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Nuclear Science User Facility: Overview of Neutron Irradiation Activities

Brenden Heidrich

November 2017

The INL is a U.S. Department of Energy National Laboratory
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Nuclear Science User Facility

nsuf.inl.gov

Overview of Neutron Irradiation Activities

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Chief Irradiation Scientist, NSUF

Annual NSUF Program Review
DOE Headquarters
Germantown, MD
November 13, 2017

NSUF Nuclear Science User Facilities

INL/EXT-17-43833

Outline

1. **NSUF Neutron Irradiation Capabilities**
   - NSUF Neutron Irradiation Capability Demand
2. **NSUF Neutron Irradiation Experiments**
   - Challenges: specimen readiness
3. **Neutron Irradiation Toolkit Development**
   - Path forward

Nuclear Science User Facilities

NEUTRON IRRADIATION CAPABILITIES

NEAC Neutron Irradiation Capabilities Conclusions

Conclusions:

1. U.S. Rx have sufficient thermal flux for fuels irradiations.
2. U.S. Rx have insufficient fast flux for accelerated testing of advanced reactor materials.
3. U.S. Rx are not currently capable of irradiating fuels and materials in thermal, hydraulic, mechanical, and chemical environments representative of advanced liquid-metal or molten-salt reactors.
4. U.S. Rx are ≥ 50 years old.

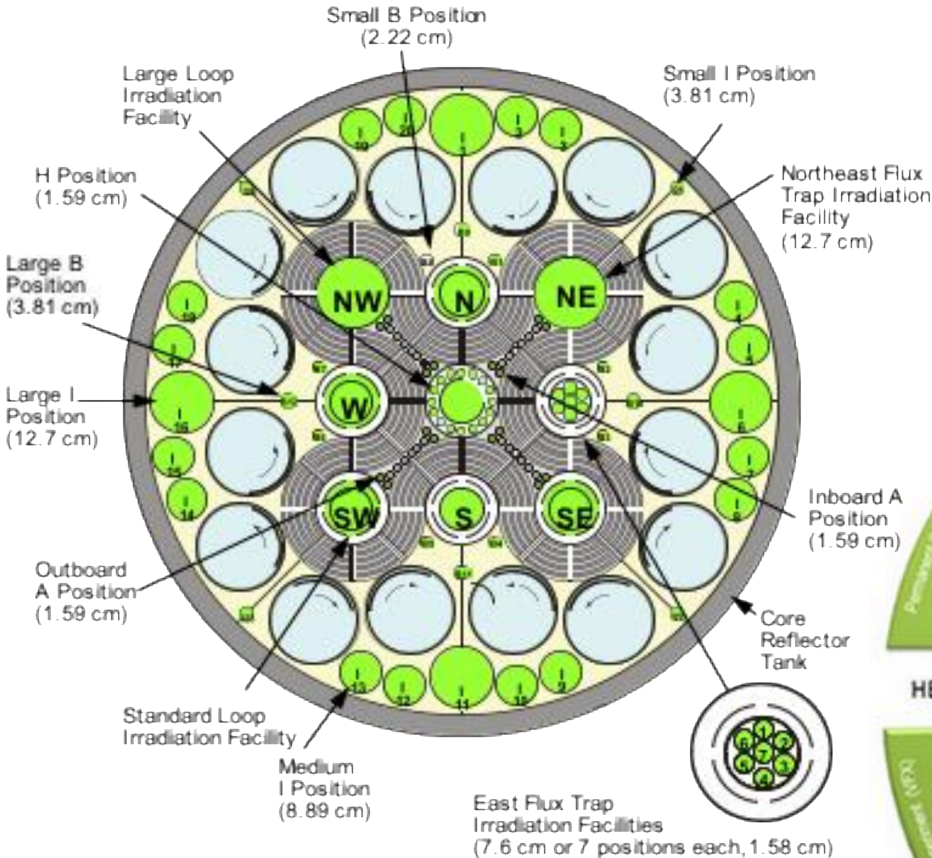
Recommendations:

1. Utilize the Gen IV Intl Forum DB to update the NSUF NEID.
2. Engage in communication with intl. facilities (incl. Russia and India).
3. Proceed immediately with pre-conceptual design planning activities to support a new test reactor.

