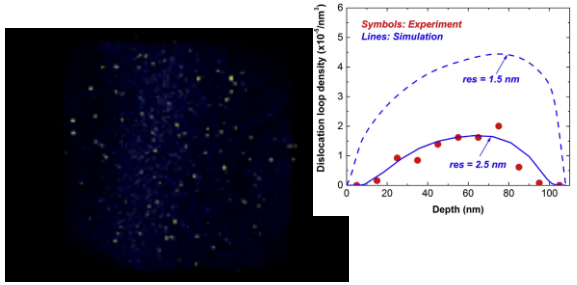
In-Situ Cryogenic Irradiation



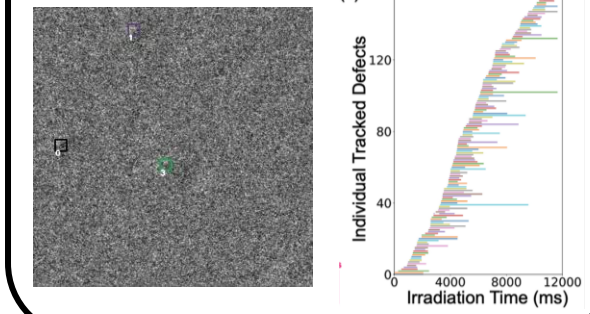
In-Situ Straining



Electron tomography



Computer Vision



Yu et al. Acta Mater. 231 (2022)
Penn State University

Kacher and Robertson, Acta Mater. 60 (2012)
University of Illinois

Li et al, Phil Mag. 92 (2012)
Argonne

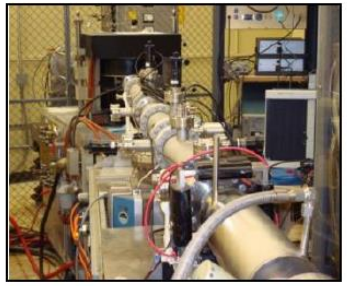
Sainju et al., Scientific Report 12 (2022)
University of Connecticut

