Brenden Heidrich, Director

Foundations of Irradiation Testing:

A Workshop for Researchers

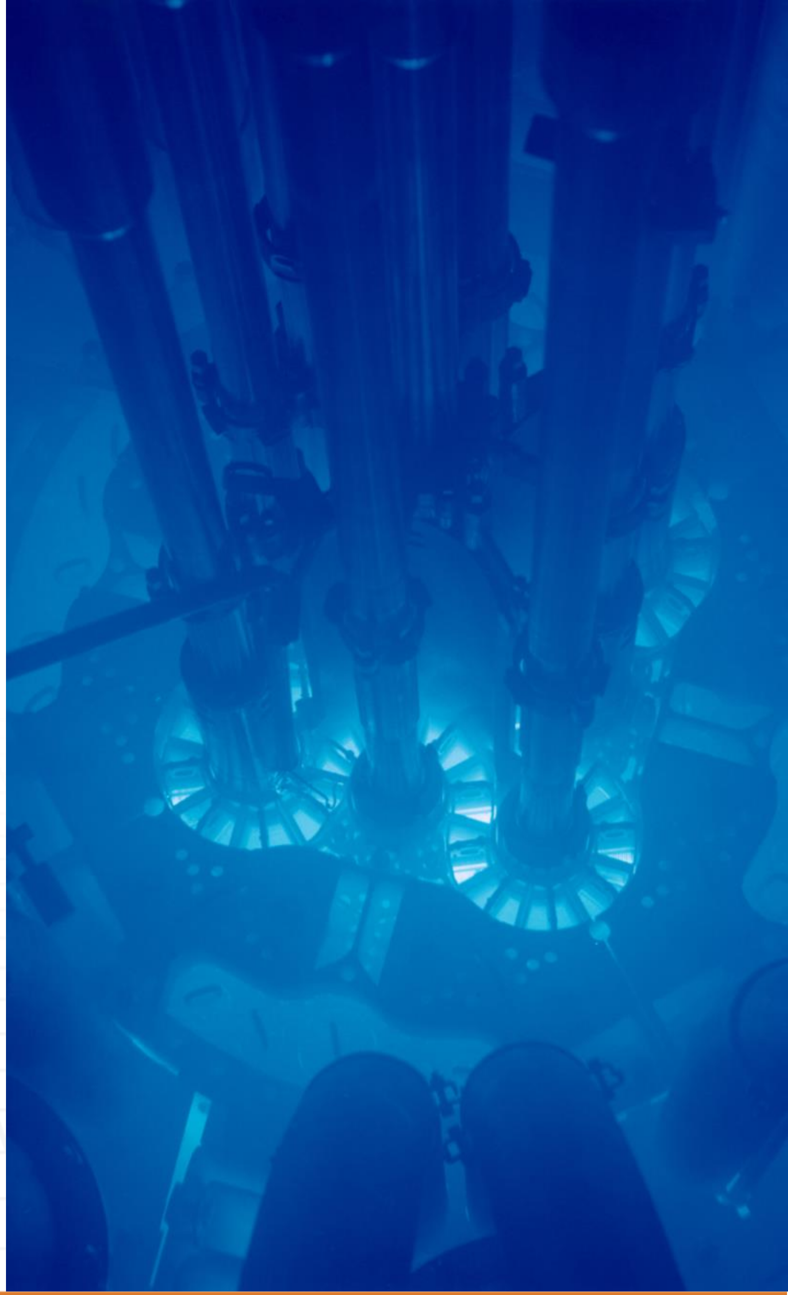
July 8, 2025

Nuclear Science User Facilities Program Overview

Nuclear Science User Facilities

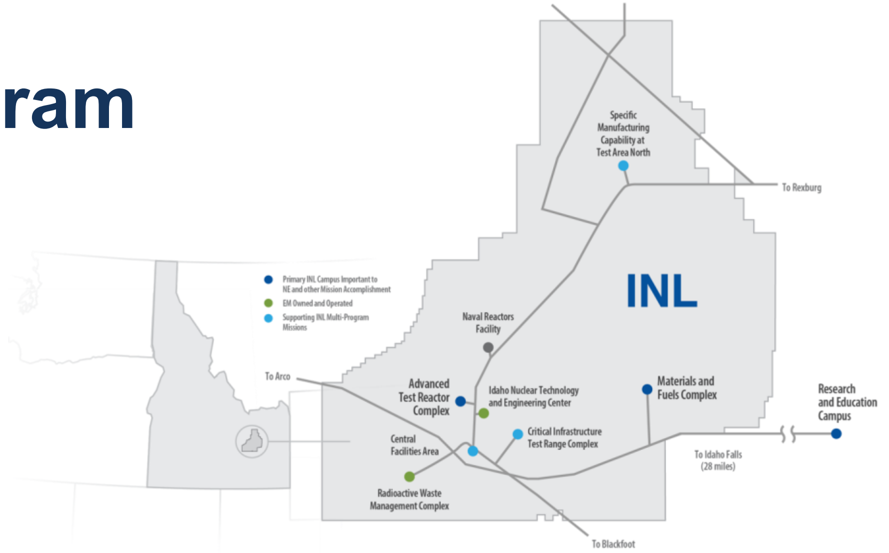
INL/MIS-25-83964

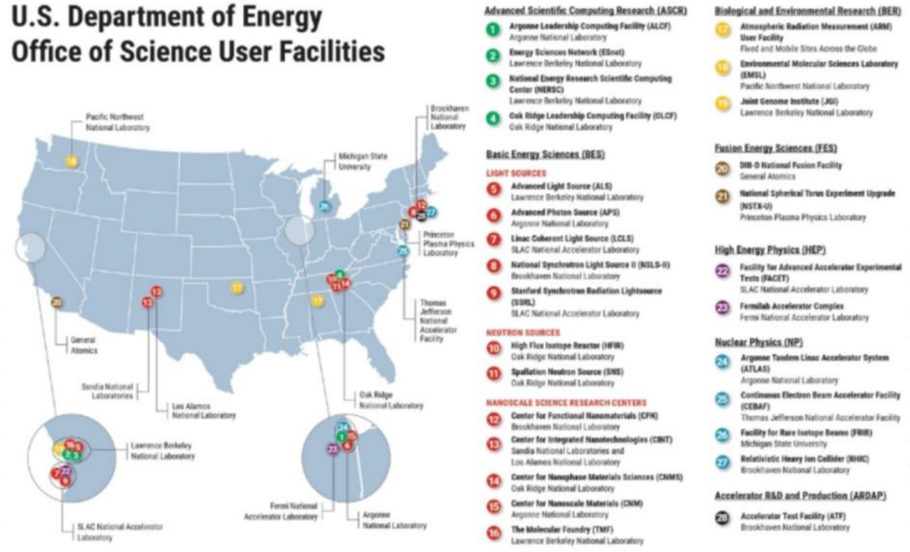
Nuclear Science User Facilities



The Nuclear Science User Facilities Program

- **Established in 2007**
  - U.S. Department of Energy Office of Nuclear Energy's first & only user facility
- **Founded at Idaho National Laboratory (INL)**
  - INL remains the lead and primary institution
- **NSUF operates similarly to other user facilities in the United States**
  - Fundamental Research - basic and applied research in science and engineering, intended to be published and shared broadly with the scientific community
  - Competitive proposal processes for access
  - No cost to user for accessing capabilities
  - No travel funding to users, etc.





The Nuclear Science User Facilities Program

Unique aspects of NSUF

Consortium of facilities/capabilities

- 21 institutions across the United States
- >50 major facilities and laboratories
- NSUF efficiently leverages existing investment in physical capabilities by utilizing excess capacity.
- Funding to partners covers only the costs for the awarded access project

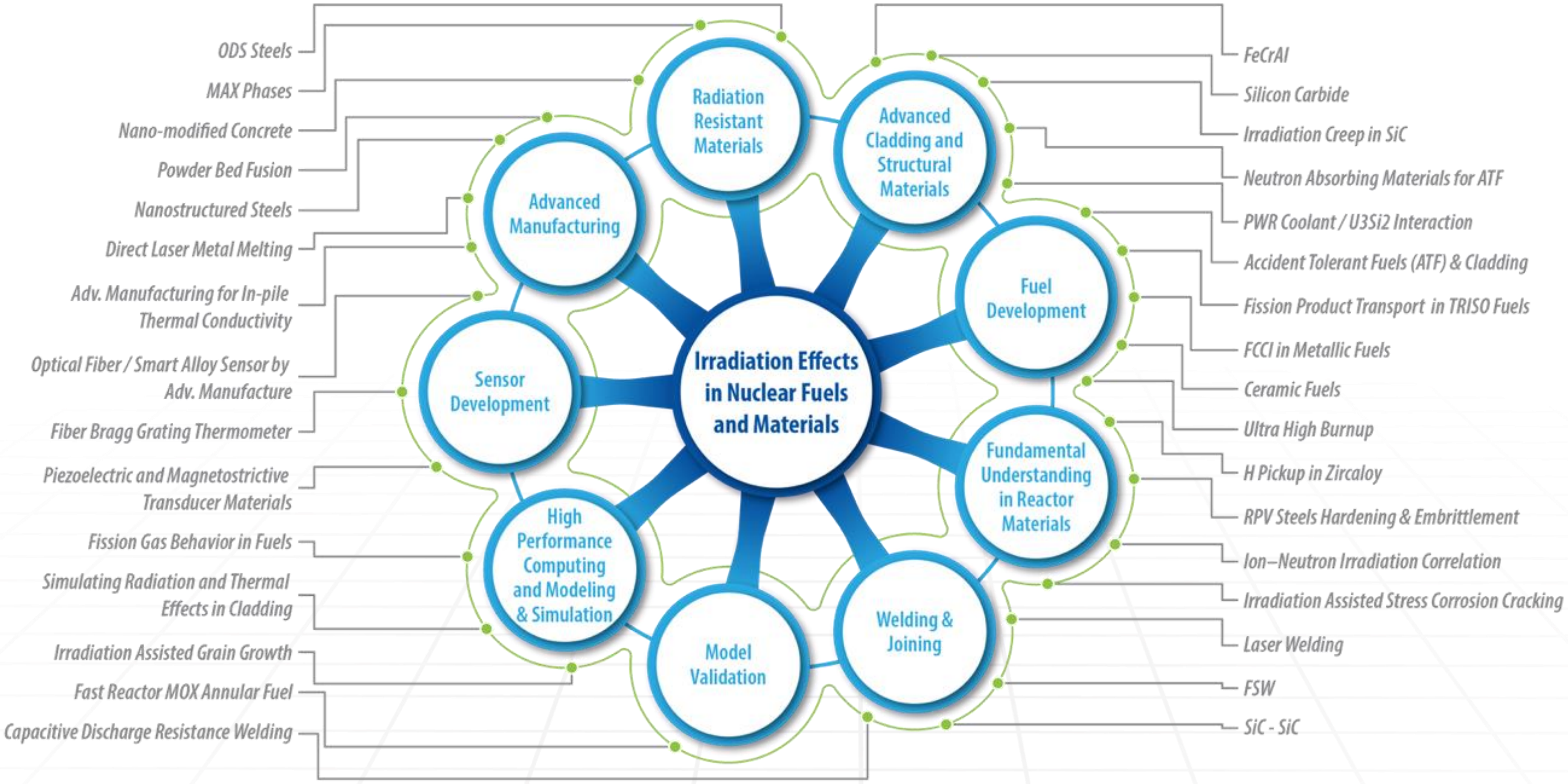
NSUF offers multiple capabilities to a single scientific area

- Fundamental irradiation effects in nuclear fuels and materials important to US nuclear energy development

Large projects can last up to 7 years

- Major projects can include design, fabrication, transport, neutron irradiation, post-irradiation examination, and final disposition.
- All projects are fully forward funded at the start.
- NSUF technical experts support the projects at all stages

NSUF research areas cover all technical readiness levels



Foundations of Irradiation Testing Workshop

Foundations of Irradiation Testing: A Workshop for Researchers (Day 1)

Tuesday, July 8 (Mountain Daylight Time)

Virtual

11:00 Introduction and NSUF Overview .... Brenden Heidrich
NSUF Director

11:30 Overview of Nuclear Energy Activities at INL.. Steven Hayes
Director, Nuclear Fuels and Materials

12:00 Brief History and Fundamentals of Nuclear Power Generation..................... Katya Le Blanc
Director, Nuclear Safety and Regulatory Research

12:30 Fundamentals of Radiation Damage in Nuclear Materials .... Stephen Taller
Staff Scientist, Oak Ridge National Laboratory

1:15 Break

1:30 Fundamentals of Structural Materials for Nuclear Energy.................. Michael Moorehead
Advanced Nuclear Materials Scientist