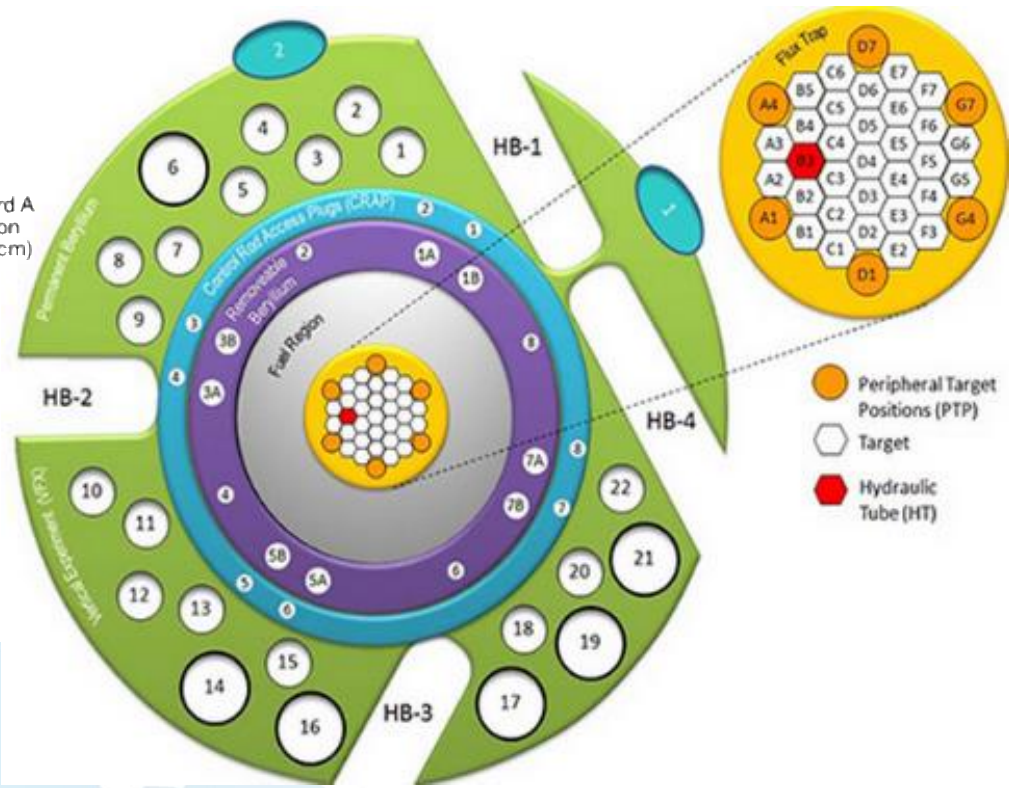
Global Research & Test Reactors

Reactor	Country	Thermal Flux [10^{14}nv]	Fast Flux [10^{14}nv]	Utilization
JOYO	Japan		40	Material, fuel
BOR-60	Russia	2	35	Material, isotopes
HFIR	US-TN	25	10	Isotopes, beam, fuel, material
BR-2	Belgium	10	7.1	Fuel & material, isotopes
ATR	US-ID	10	5	Material, fuel, isotopes
HANARO	S. Korea	4.5	3	Isotope, beam, fuel, material
SAFARI-1	S. Africa	2.4	2.8	Isotopes, beam, radiography
NBSR	US-MD	4	2	Neutron scattering, beam
MITR	US-MA	0.5	1.7	Material, beam, silicon
MURR	US-MO	6	1	Material, silicon, isotopes
HBWR	Norway	1.5	0.8	Material, fuel, loops
PULSTAR	US-NC	0.20	0.02	Isotope, silicon, beams
OSURR	US-OH	0.12	0.05	Sensors, high-temp testing
ACRR	US-NM			Transient testing, rad effects
SPR-CX	US-NM			Critical facility