NSUF Nuclear Science User Facilities

ACCELERATOR LABORATROY at Texas A&M University



10 kV



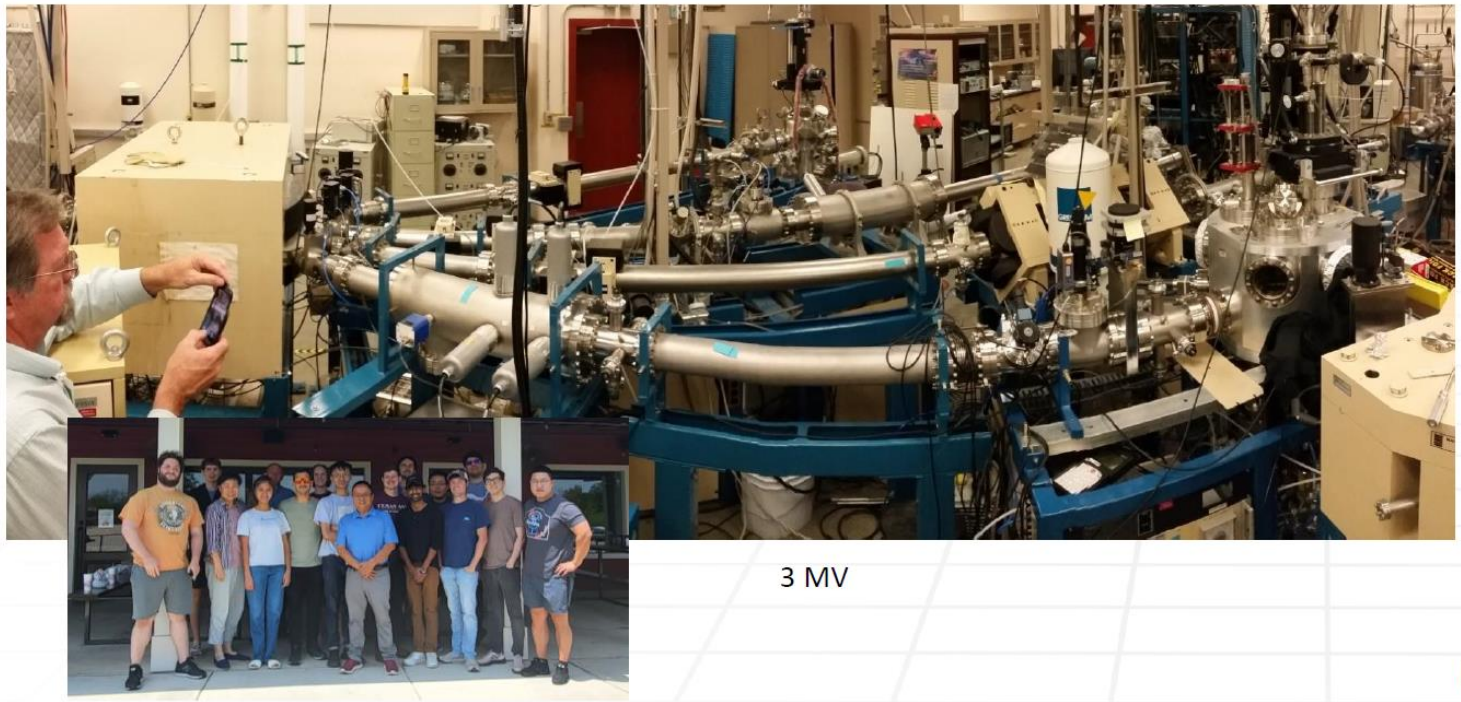
140 kV



400 kV

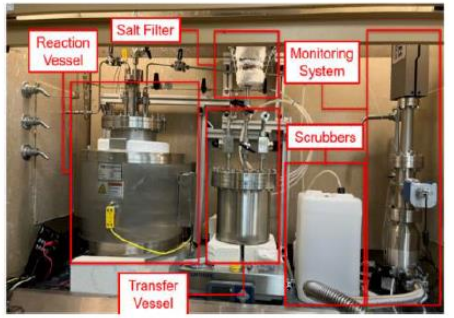


1.7 MV



3 MV

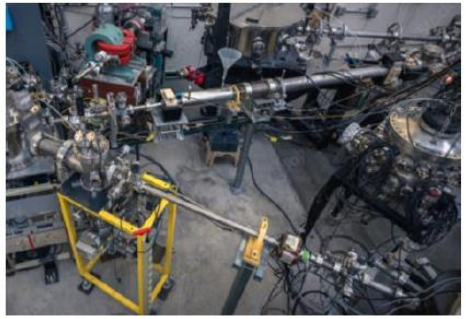
Novel/new capabilities



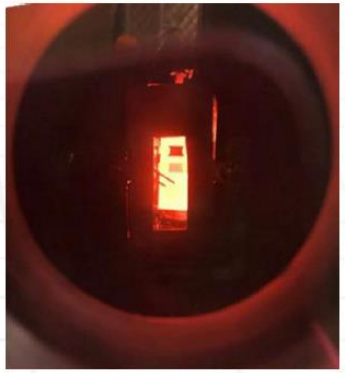
Molten salt purification



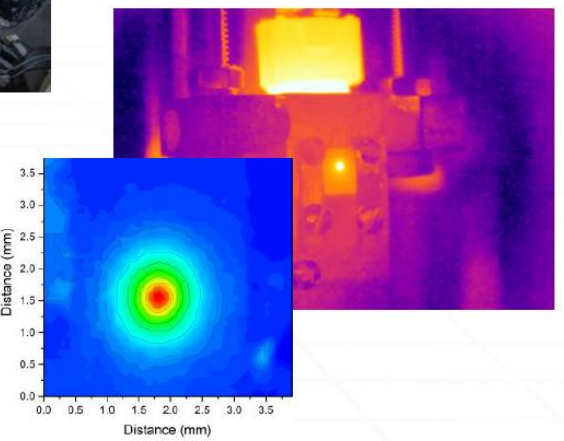
Irradiation + salt corrosion



Triple beams (10 kV+400 kV+1.7 MV)