2:15 Fundamentals of Nuclear Fuels.. Nicolas Woolstenhulme
Research Scientist

3:00 Adjourn

Foundations of Irradiation Testing: A Workshop for Researchers (Day 2)

Wednesday, July 9

Virtual

11:00 Fundamentals of Irradiation Testing .... Keith Jewell
NSUF Chief Scientist

11:45 Irradiation Testing and Experiment Design .... Bryce Kelly
Division Director, Applied Engineering

12:15 Fundamentals of Safety Testing .... Colby Jensen
Research Scientist

12:45 Break

1:00 Fundamentals of Post-Irradiation Examination .... Daniel Murray
Sr. Manager, Advanced Materials Characterization Department

1:45 Mechanical and Environmental Testing .... Jason Schulthess
Research Scientist

2:30 Adjourn

Foundations of Irradiation Testing: A Workshop for Researchers (Day 3)

Thursday, July 10

Virtual

11:00	NSUF User Access Opportunities	Joanna Taylor and Derek Whipple *NSUF Program Administrators*
11:30	Internship Opportunities at INL	Jeff Benson *Research Excellence Programs*
11:45	NRAD Irradiation Capabilities	Peng Xu *Research Scientist*
12:00	Open Q/A – NSUF Irradiation Experiments	Brenden Heidrich and Keith Jewell *NSUF Program*
12:45	Open Q/A - NSUF Post-Irradiation Examination	Mukesh Bachhav and TK Yao *Research Scientists*
1:45	General Q&A and Closeout	Brenden Heidrich *NSUF Director*
2:15	Adjourn	

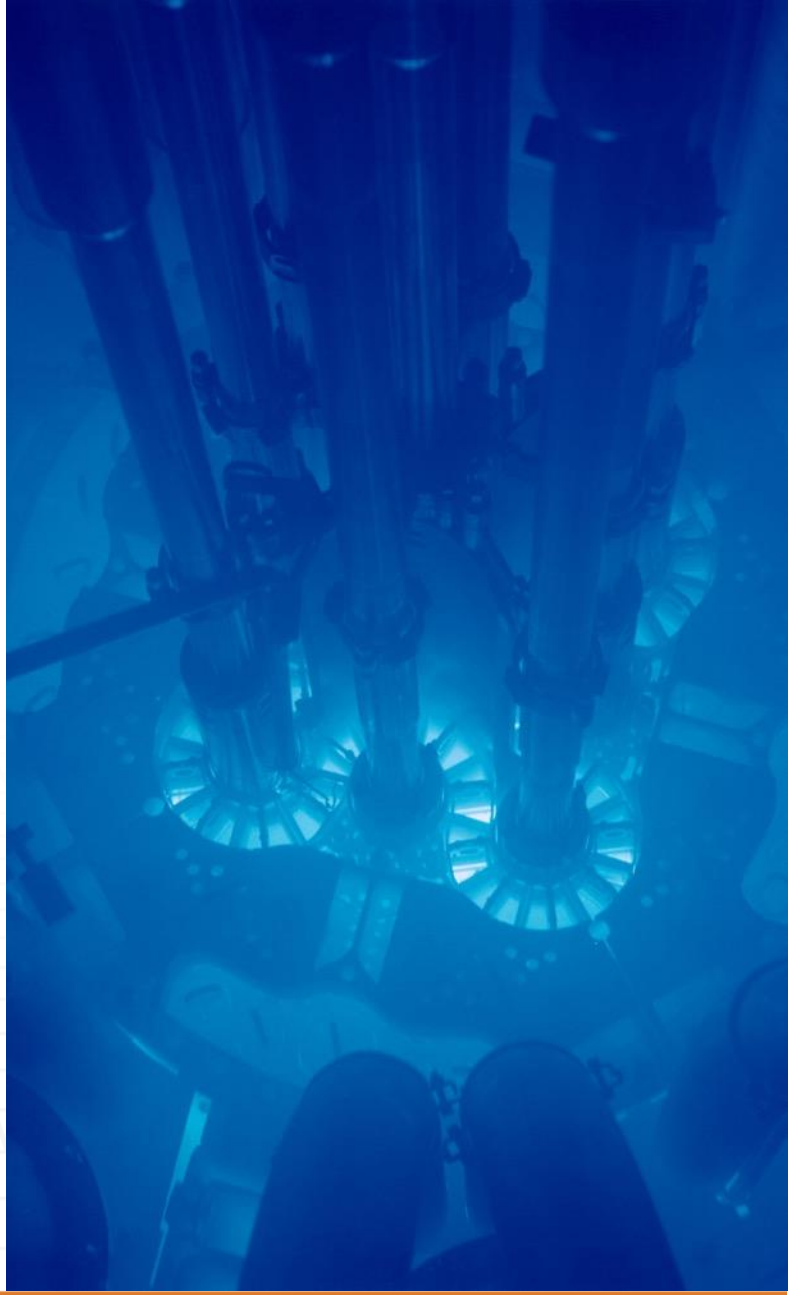
FIT Workshop Guidelines

- **Punctuality:** Please join the meeting 5-10 minutes before the scheduled start time to ensure you are ready when the session begins.
- **Mute Your Microphone:** To avoid background noise, keep your microphone muted when you are not speaking. You can unmute yourself when you need to ask a question or participate in discussions.
- **Use the Chat Function:** Feel free to use the chat function to ask questions or make comments during the presentation. Our moderators will monitor the chat and address your queries at appropriate times.

FIT Workshop Guidelines

- **Camera Usage:** While it is not mandatory, we encourage you to turn your camera on during interactive portions of the workshop, such as question-and-answer sessions, to foster engagement and collaboration. However, due to the high volume of registrations, we request that cameras remain off during presentations to ensure the quality and stability of the meeting.
- **No Bots:** Please refrain from using automated bots or scripts to interact with the meeting. Any bots detected will be removed from the meeting to ensure a smooth and genuine experience for all participants.
- **Technical Issues:** If you experience any technical difficulties, please notify us through the chat or contact our program office at nsuf@inl.gov.
- **Respect and Professionalism:** Please be respectful and professional in your interactions with the presenters and fellow participants.

NSUF Capabilities for Irradiation Testing



NSUF offers the best capabilities across the nation

Cutting-Edge Resources: Access to infrastructure and associated capabilities across 21 partner sites

Open access: Available to industry, academia, and national labs for non-proprietary R&D

Education and training: Workshops, webinars, and hands-on skill development

Impact: Increase understanding to drive innovation across nuclear energy technologies

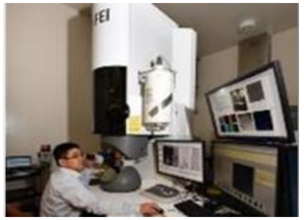
Neutron Reactors

12 reactor facilities at national laboratories and universities including the Advanced Test Reactor at INL

Gamma & Ion Irradiation

7 gamma irradiation facilities and 7 ion beam facilities at national laboratories and universities

Post-Irradiation Examination

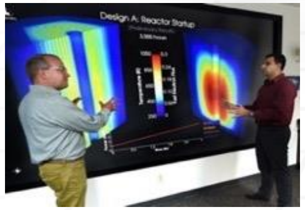


Multiple hot cell and broad post-irradiation examination facilities including advanced characterization methods

Beamlines

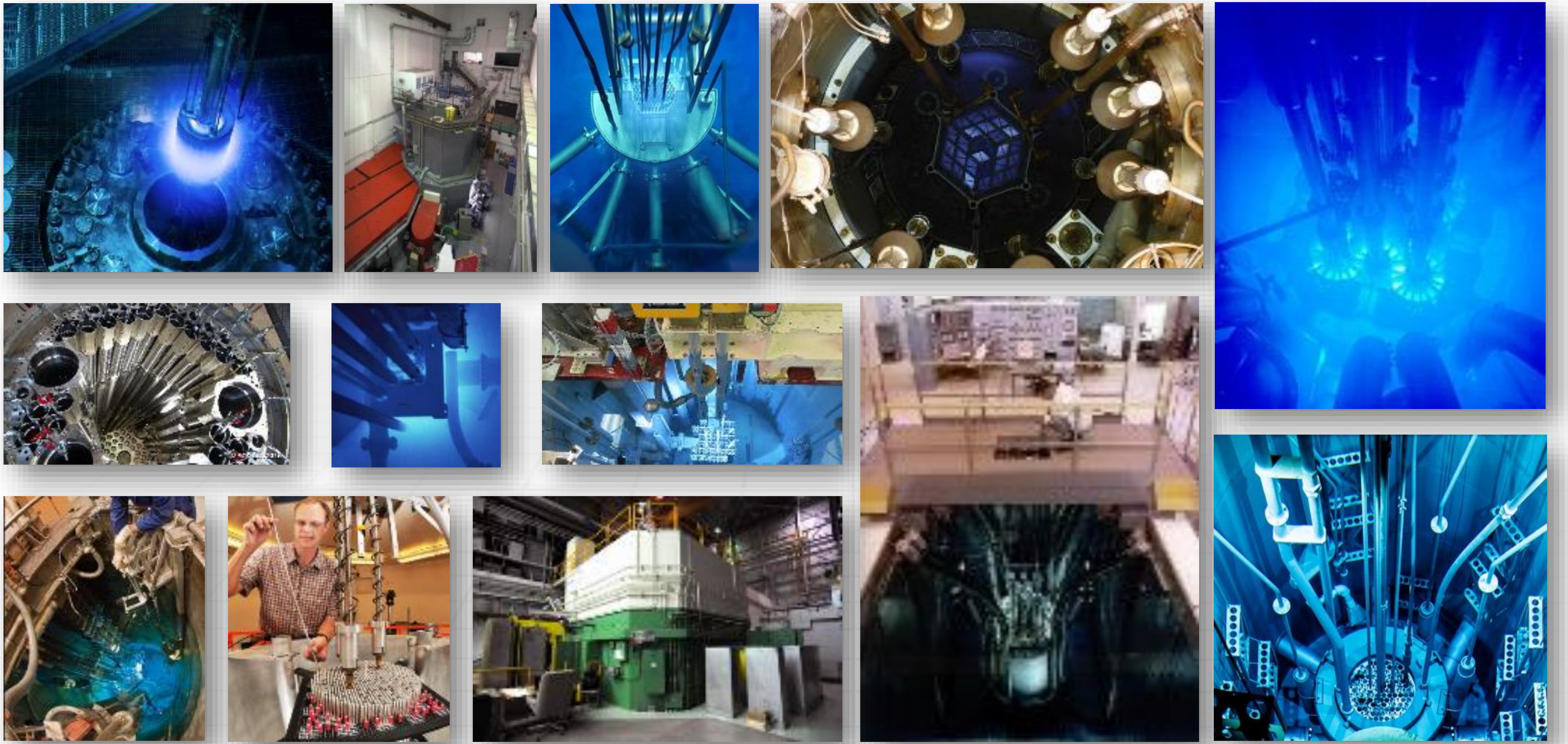
Synchrotron and neutron beamlines for nuclear fuel and materials studies

Computational Resources



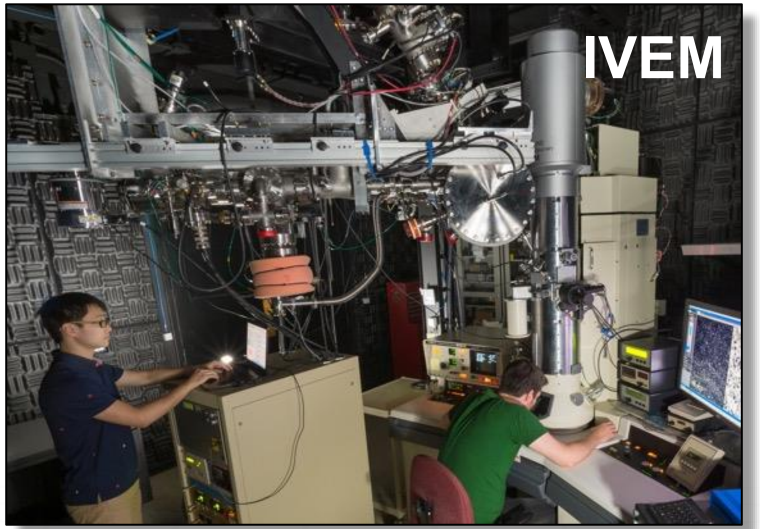
Scientific high-performance computing capabilities for advanced modeling and simulation at INL