Advanced Test Reactor

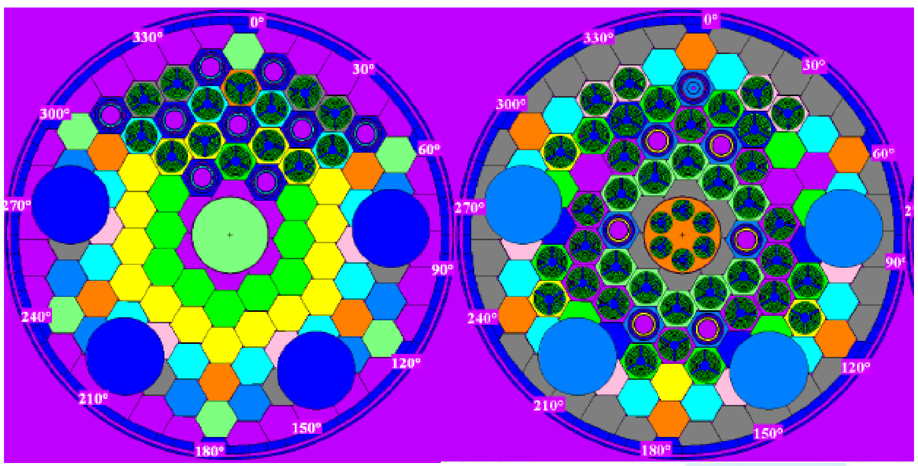


High Flux Isotope Reactor



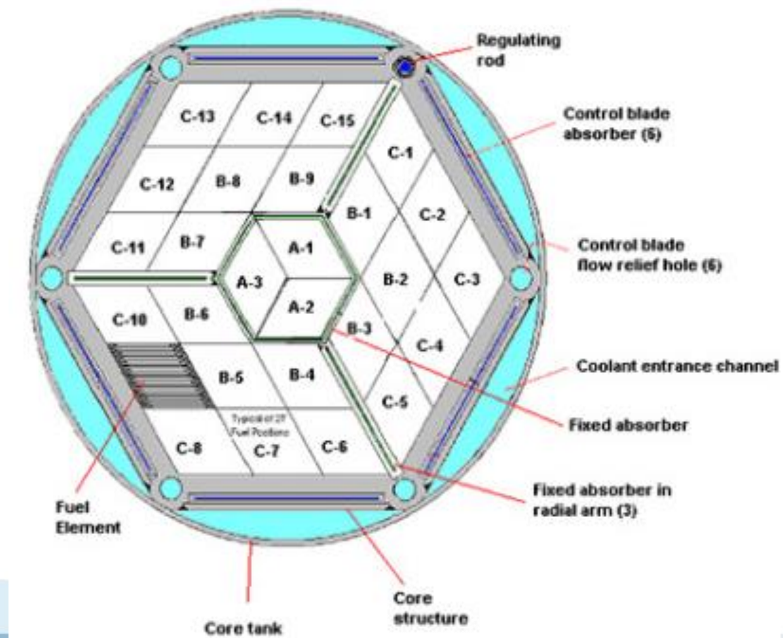
Belgian Reactor-2

- Multiple experiment vehicles
  - Static Capsules & Instrumented Leads
  - Pressurized water capsules for fuel tests (PWC)
  - PWR loop (CALLISTO)
  - Sodium loop (IPSL)
- SS and transient tests
  - SS: 600w/cm^2
  - TT: 100 W/cm/min



MIT Reactor-II

- Inert gas (He/Ne mix) irradiation:
  - Instrumented (ICSA facility)
  - High temperature (>900 ºC)
- Forced-circulation coolant loops for LWR conditions,
- Custom facilities for unique conditions (molten F salts).
- Thermal flux 0.4×10^{14} n/cm^2-s
- Fast flux 1.2×10^{14} n/cm^2-s.



NCSU PULSTAR Reactor

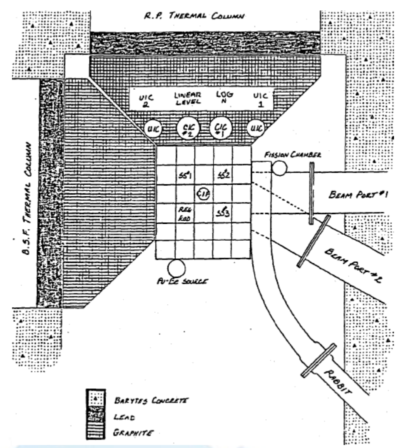
- 1 MW_{th} (upgrading to 2MW)
- 4% enriched pellets with Zirc-2 clad
- Sample sizes range: 3.175–8.89 cm
- Thermal Flux range: 10^{12}-10^{13} n/cm^2/s
- Fast Flux range: $5x10^9$-10^{12} n/cm^2/s
- Capabilities
  - Positron intense beam facility
  - Neutron powder diffraction facility
  - Neutron imaging facility
  - Ultra-cold neutron source
  - TRISO fission gas sampling

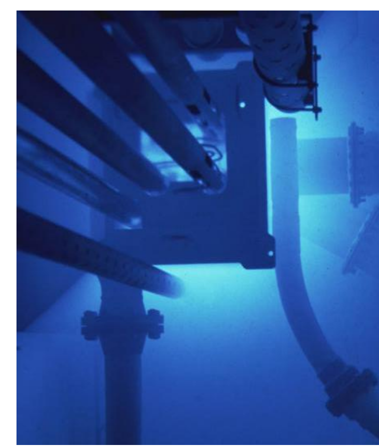
Ohio State University Research Reactor

500kW LEU pool-type URR

- CIF, AIF & Rabbit system in-core
- 7 & 10" Dry Tubes at core edge
  - Temperature control from 4-1873K