Ion irradiation up to 1200°C



Beam + IR imaging → thermal property measurement

Sandia National Laboratories

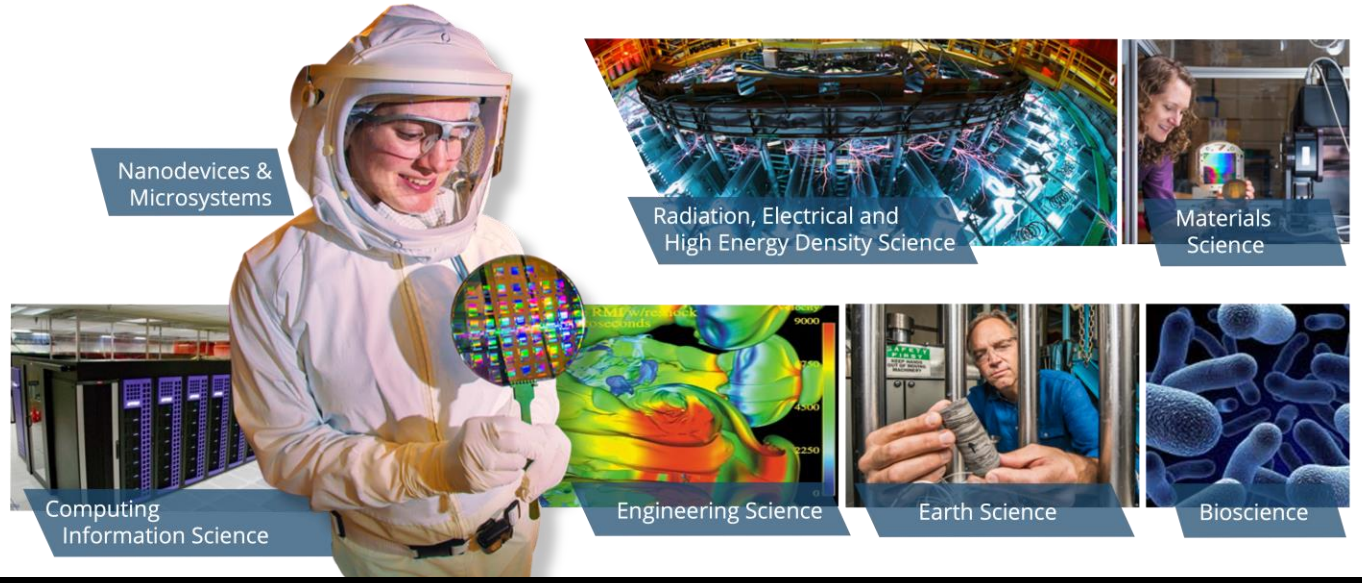


Sandia is a federally funded research and development center (FFRDC)

Five major program portfolios (Nuclear Deterrence, Energy & Homeland Security, National Security Programs, Global Security, Advanced Science & Technology)