Simulated Reactor Environments: Neutron Irradiation

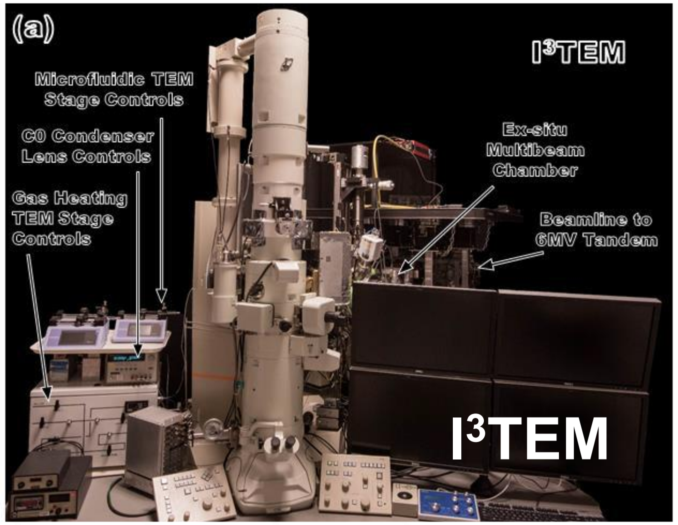


Simulated Reactor Environments: Ion Irradiation

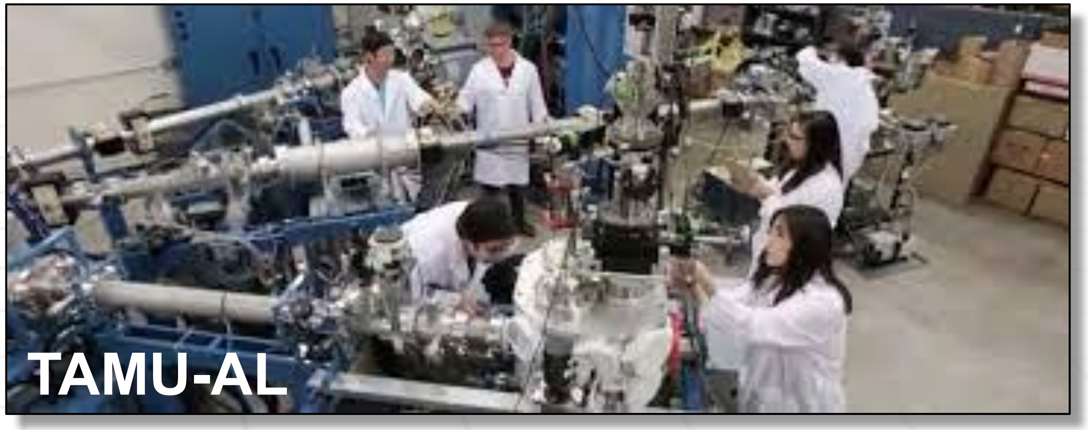
In Situ TEM



In Situ TEM



In Situ TEM



Hot Cells

Idaho National Laboratory

Oak Ridge National Laboratory

Westinghouse

Massachusetts Institute of Technology

PNNL

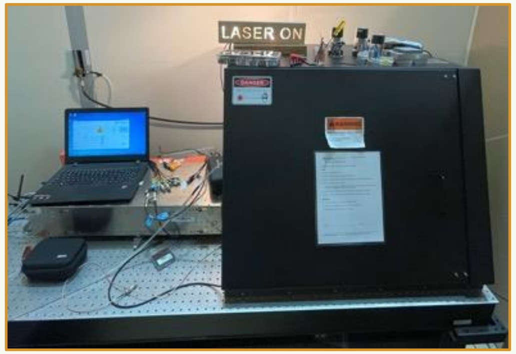
Argonne National Laboratory

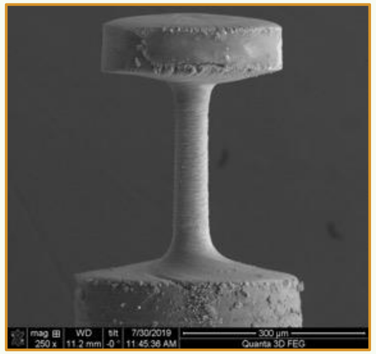
PennState

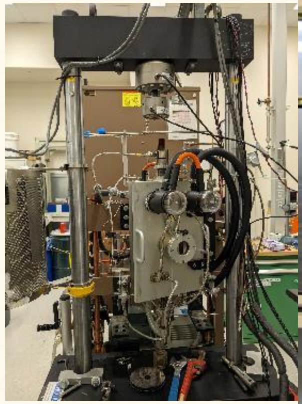
NC State University

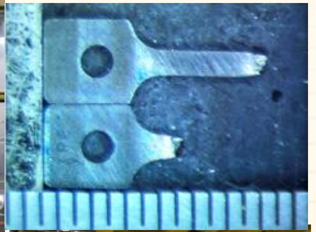
Simulated Reactor Environments: Mechanical Testing

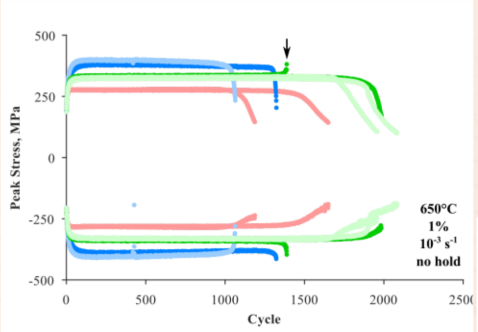
- Hardness / Bend test / Tensile/ Creep / Fatigue / Compact tension / Charpy impact (toughness)

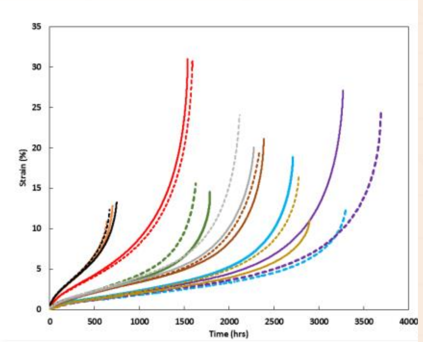








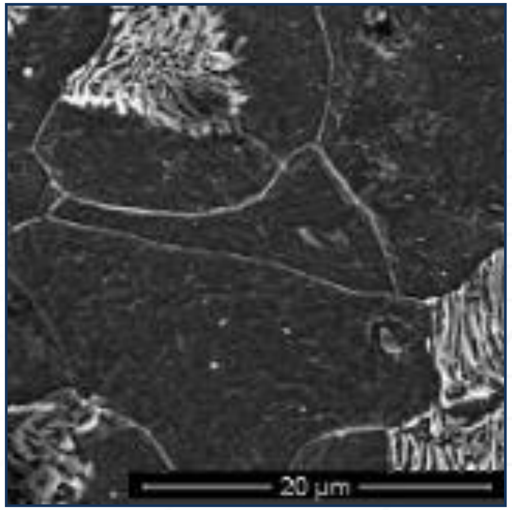


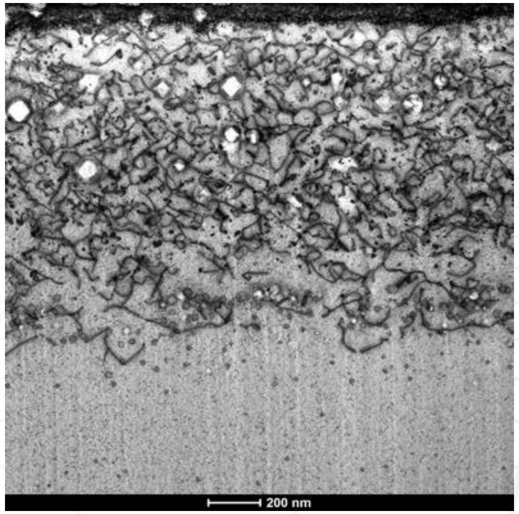


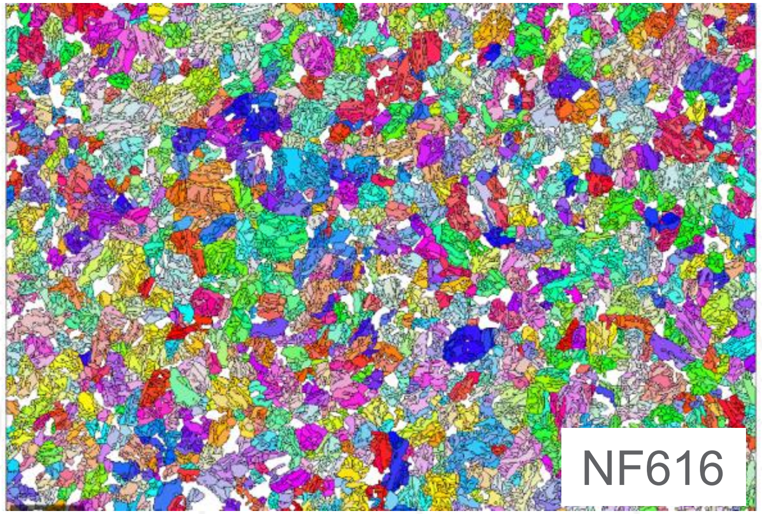
Advanced Microstructure Characterization Capabilities

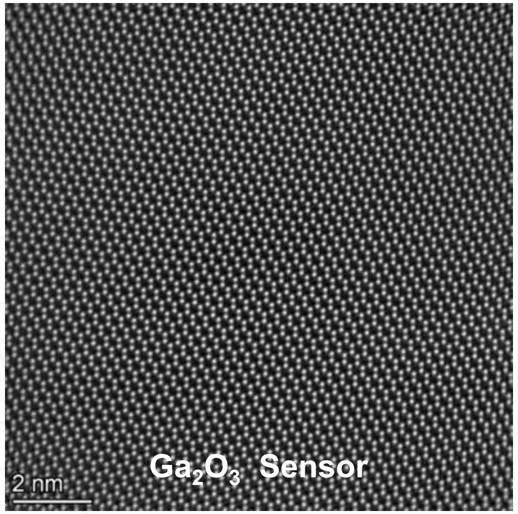
- Optical metallography
- Scanning electron microscopy (SEM)
  - BSE/EBSD/FIB
- Transmission electron microscopy (TEM)

Spectra 300 STEM
STEM resolution 50 pm
(125 pm at 30kV)