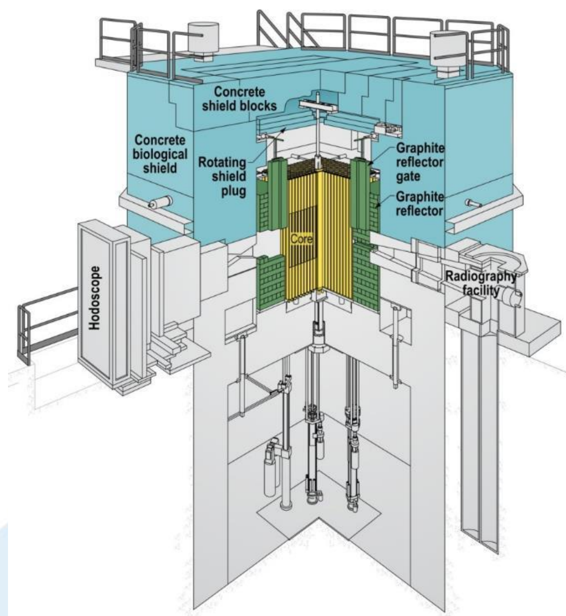
Facility	Thermal Flux [nv < 0.5eV]	Fast Flux [nv > 1Mev]
CIF	1.4E+13	4.7E+12
10" Dry Tube	3.1E+11	1.6E+11





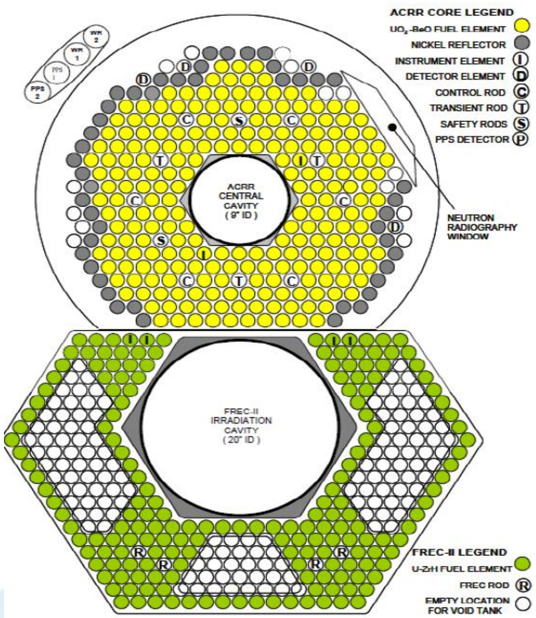
Transient Reactor Test (INL)

- Induce intense fission heating in the nuclear fuel being tested.
- Test nuclear reactor fuels under severe reactor-accident conditions.
- Provide nondestructive test data through neutron radiography of fuel samples.



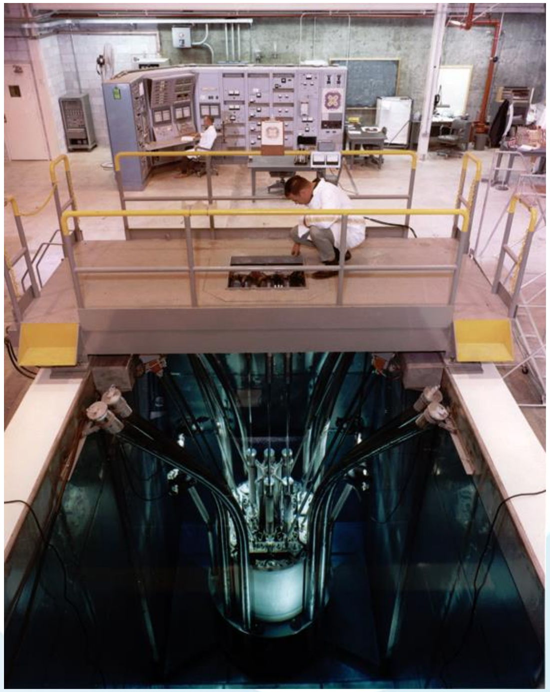
Annular Core Research Reactor

- High-flux pulsing reactor w/ tunable spectrum
- 9” diameter central cavity
- 20” diameter FREC-II cavity
- 10^{15}nvt E>1 MeV pulse
- 6.4×10^{15}nvt total MeV pulse



ATR Critical Facility

- 0.1kW$_{th}$ (typical) 5 kW$_{th}$ (max)
  - Thermal Flux 2.3x10^{10} n/cm^2/s
  - Fast Flux 0.7x10^{10} n/cm^2/s
- ATR-C provides physics data for:
  - worth and calibration of control elements,
  - excess reactivity and charge lifetimes,
  - thermal and fast neutron distributions,
  - gamma heat generation rates