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

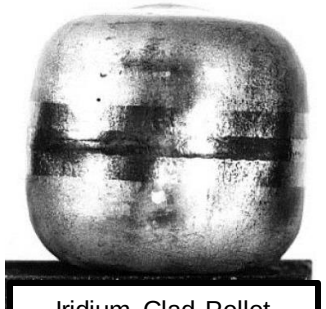


SPACE LAUNCH SAFETY

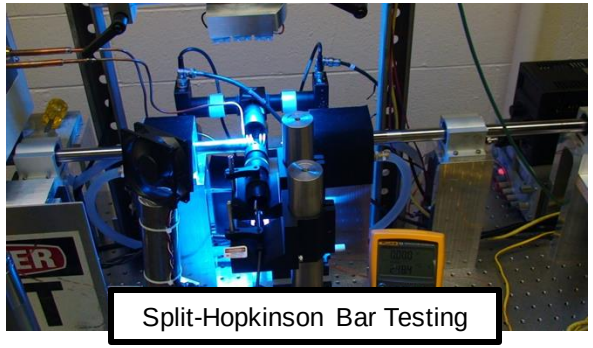
Analysis framework to quantify consequence in the event of an accident



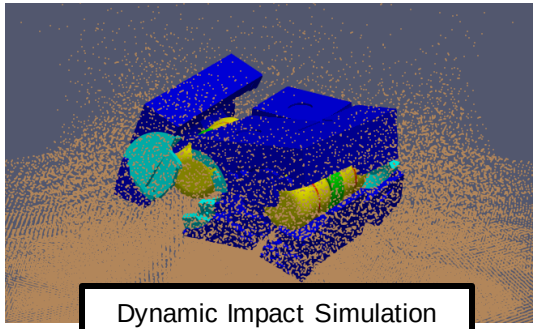
PuO2 Pellet



Iridium Clad Pellet

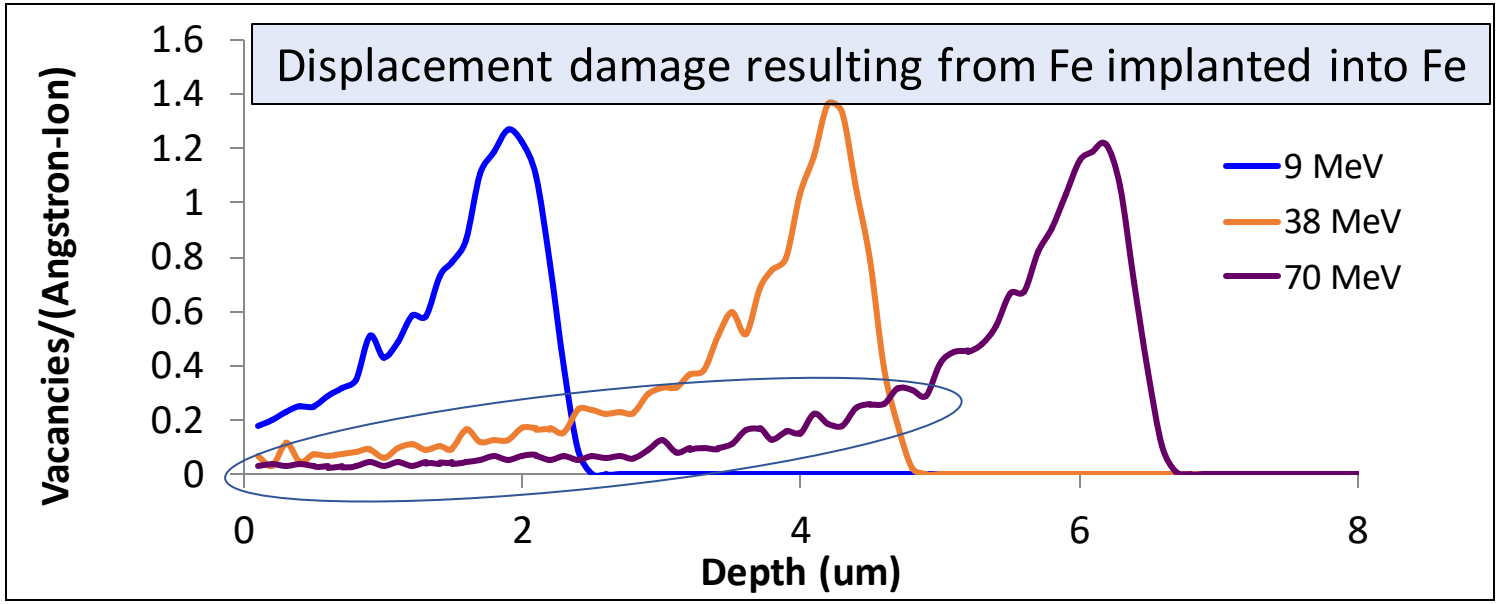