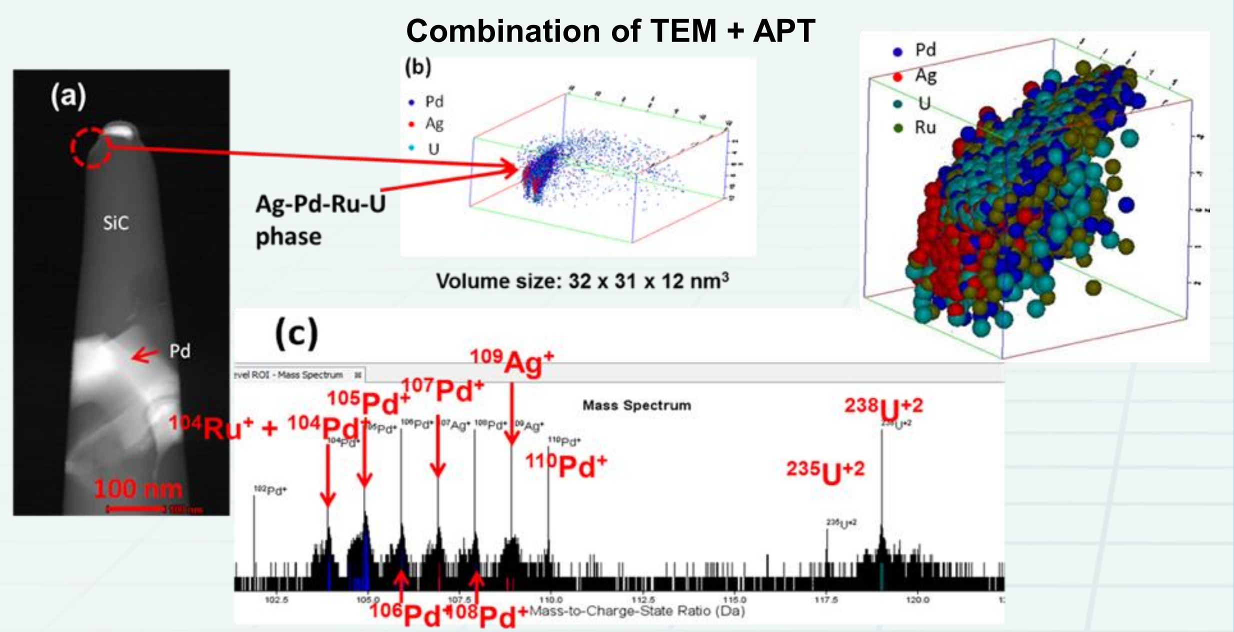




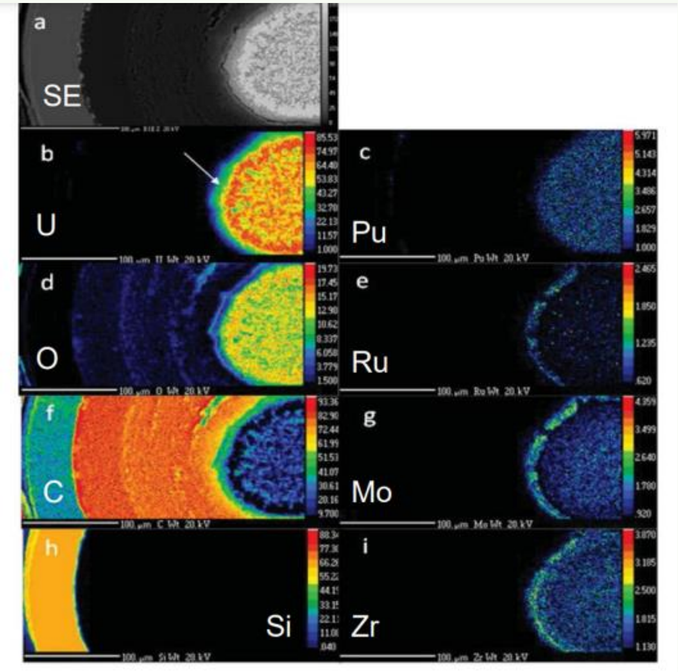


Advanced Microstructure Characterization Capabilities

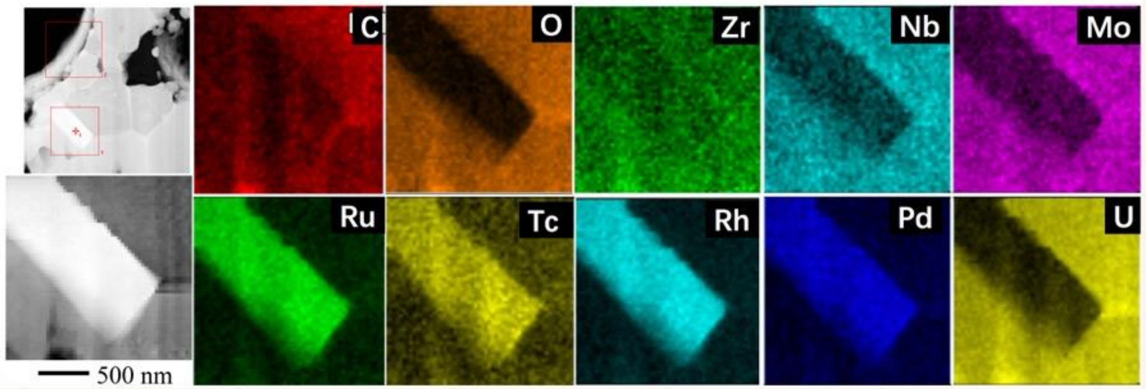
- Atom probe tomography (APT)
- Electron Probe MicroAnalysis (EPMA)
- Energy Dispersive Spectroscopy (EDS)
- Electron Energy Loss Spectroscopy (EELS)



STEM HAADF image of an irradiated TRISO APT sample tip (a), corresponding reconstructed three-dimensional APT maps showing a Ag-Pd-Ru-U - rich phase in a volume size of 32 nm x 31 nm x 12 nm (b) and mass spectrum showing detected isotopes of Ag, Pd, Ru and U (c).



WDS maps of a TRISO fuel particle

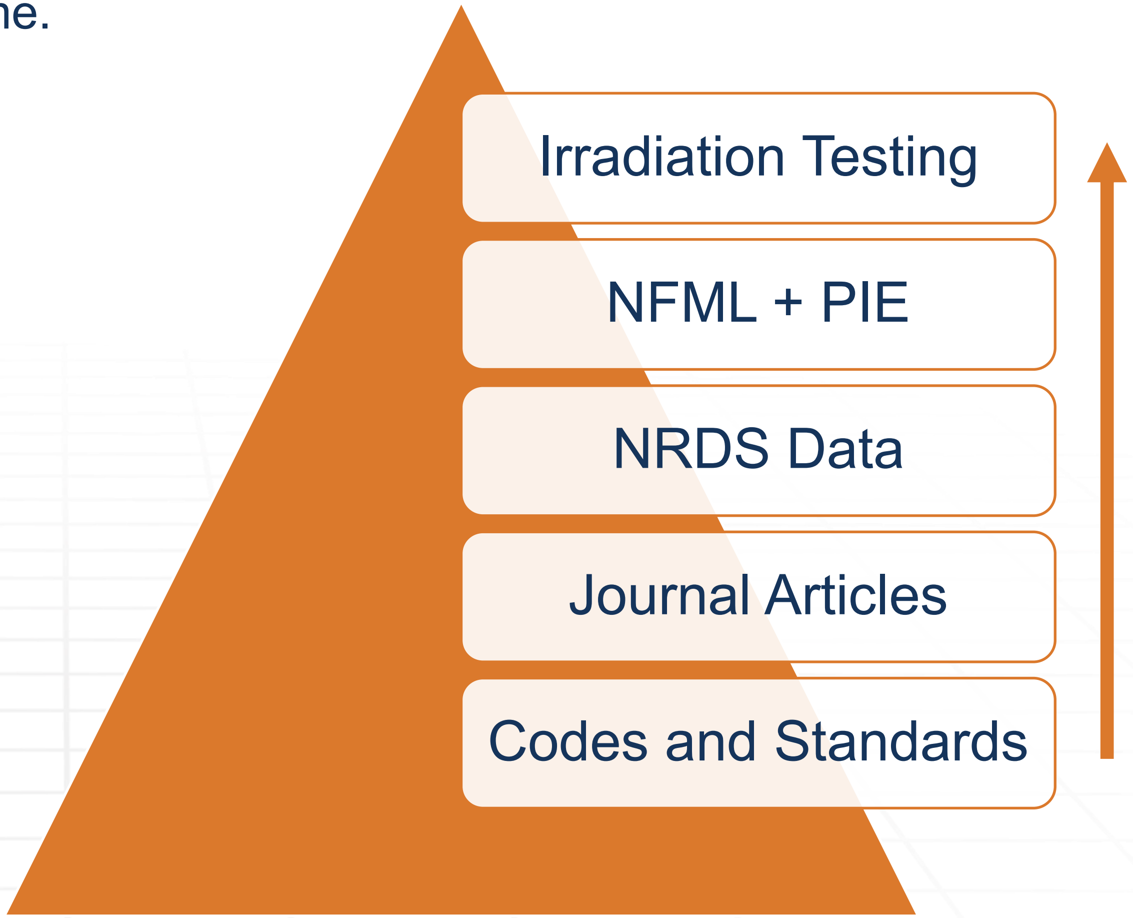


TEM images and EDS maps of irradiated fuel particle

Answering the need for a nuclear energy material

If you need a material for a nuclear energy system, start at the bottom and work upward. Higher up the pyramid is costlier and will take more time.

1. The material might already be in the marketplace. Search for ASME code cases.
2. Perhaps there is not a code, but there has been research. Do a search of the academic literature.
3. Maybe there has been research, but it doesn't answer your questions, find the project data at NSUF's Nuclear Research Data System and do your own analyses.
4. If you need to create your own data, find material specimens in the Nuclear Fuels and Materials Library.
5. Finally, if all else has failed, get your data from performing a new irradiation test.



Testing Strategy for Novel Materials

Irradiation Testing Hierarchy

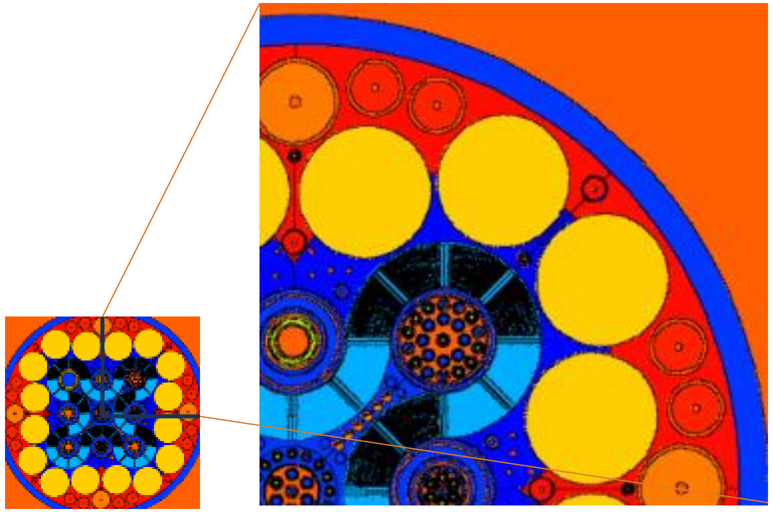
1. **Ion Beam Irradiation Facilities**
   - Allow immediate feedback of performance
   - Ease of instrumentation
   - Ease of environmental tuning
2. **Low-Power Research Reactors**
   - First 1% and 10% testing
   - Instrumentation development (pulsing for TREAT)
   - Neutron radiography
   - Experiment modeling & validation efforts

URR advantages:

- Ease of use & lower cost
- Expertise in handling and shipping/receiving RAM
- Co-located with hot cell facilities (sample preparation)
- May have gamma facilities as well

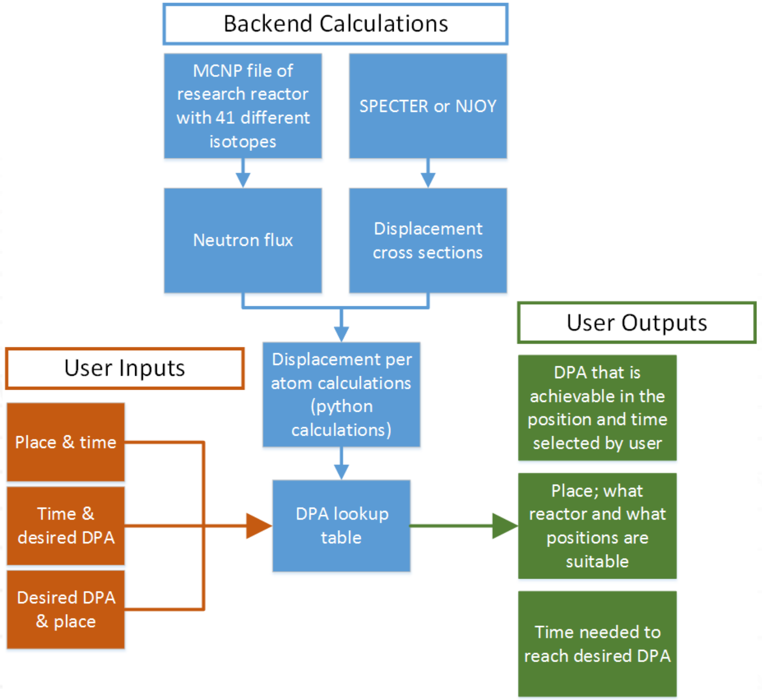
NSUF RAD Calculator - Irradiation resource tool

RAD Calc is a tool that NSUF users can access during the conceptual design phase of the proposal to select the irradiation location which is the most appropriate for their project.



The tool has four main functions:

1) calculate displacements per atom (DPA) for multiple different materials,
2) calculate the time needed to reach the desired DPA,
3) inform users what position in what reactor will give them the desired radiation damage the most effectively.
4) Estimate residual radioactivity of the specimens following neutron irradiation.