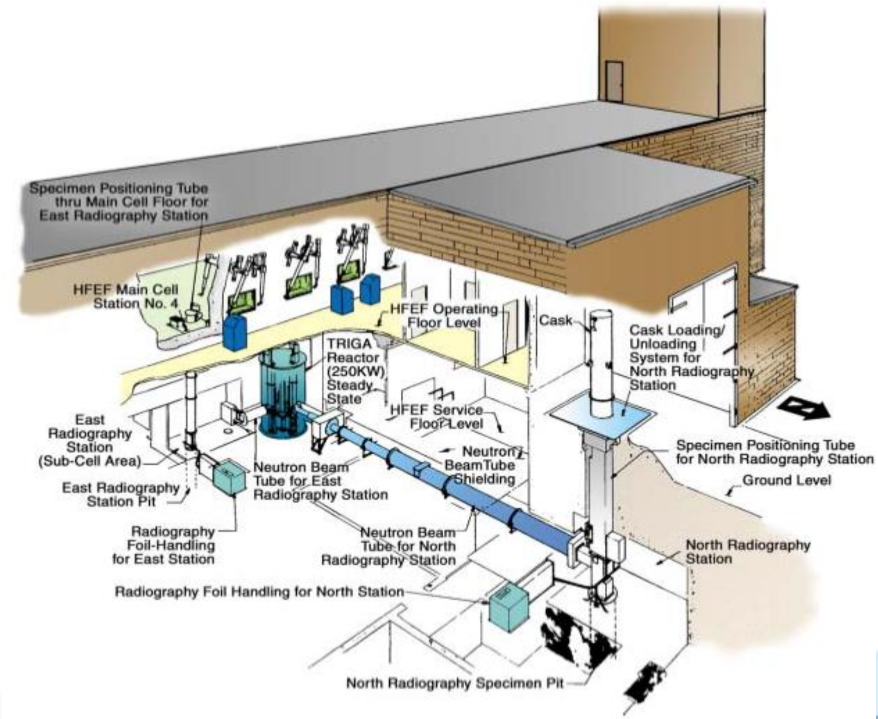


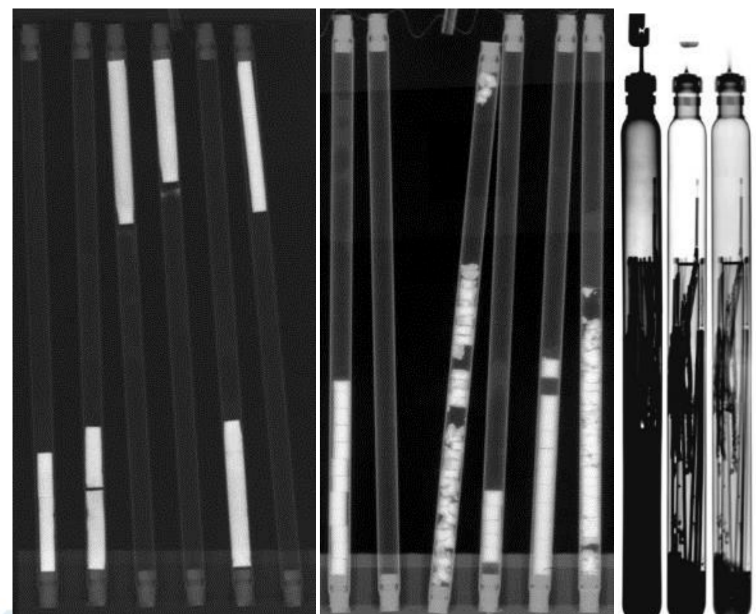
SPR-CX Critical Facility

- 7.2% LEU UO_2
- BUCCX (BurnUp Credit Critical Experiment)
- 7uPCX (Seven Percent Critical

Nuclear Radiography Reactor

- 250kW TRIGA Reactor
- Purpose: Non-destructively interrogate internals
- Application:
  - Evaluate fuel integrity and movement
  - Hydriding in LWR cladding