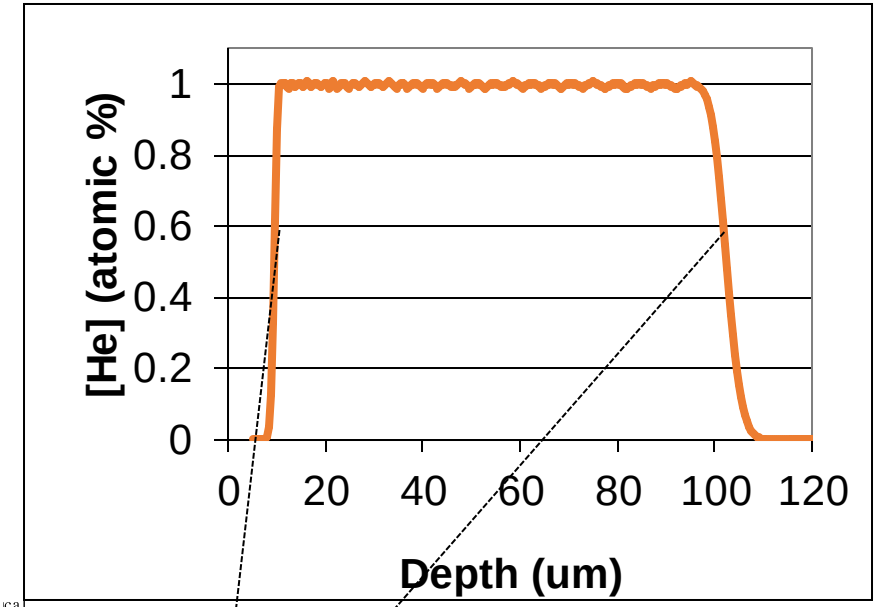
Split-Hopkinson Bar Testing

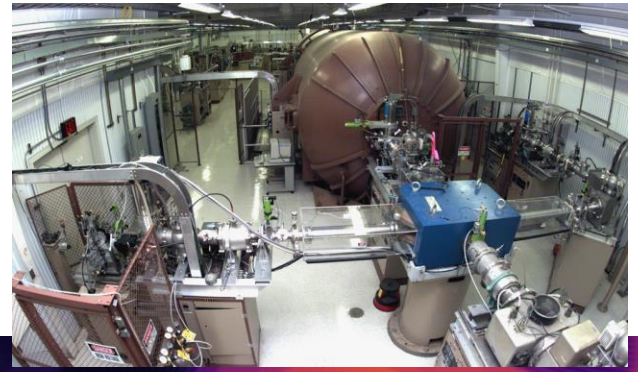


Dynamic Impact Simulation

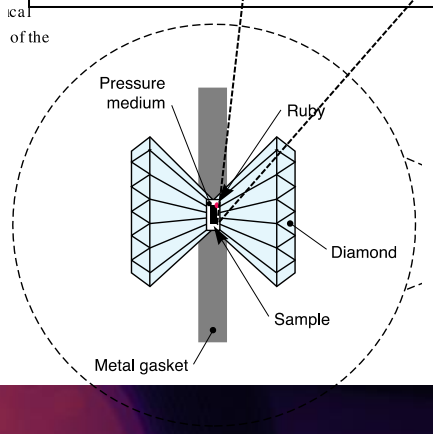
LLNL's Center for Accelerator Mass Spectrometry offers the ability to study effects of radiation damage on bulk properties.