High Performance Computing (HPC) resources

NSUF HPC systems support a wide range of users and programs

- **Teton (2026)**
  - 15.6 Petaflops performance
  - 393,216 AMD 9965 Turin cores
  - 1024 nodes - 384 cores/node – 768GB/node memory
- **Windriver (2025)**
  - 5.4 Petaflops performance
  - 94,416-core Dell CTS-2 system
  - 211 TB total memory
- **Bitterroot (2024)**
  - 2 Petaflops performance
  - 43,008-core Dell CTS-2 system
  - 90 TB total memory
- **Hoodoo (2021)**
  - Machine Learning Cluster with 108 A100 GPUs
- **Sawtooth (2020)**
  - 5.6 Petaflops performance (was #37 on Top 500 list in 2020)
  - 99,972 compute cores HPE SGI 8600 system
  - 395 TB total memory

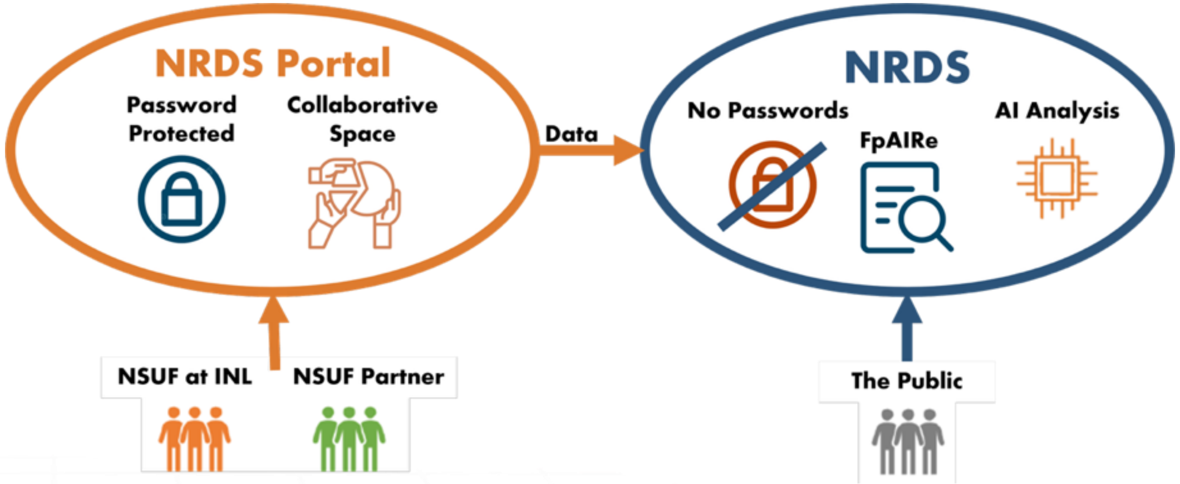
Teton

Bitterroot & Windriver

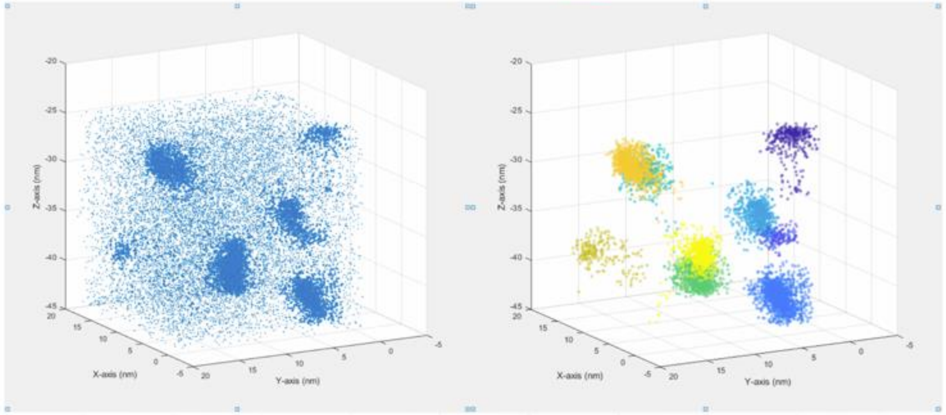
Sawtooth

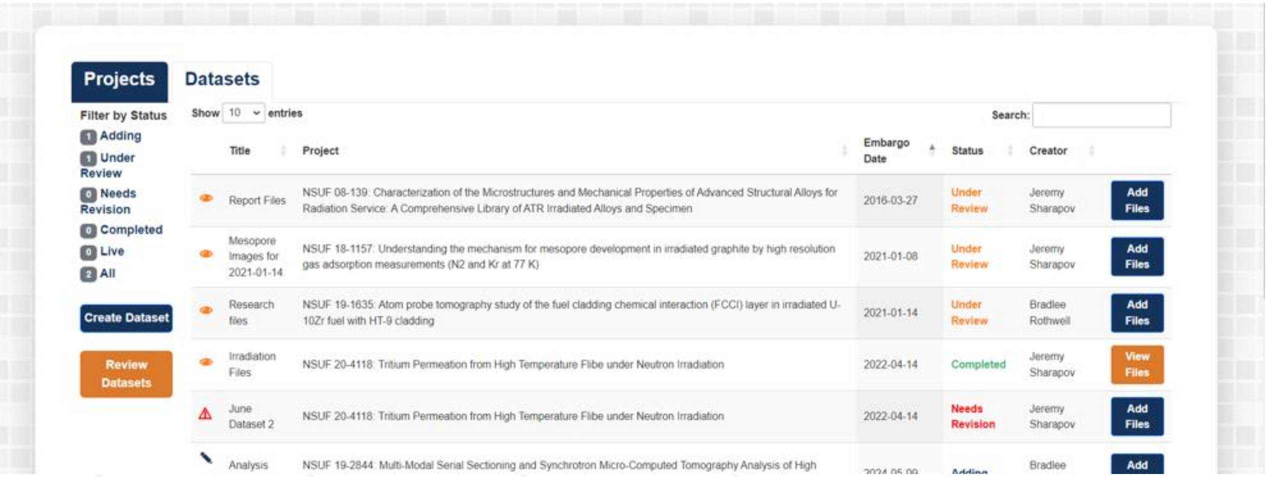
Nuclear Research Data System (NRDS)

- **NRDS Portal released to public**
  - Site for registered NSUF PIs or co-PI users
  - Workspace for data uploads to allow for project user collaboration
  - https://nrds-portal.inl.gov/
- Added **NextCloud connectivity** to allow for desktop app automatic uploads to the NRDS Portal
- 4 New **AI/ML Models** added to NRDS



Atom Probe Tomography Clustering Analysis via AI courtesy Yalei Tang





Images from NRDS Portal

NSUF User Access

NSUF Funding Calls

- **Consolidated Innovative Nuclear Research (CINR NOFO)**
  - One call per year
  - Projects include design, analyses, fabrication, transport, irradiation, disassembly, PIE, disposition
  - Possibility to also receive user R&D funding on university topic areas
  - Guidance on project costs and timelines

Neutron Irradiation + PIE	$0.5M - $4.0M	≤7 years
Neutron Irradiation only	up to ~$750K	3 years
PIE only	up to $250K	3 years
Ion or Gamma Irradiation + PIE	up to $250K	3 years
Ion or Gamma Irradiation only	up to $100K	3 years
Beamlines at other user facilities	(cost included)	3 years

The CINR NOFO is open to only U.S. universities, national laboratories, and U.S. industry entities, as principal investigators for NSUF access.

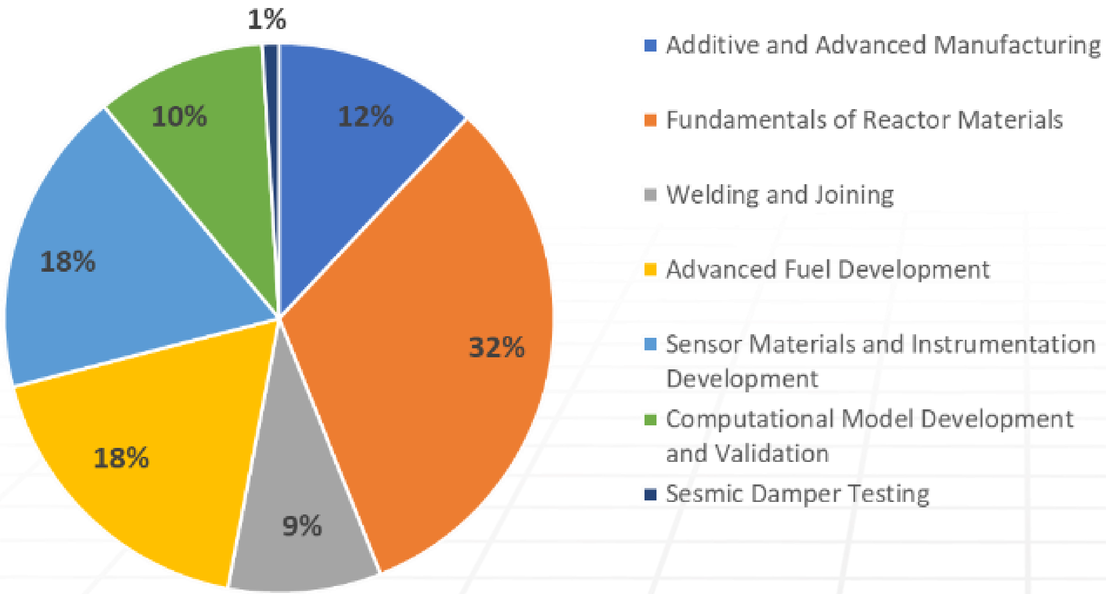
NSUF Access Award Projects Summary: FY07-FY24

- Total NSUF Access Award Funding: **$137M**
- **816** total projects awarded
  - **45** CINR type projects executed
  - **32** CINR type projects currently ongoing
  - **661** RTEs executed
  - **78** RTEs ongoing
- Awards distribution by institution type
  - **495** projects to **55** U.S. universities
  - **253** projects to **10** national laboratories
  - **35** projects to **13** industrial users*

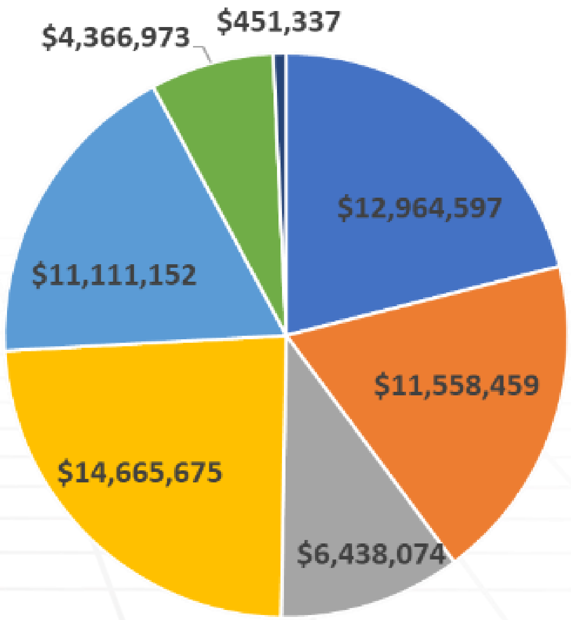
All NSUF access awards support non-proprietary fundamental science and are intended for full public release

CINR awarded projects up to FY24 by research field

Number of awards by field



Value of awards by field

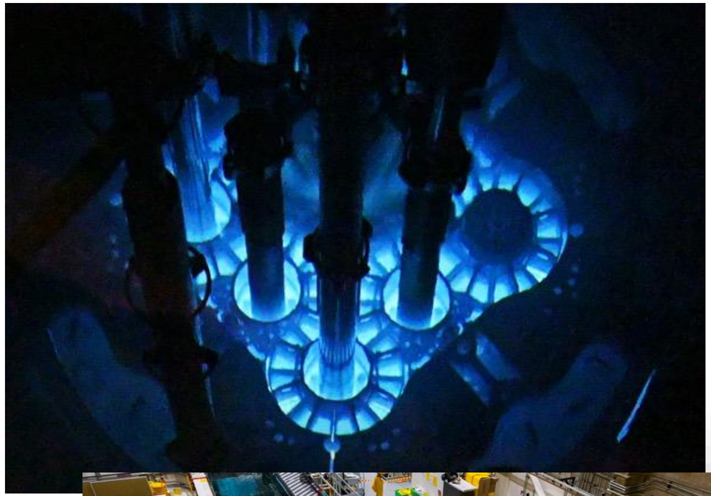


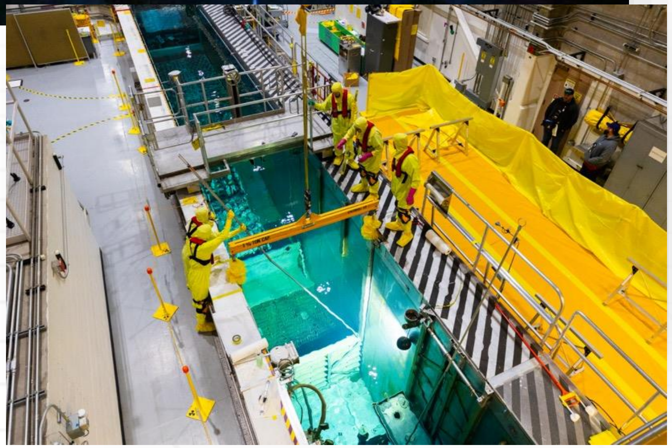
NSUF Funding Calls - Rapid Turnaround Experiments (RTE)

- Three calls per year +1 SuperRTE call
- Limited funding and scope, executed within 9 months
- Projects are selected through open competitive proposal processes
- Proposals welcome from university, government laboratory, industry, and small business researchers
  - Only non-proprietary projects accepted.
  - All awarded projects are fully forward funded.