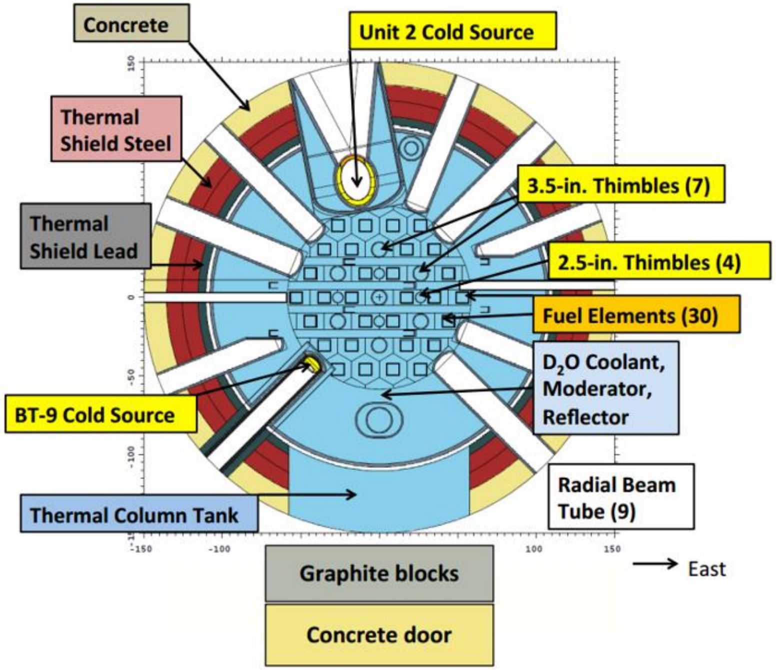


What are the remaining gaps?

- High(er) fast flux
- LWR loop (more)
- Non-LWR loop
- Pulsing (TRIGA)

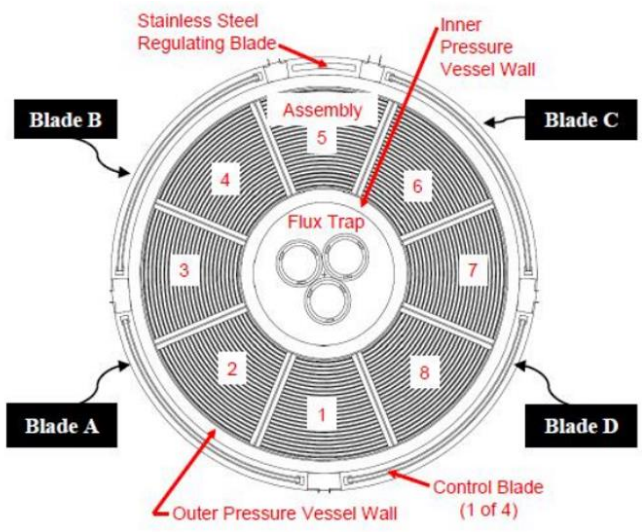
National Bureau of Standards Reactor

- HEU Fuel: 93% $^{235}U_3O_8$ + Al with D_2O Coolant, Moderator, Reflector
- Fuel cycle: 38 days with a peak flux of 3.5 x 10^{14} n/cm^2/sec
- 9 radial thermal neutron beams, 5 “rabbits” and 10



University of Missouri-Columbia Reactor

- 8 93% HEU fuel elements
- 10 MW, 53ºC, 85 psia
- 3 flux trap locations, 15 reflector locations
- 6 beam ports for neutron scattering
- Primary mission is isotope production