- 10-MV Tandem Accelerator
- Wide range of ions (H,D,He, Heavy Ions)
- Cryogenic temps to 800C
- Damage rates up 10^{-3} dpa/sec



EOS measurement of He-implanted Pu via DAC

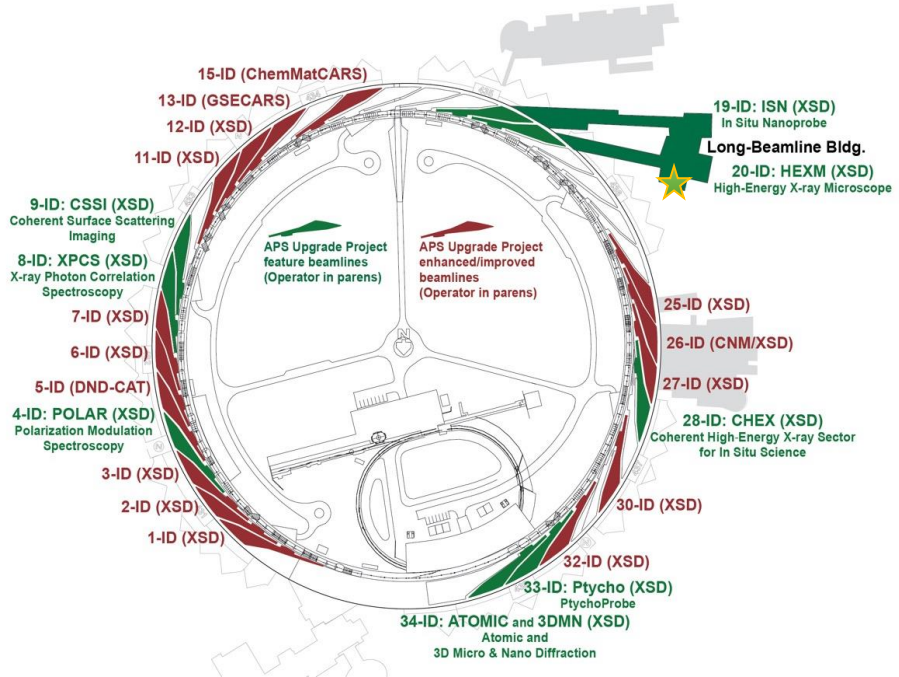
Activated Materials Laboratory (AML)

- AML is a **Low-Activity Specimen Preparation Laboratory** next to the **High Energy X-ray Microscope (HEXM)** beamline in the **Long Beamline Building** being constructed at the APS, as part of the APS Upgrade Project.
- AML is an NSUF partner user facility.

Key dates:
- APS dark period: 2023-04 to 2024-04
- AML user access: 2024 fall







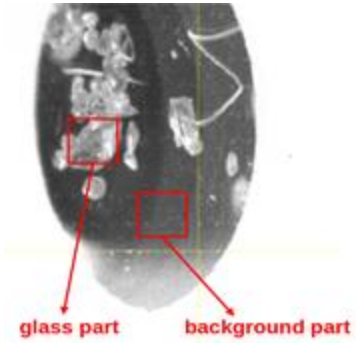
Some updates from ***National Synchrotron Light Source (NSLS-II)***