SuperRTEs offer a broader scope than a traditional RTE and allow for more time at NSUF facilities:

- Limited funding and scope, but larger questions can be addressed
- Twice the allowable access time at NSUF partner facilities
- Two NSUF partner institutions for post-irradiation examination
- 12-month project duration
- Support for shipping between multiple NSUF partner institutions
- Increased page limit for project narrative





Nuclear Fuels and Materials Library

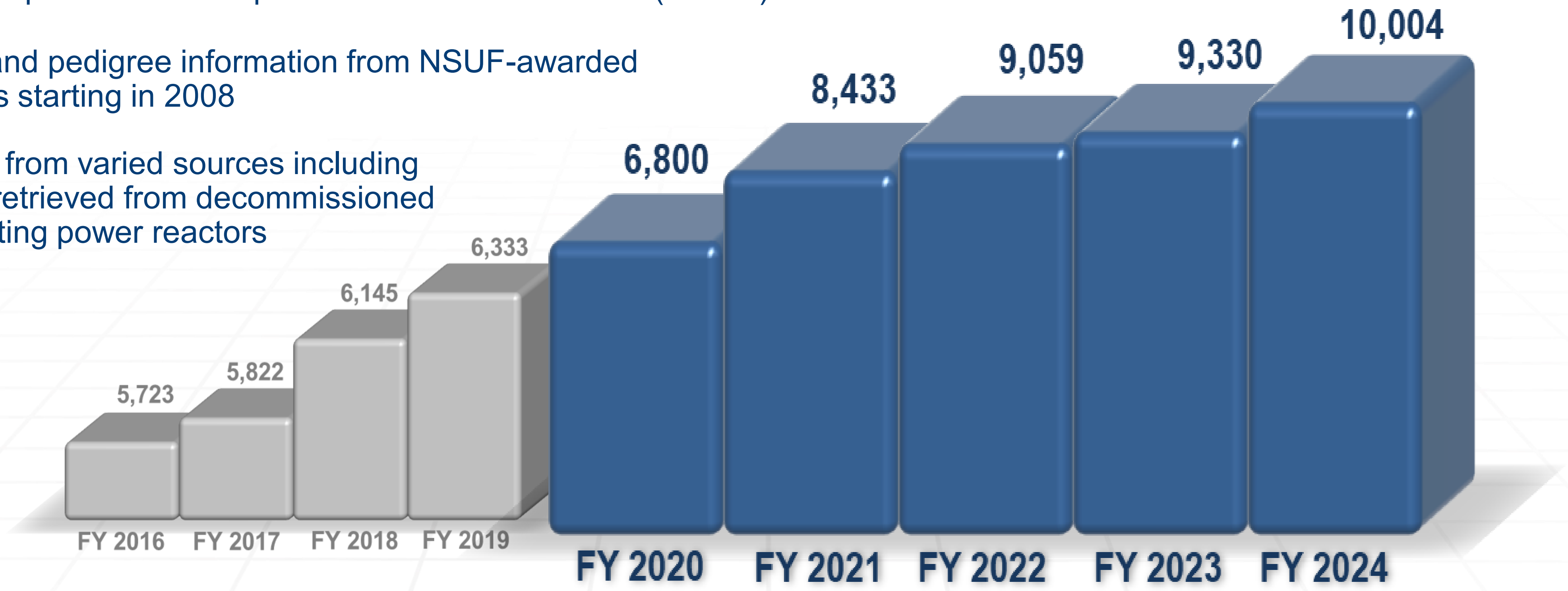
Inventory, Harvesting, and Donations

Nuclear Fuels and Materials Library

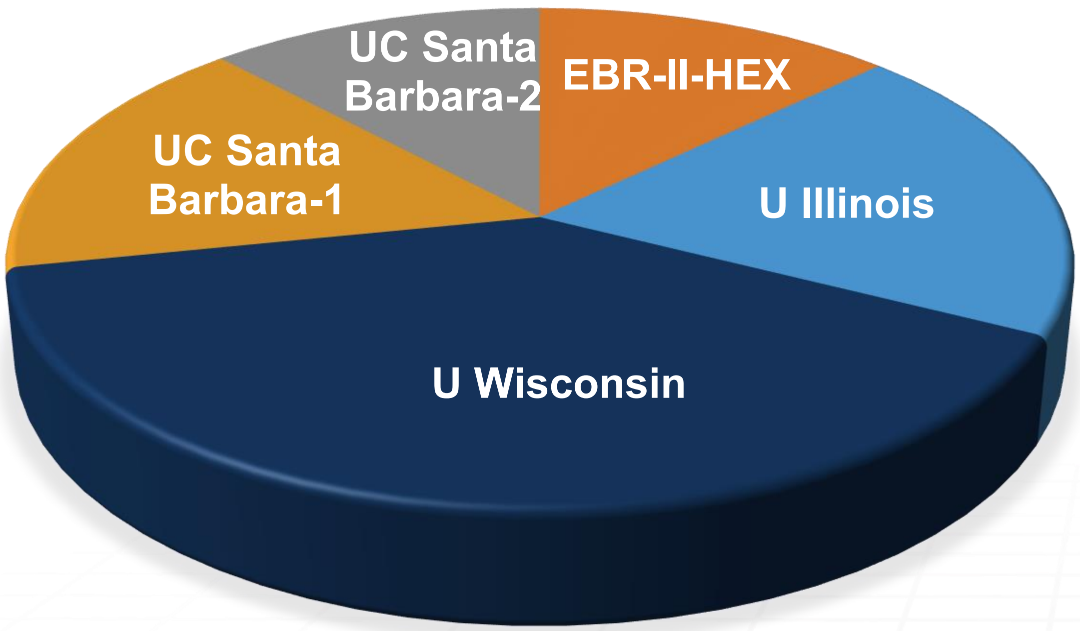
The Nuclear Fuels and Materials Library (NFML) is owned by the U.S. Department of Energy's Office of Nuclear Energy (DOE-NE) and curated by NSUF. It provides public access to over **9,000 samples** through NSUF competitive award processes or direct requests approved by the NSUF Program Leadership.

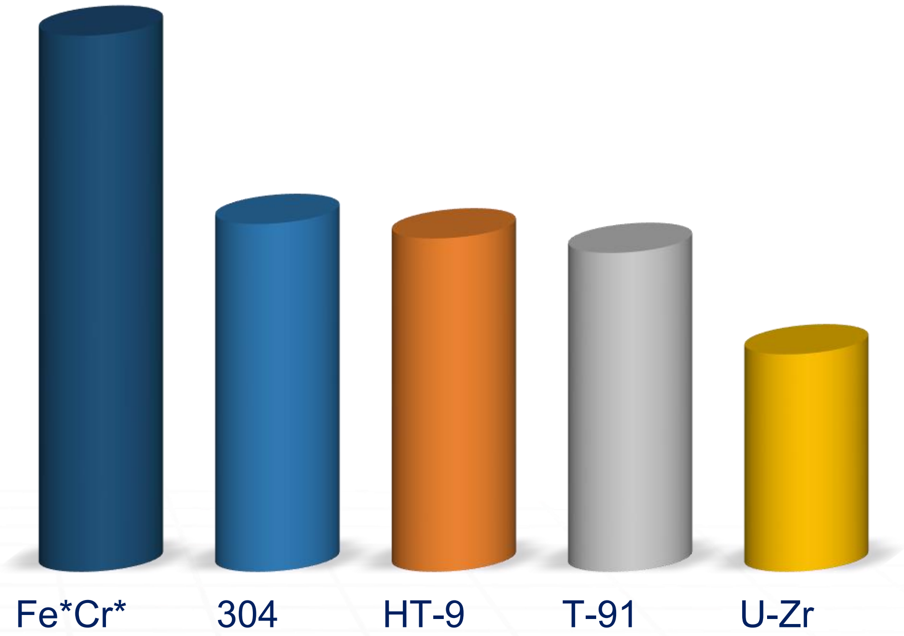
Launched online in 2016, the NFML includes:

- Legacy samples from the Experimental Breeder Reactor (EBR-II) shutdown in 1994
- Samples and pedigree information from NSUF-awarded irradiations starting in 2008
- Donations from varied sources including materials retrieved from decommissioned and operating power reactors



Top Five Requested Projects and Materials (2010-2023)





U Wisconsin: Irradiation Test Plan for the Advanced Test Reactor National Scientific User Facility/University of Wisconsin Pilot Project

UCSB-1: Characterization of the Microstructures and Mechanical Properties of Advanced Structural Alloys for Radiation Service: A Comprehensive Library of ATR Irradiated Alloys and Specimen

U Illinois: Irradiation Performance of Fe-Cr Base Alloys

UCSB-2: High Fluence Embrittlement Database and ATR Irradiation Facility for LWR Vessel Life Extension

EBR-II-HEX: EBR-II Legacy Hexblocks and Assemblies

NSUF Nuclear Fuels and Materials Library

FY24 Acquisitions: Nuclear Industry Donations (BWXT NOG)

Harvested LWR Core Shroud Material

Donor: EPRI/Southern Nuclear/BWXT

- 304 SS core shroud samples (weld and base metal and Heat Affected Zones (HAZ) from a commercial LWR NPP
- Legal transfer of Title and Ownership signed in FY 2022
- Samples delivered in batches from BWXT to INL
- Last shipment arrived in early March of 2025

Program	NSUF
Reactor Id	LWR
Reactor Position	core shroud
Sample Id Code	22-BWXT-01
Material Code	Piece A1
Material Name	304 SS
Material Type Id	Structural Material
Material Description	Piece A Base Metal
Specimen Type	remnant
Dimensions	2" x 1" x 0.063"
Number Of Samples	1
Samples Remaining	1
Specimen Availability Id	Yes
Availability Date	12/5/202
Date Added	3/12/2024
Facility Id	Hot Fuel Examination Facility
Notes	Skim cut of wetted surface. Weight 16 g. Estimated Dose Rate at1' = 8 R/hr
As Run Temp	288
As Run Dose	3.25
As Run Fluence	2.3E+21
As Run Flux	1.00E+10
Material Tags	In-Service LWR, 304, Core Shroud

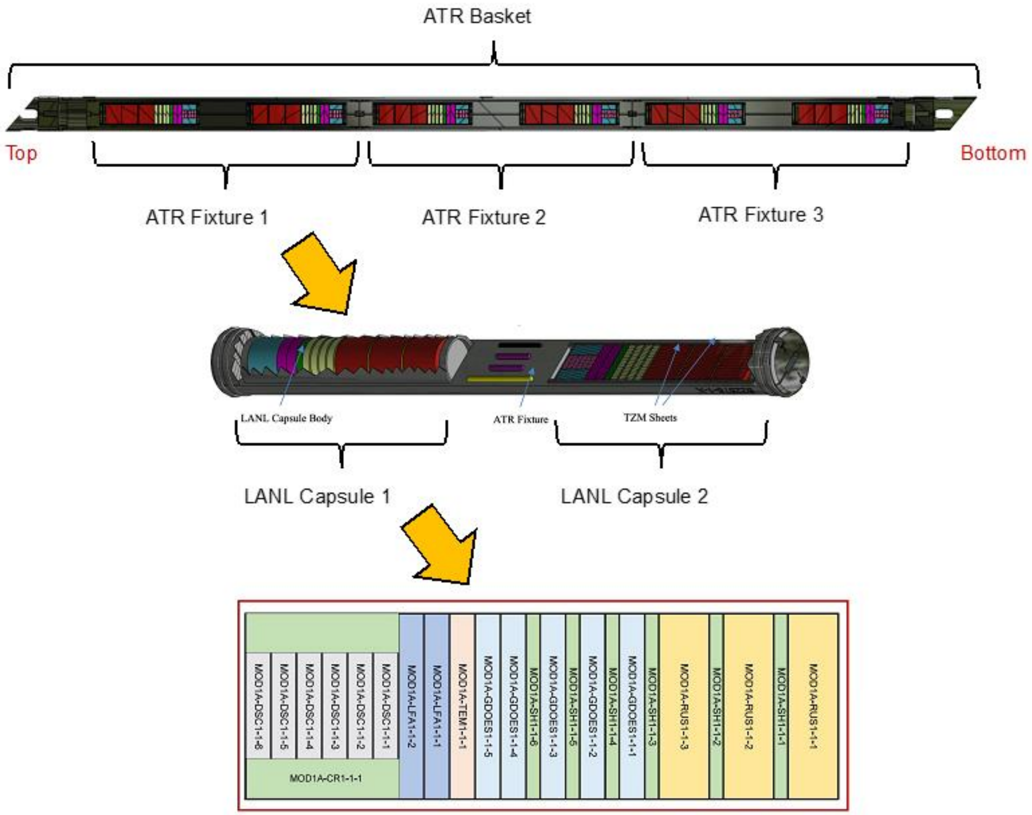
NSUF Nuclear Fuels and Materials Library

FY24 Acquisitions: Microreactor Program Donation

Yttrium-Hydride Solid Neutron Moderator

Donor: DOE-NE Microreactor Program

- ATR-irradiated samples fabricated by LANL
- Yttrium-hydride can be used as a moderator for microreactors or space reactors due to its stability at higher temperatures.