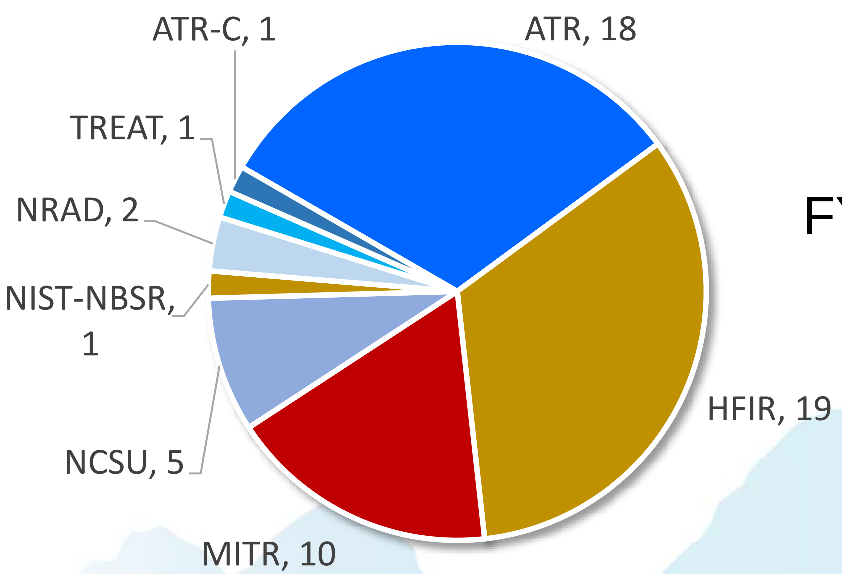
MURR Core

Nuclear Science User Facilities

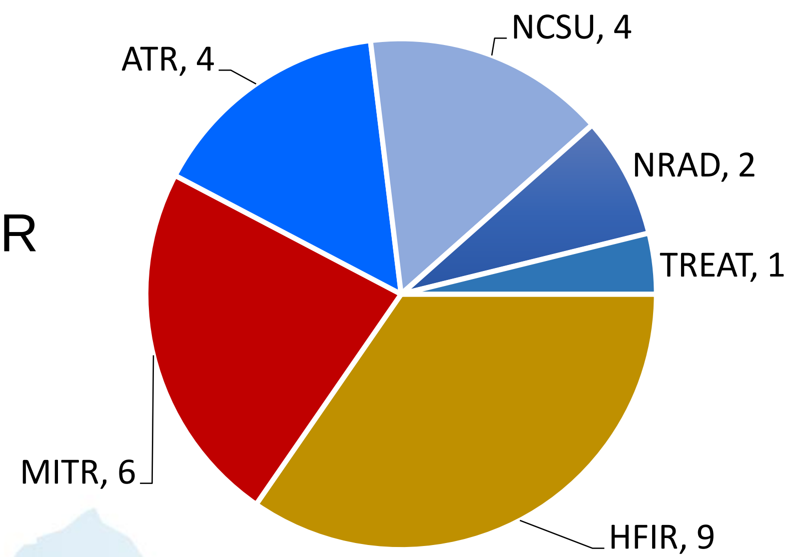
FY2018 CINR IRRADIATION PROPOSALS

NSUF Irradiation Utilization (by CINR)

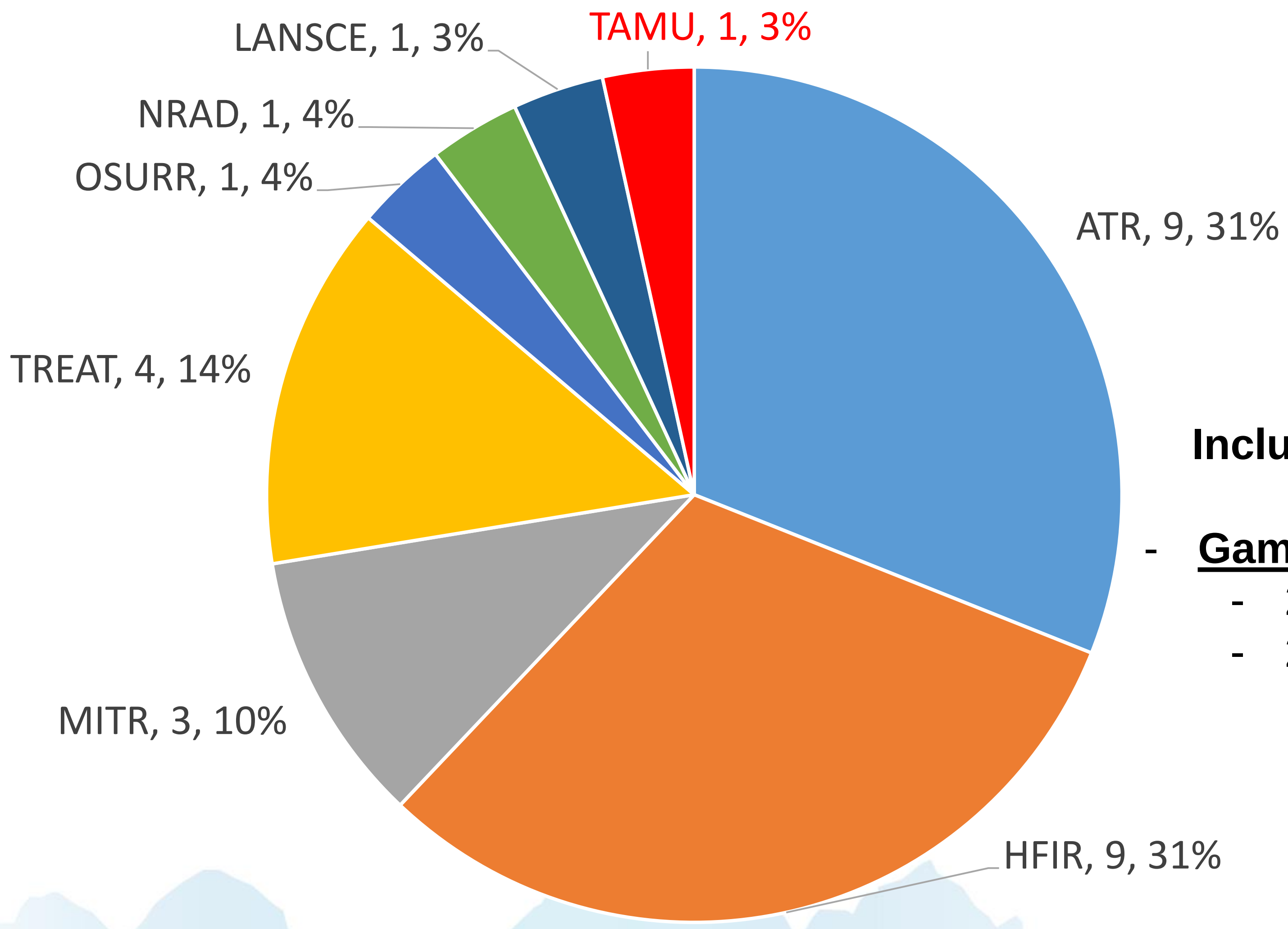
Reactor	FY15 FOA	FY16 FOA	FY17 FOA
ATR (INL)	1	3 + SAM1	1 + SAM2(?)
HFIR (ORNL)	0	2	2
MITR-II (MIT)	1	1	2
PULSTAR (NCSU)	0	1	2
BR-2 (SCK-CEN)	0	3	0