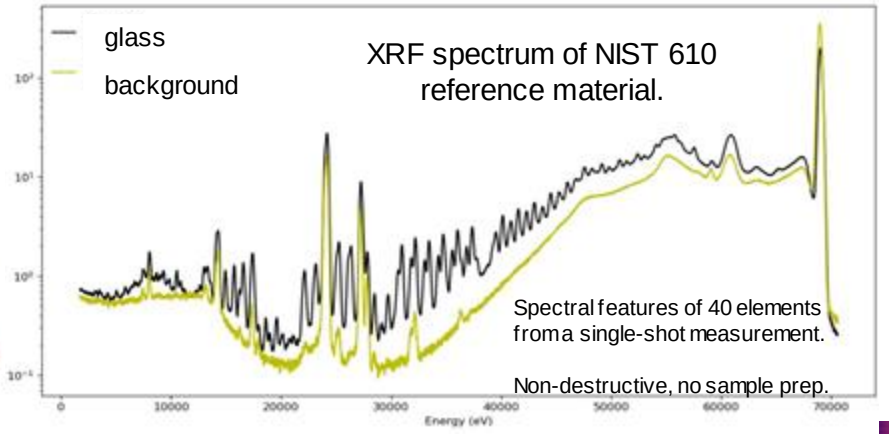
update -1

High-energy synchrotron X-ray fluorescence (s-XRF) is now available for NSUF users' access at 28ID-2 beamline of NSLS-2.



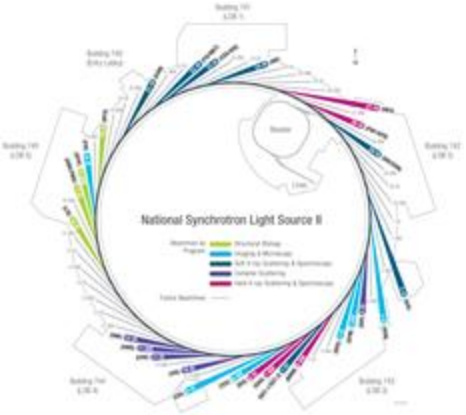
- A new XRF detector was installed at 28ID-2 (XPD) beamline of NSLS-2 which is accessible to NSUF users.
- Elemental information for majority of elements in periodic table from Si (Z=14) to Pu (Z=94).
- 2D XRF-mapping with ~25-micron size beam.
- Enabling multi-modality (XRD+XRF, simultaneously)



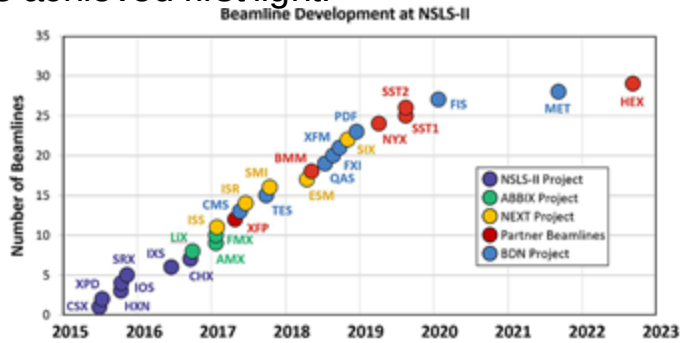


update -2

The High Energy Engineering X-ray scattering (HEX) beamline has achieved first light!







- Monochromatic X-rays in the energy range from 30 keV - 150 keV
- Continuous spectrum (white) of X-rays from 30 keV to 250 keV.
- Beam size from 20 μm × 20 μm to 100 mm × 10 mm (H×V)
- High-energy X-ray imaging with 1-micron resolution
- Non-destructive, highly-penetrating
- General user operations in Jan 2024.

This new beamline may offer unique opportunities for nuclear science community in US.

(*) currently there is no partner user agreement between HEX and NSUF.

Mehmet Topsakal, Ph.D (mtopsakal@bnl.gov)

Nuclear Science and Technologies Dept.
Brookhaven National Laboratory

NSUF Partner: Los Alamos National Laboratory





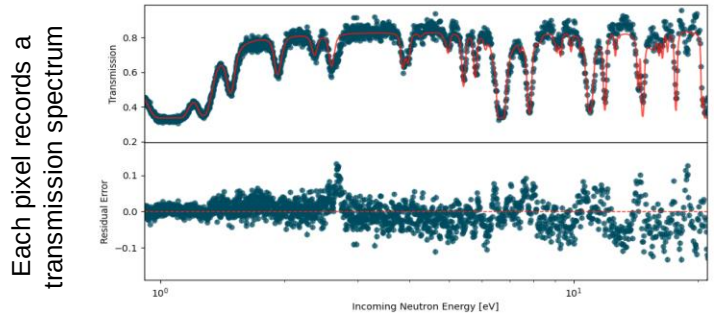
Alex Long is an instrument scientist at the Lujan Center focused on developing advanced neutron imaging techniques for materials characterizations