Sample placement in the LANL capsule

Nuclear Fuels and Materials Library

Directed Irradiation Campaigns

“SAM” Collaborative ATR Irradiation Campaigns

- **Objective**
  - Irradiate various structural/cladding materials important to current and advanced civilian nuclear energy technologies
  - Add highly interested/demanded structural/cladding materials from donations and harvesting
    - Materials will be characterized to accelerate nuclear structural/ cladding materials development / qualification / deployment.
- **Approach**
  - Select high priority nuclear structural/cladding materials for irradiation
  - Utilize a standard irradiation capsule design and bounding safety analyses to irradiate structural/cladding material specimens, such as SSJ tensile bars, and three and six mm disks

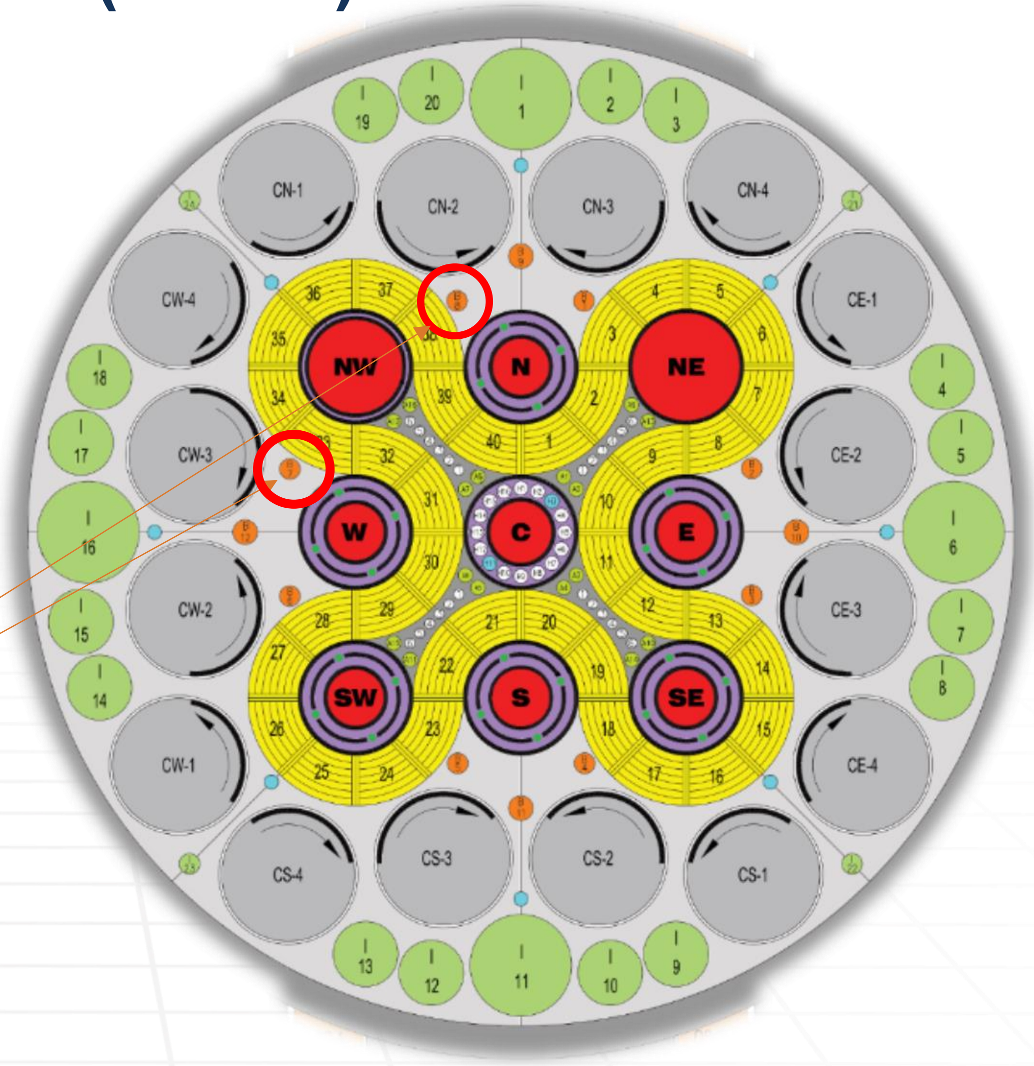
Structural Material Standard Capsule (SMSC)

Materials and Irradiation Limits

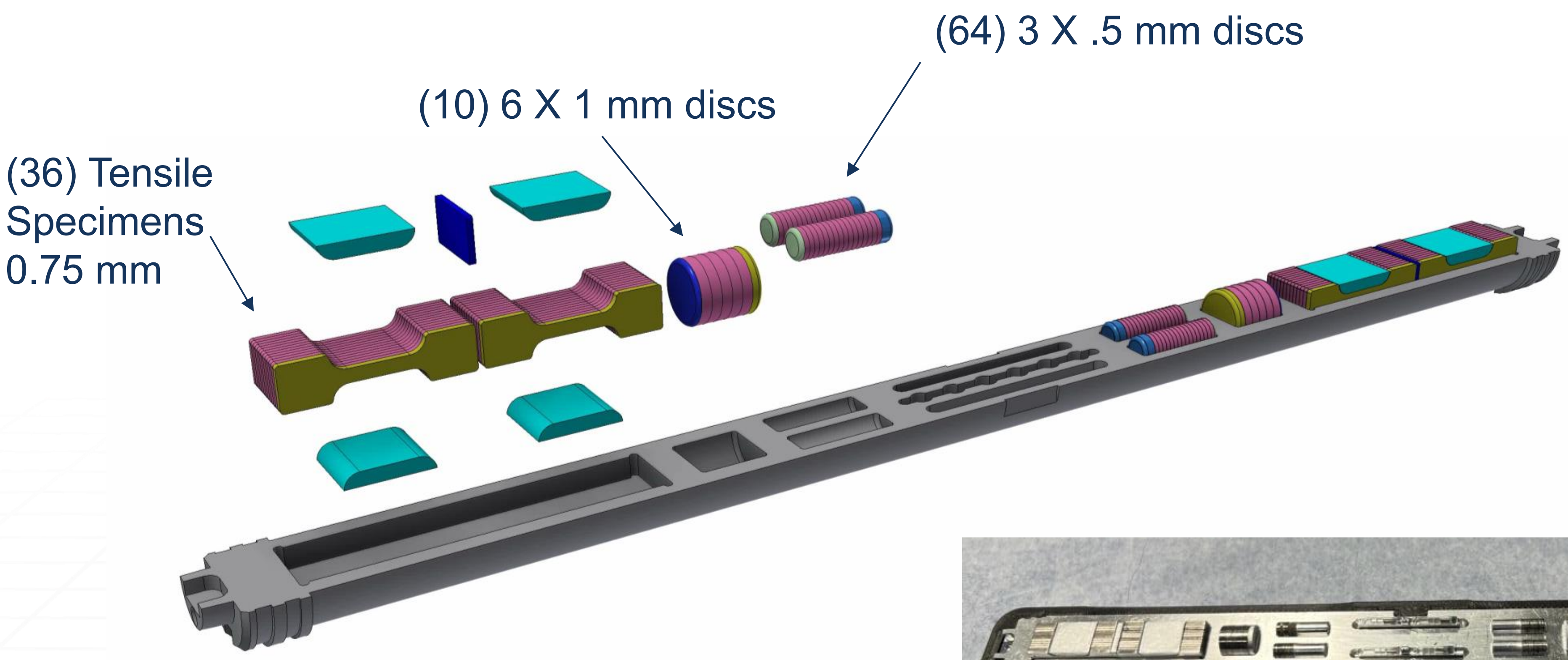
- **Materials**: non-fuel, structural and cladding materials, materials should not be brittle.
- **Maximum dpa**: 6 dpa (in stainless steel)
- **Temperature range**: ~200-700 °C.

Experimental Overview

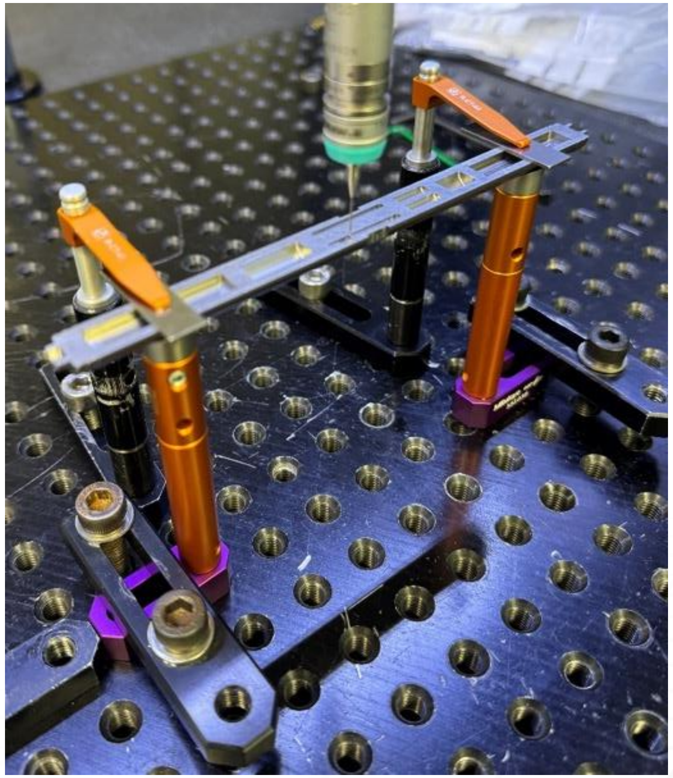
- Drop In materials experiment
  - 6 capsules (initial loading)
- 60 days ATR cycle
- B7 or B8 positions ("small B")
- Concept maximizes the efficiency of the ATR, utilizing all three dimensions available

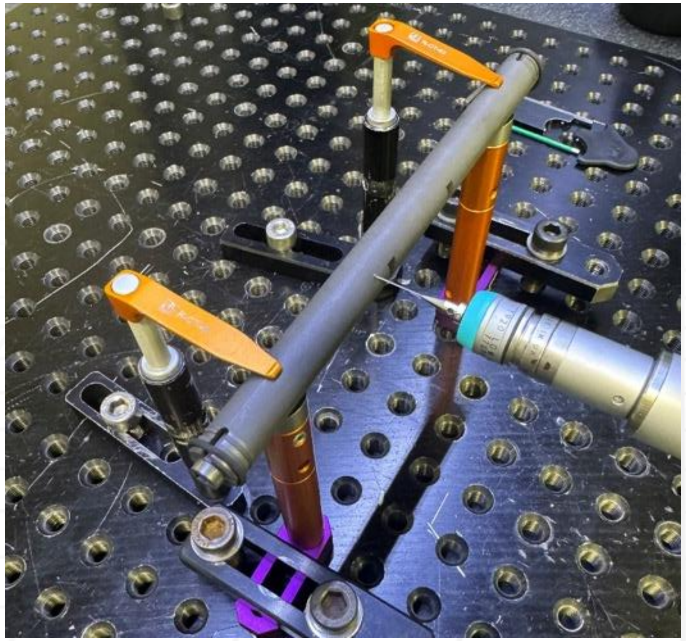


5/8” NSUF Structural Material Standard Capsule (SMSC)