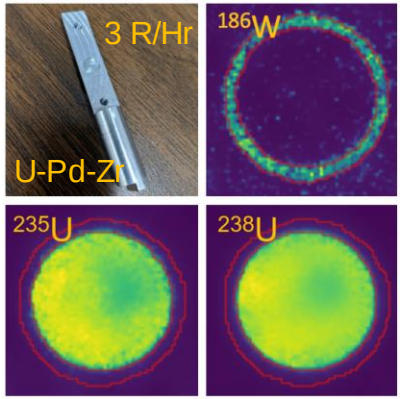


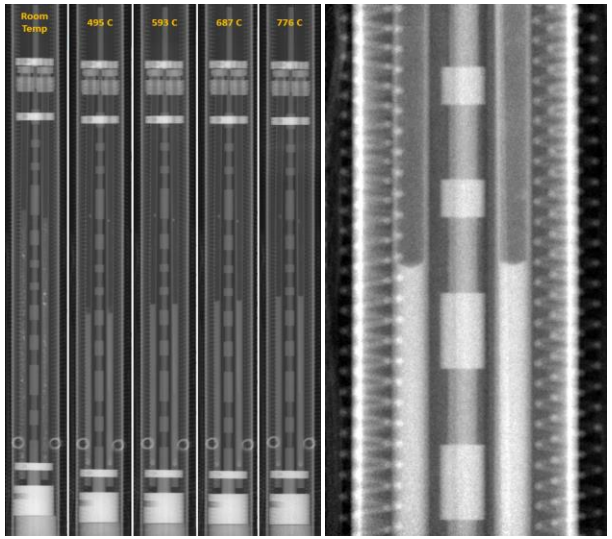
Tarik Saleh is the deputy group leader MST-8 & the current NSUF POC at LANL. His research focuses on actinide-based material science.

Advanced Neutron Imaging for Materials Science

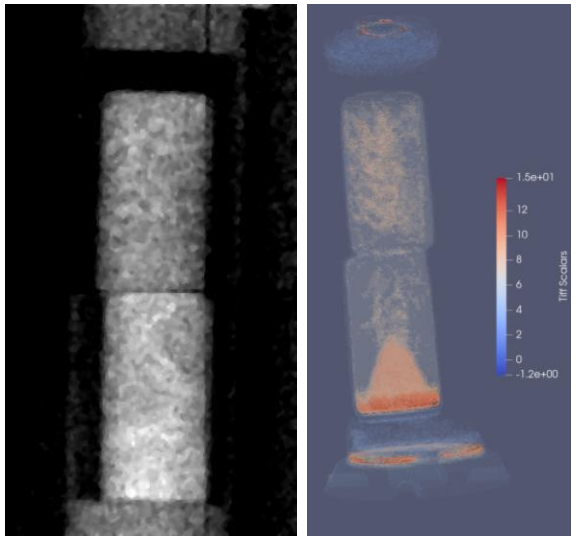
Neutron resonance imaging of irradiated fuels







Thermophysical measurements of salts



In situ H-distribution measurements

Long *et. al*. "Remote Density Measurements of Molten Salts via Neutron Radiography" Journal of imaging, 7(5), 88. (2021)
Trellue *et al.* "Effects of Hydrogen Redistribution at High Temperatures in Yttrium Hydride Moderator Material" JOM 73, 3513–3518 (2021)
Balke et al. "TRINIDI: Time-of-Flight Resonance Imaging with Neutrons for Isotopic Density Inference" IEEE Transactions on Computational Imaging (2023) *[under review]*

NSUF Nuclear Science User Facilities