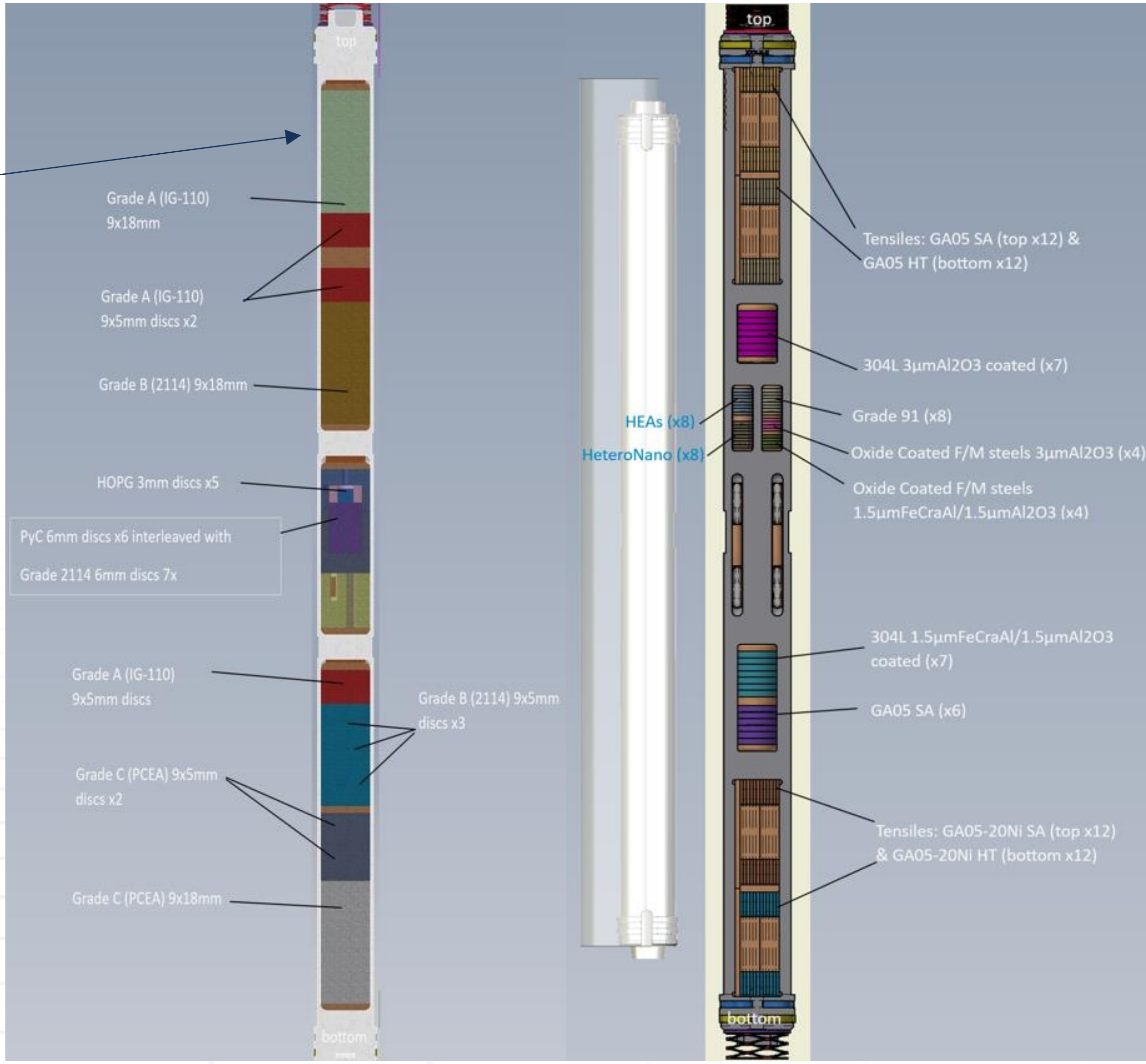
NIFT-E Capsules & Specimens



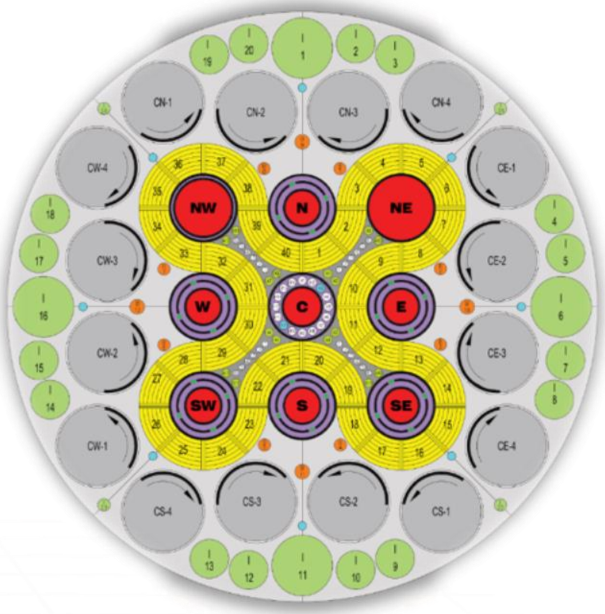


Qualification of the UKAEA for construction of the SMSC

Adaptation of the SMSC for large-grained graphite



NSUF-NNUF Cooperative ATR Project (NIFT-E)



NIFT-E "**N**eutron **I**rradiation as a **F**unction of **T**emperature – **E**xperiment"

Strategic Objectives

- Explore sharing of nuclear facilities between US and UK
- Further nuclear energy research collaboration

Technical Objectives

- Capture effects of neutron irradiation as a function of temperature on dose on nuclear graphite and on alumina-forming austenitic (AFA) steels
- Targets microstructure and mechanical property plus corrosion behavior

Stakeholders

US: NSUF plus INL, PNNL, Purdue University, Westinghouse

UK: NNUF plus UK NNL, Univ. of Manchester, Univ. of Oxford, Univ. of Sheffield, UKAEA

Graphite
IG110
2114
PCEA
HOPG
IPyC

Miscellaneous Material
Oxide-Coated F/M Steels 3µm Al2O3 coated
Oxide-Coated F/M Steels 1.5 µm FeCrAl 1.5 µm Al2O3 coated
Adv Mfg Grade 91
HEAs
Hetero Nano-composites

Alumina-Forming Alloys
GA05 SA
GA05 HT
GA05 20Ni SA
GA05 20Ni HT
AISI Type 304L SS 3 µm Al2O3 coated
AISI Type 304L SS 1.5 µm FeCrAl 1.5 µm Al2O3 coated

NIFT-E Project Timeline & Strategy

Activity	Finish Date
Final Design Complete	September 2023
Assembly Complete	September 2024
Commence Irradiation	November 2024

Capsule	DPA Target	Temperature
C1	1.0 dpa minimum	750 ± 50°C
C2	2.0 dpa minimum	750 ± 50°C
C3	3.0 dpa minimum	750 ± 50°C
AFA1	1.0 ± 0.3 dpa	400 ± 50°C
AFA2	1.0 ± 0.3 dpa	650 ± 50°C
AFA3	8.0 dpa nominal	400 ± 50°C
AFA4	4.0 dpa nominal	400 ± 50°C
AFA5	4.0 dpa nominal	650 ± 50°C

CAPSULE	CYCLES	EFPD
NIFT-E-AFA1	1	60
NIFT-E-AFA2	1	60
NIFT-E-AFA3	11	540
NIFT-E-AFA4	6	300
NIFT-E-AFA5	4	240
NIFT-E-C1	3	180
NIFT-E-C2	6	280
NIFT-E-C3	9	400

		CYCLE 1	CYCLE 2		CYCLE 3	CYCLE 4	CYCLE 5	CYCLE 6	CYCLE 7	CYCLE 8	CYCLE 9	CYCLE 10	CYCLE 11	CYCLE 12	CYCLE 13
ATR Position		B2	B2	N/A	B7	B7	B7	B7	B7	B7	B7	B7	B7	B7	B7
		STACKUP 1	STACKUP 2		STACKUP 2	STACKUP 3	STACKUP 4	STACKUP 4	STACKUP 4	STACKUP 5	STACKUP 5	STACKUP 6	STACKUP 6	STACKUP 6	STACKUP 7
		60 day	60 day		60 day	60 day	60 day	60 day	60 day	60 day	50 day	50 day	50 day	60 day	50 day
		173C	175A	175B	175C	175D	175E	177A	177B	177C	179A	179B	179C	179D	181A
CAPSULE POSITION	A	1025376-10	1025376-10	Unable to insert	1025376-10	1025376-10	1025376-10	1025376-10	1025376-10	1025376-10	1025376-10	1025376-10	1025376-10	1025376-10	1025376-10
	B	NIFT-E-AFA1	NIFT-E-AFA4		NIFT-E-AFA4	NIFT-E-AFA4	NIFT-E-AFA4	NIFT-E-AFA4	NIFT-E-AFA4	1025376-10	1025376-10	1025376-10	1025376-10	1025376-10	1025376-10
	C	NIFT-E-C1	NIFT-E-C1		NIFT-E-C1	NIFT-E-C2	NIFT-E-C2	NIFT-E-C2	NIFT-E-C2	NIFT-E-C2	NIFT-E-C2	1025376-10	1025376-10	1025376-10	1025376-10
	D	NIFT-E-AFA5	NIFT-E-AFA5		NIFT-E-AFA5	NIFT-E-AFA5	NIFT-E-C3	NIFT-E-C3	NIFT-E-C3	NIFT-E-C3	NIFT-E-C3	NIFT-E-C3	NIFT-E-C3	NIFT-E-C3	NIFT-E-C3
	E	NIFT-E-AFA2	NIFT-E-AFA3		NIFT-E-AFA3	NIFT-E-AFA3	NIFT-E-AFA3	NIFT-E-AFA3	NIFT-E-AFA3	NIFT-E-AFA3	NIFT-E-AFA3	NIFT-E-AFA3	NIFT-E-AFA3	NIFT-E-AFA3	1025376-10
	F	1025376-10	1025376-10		1025376-10	1025376-10	1025376-10	1025376-10	1025376-10	1025376-10	1025376-10	1025376-10	1025376-10	1025376-10	1025376-10
START		11/28/2024	5/5/2025		11/1/2025	1/30/2026		9/16/2026		3/15/2027	9/27/2027	12/16/2027	3/5/2028		10/30/2028
FINISH		1/27/2025	7/4/2025		12/31/2025	3/31/2026		11/15/2026		5/14/2027	11/16/2027	2/4/2028	4/27/2028		12/19/2028

Expected Impacts of the SAM Campaign

- Efficient use of limited neutron irradiation resources
- Improved utilization of the NSUF NFML system
- Increased integration of NSUF with relevant DOE-NE programs
- Impactful scientific publications and presentations
- Talent pipeline (graduate student training, workforce development)
- The knowledge gained from SAM-3 and resultant PIE studies will accelerate structural materials development/qualification/deployment for advanced nuclear reactor technologies in the US

Additional References

Department of Energy Technical Standards and Handbooks

https://www.standards.doe.gov/

- Reactor Physics 1: https://www.standards.doe.gov/standards-documents/1000/1019-bhdbk-1993-v1
- Reactor Physics 2: https://www.standards.doe.gov/standards-documents/1000/1019-bhdbk-1993-v2
- Material Science 1: https://www.standards.doe.gov/standards-documents/1000/1017-BHdbk-1993-v1
- Material Science 2: https://www.standards.doe.gov/standards-documents/1000/1017-BHdbk-1993-V2
- Mechanical Science 1: https://www.standards.doe.gov/standards-documents/1000/1018-bhdbk-1993-v1
- Mechanical Science 2: https://www.standards.doe.gov/standards-documents/1000/1018-bhdbk-1993-v2
- Chemistry 1: https://www.standards.doe.gov/standards-documents/1000/1015-bhdbk-1993-v1
- Chemistry 2: https://www.standards.doe.gov/standards-documents/1000/1015-bhdbk-1993-v2
- Thermal Hydraulics 1: https://www.standards.doe.gov/standards-documents/1000/1012-BHdbk-1992-V1
- Thermal Hydraulics 2: https://www.standards.doe.gov/standards-documents/1000/1012-bhdbk-1992-v2
- Thermal Hydraulics 3: https://www.standards.doe.gov/standards-documents/1000/1012-bhdbk-1992-v3

Nuclear Energy Education Resources

- https://www.energy.gov/ne/office-nuclear-energy
- https://www.energy.gov/ne/stem-resources
- https://inl.gov/nuclear-energy/
- https://www.nrc.gov/reading-rm/basic-ref/students/elearning.html

- https://www.ans.org/nuclear/energy/
- https://www.ans.org/nuclear/science/
- https://hps.org/publicinformation/

Nuclear Reactors and Nuclear Energy References

- https://www.energy.gov/ne/articles/nuclear-101-how-does-nuclear-reactor-work
- https://www.energy.gov/ne/light-water-reactor-sustainability-lwrs-program
- https://www.energy.gov/ne/articles/7-moments-december-changed-nuclear-energy-history
- https://www.energy.gov/ne/enhanced-safety-advanced-reactors
- https://www.energy.gov/ne/advanced-reactor-technologies
- https://www.energy.gov/ne/nuclear-fuel-cycle
- https://www.energy.gov/ne/fuel-cycle-technologies
- https://www.energy.gov/ne/office-spent-fuel-and-high-level-waste-disposition
- https://inl.gov/proving-the-principle/
- https://inl.gov/52-reactors/
- https://www.energy.gov/ne/articles/history-nuclear-energy
- https://www.eia.gov/energyexplained/nuclear/us-nuclear-industry.php
- https://www.epa.gov/radtown/nuclear-power-plants
- https://www.nrc.gov/about-nrc/history.html

Learning Resources

- Short courses and Summer schools
  - https://www.mevschool.net/
  - https://www.anl.gov/education/national-xray-school
  - https://neutrons.ornl.gov/nxs
  - https://www.nist.gov/ncnr/chrns/education-and-outreach/chrns-summer-school-neutron-scattering
-
- User Facilities and Research Tools
  - https://nsuf.inl.gov/
  - http://science.energy.gov/user-facilities/ (DOE-supported)
  - https://www.nsf.gov/focus-areas/infrastructure (NSF-supported)
  - https://ssurf.org/

Questions?

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Nuclear Science User Facilities

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