FY17 CINR Demand



Neutron Irradiation Proposals
(FY 2018 access requests)



Including:

- **Gamma Irradiation**
  - 2x ATR
  - 2x HFIR

Irradiation Requests by Workscope

- **Likely to fund only**:
  - one in each R&D workscope and
  - One or two in the NSUF2.1 & 2.2 workscopes.

	1.1	1.2	NEAMS 2	2.1	2.2
ATR		5	2	2	
HFIR	4	3		2	
MITR	2	1			
TREAT	1		2		1
OSURR	1				
NRAD				1	
LANSCE				1	
TAMU	1				
Total	9	9	4	6	1

ATR Position Strategy

- Specific call in CINR
- 3D programming of ATR
- Fill in the gap with SAMs

Nuclear Science User Facilities

NEUTRON IRRADIATION PROJECTS

Nuclear Fuels

Number	Institution	PI	Purpose	Materials	Reactor	Status
10-242-2	Univ. Central Florida	Yongho Sohn	Metallic fuels at low fluences (AFCI, M^3)	Diffusion Couples	ATR (HSIS)	On hold
10-242-3	Univ. Central Florida	Yongho Sohn	Metallic fuels at low fluences (AFCI, M^3)	DC, TEM, MPC	ATR (B8)	Running, done in 2Q18
10-269-1	Boise State Univ. (Utah State Univ.)	Darryl Butt	U_3Si_2 fuel interaction	Diffusion couples (U_3Si_2, Zr, FeCrAl, SiC)	ATR (I14)	Running, done post-CIC
17-12985	Electric Power Research Institute	Ken Yueh (EPRI) & Michelle Bales (NRC)	Irradiation, and PIE of Ultra High Burnup Fuel (LOCA perf.)	Irradiated UO_2 from LWR	ATR (CFT)	Specimen selection 1Q18
BR2-2 DISECT	Purdue and INL	Dan Wachs and Maria Okuniewski	Separate effects testing under controlled temperatures	Foils and matchsticks of U-Zr and U-Mo fuel	BR2	Mature design, fabrication underway
BR2-3 ATTICUS	BSU & INL	Darryl Butt & Jason Harp	U_3Si_2 fuel water interaction and corrosion	Fuel pins of U_3Si_2 & UN/U_3Si_2	BR2 (PWC)	INL FDR due 3Q18

Advanced Manufactured Materials

Number	Institution	PI	Purpose	Materials	Rx	Status
EPRI-ZG (2010)	Electric Power Research Institute		Radiation-induced growth of LWR cladding	Various pre-hydrided zirconium alloys for LWR cladding	ATR (A13-16)	• TEM analysis completed • 20 & 30 dpa in ATR
15-8242	Boise State Univ. (Purdue)	Janelle Wharry	HIP-PIM metals vs. cast/forged (weldability & inspectability)	TEM & tensile for 625, 690, Grade 91, 304L, 316L SA 508	ATR (A4-6)	• FDR comp. • Insert 2Q18 • Done 3Q19
15-10537 N-SERT	Idaho State Univ. (MS&T)	Haiming Wen	Nanostructured steels for rad. tolerance	Tensile, hardness, and TEM specimens for ECAP and HPT (steels + HEA)	ATR (B6)	• FDR comp. • Insert 2Q18 • Done 2Q21
16-10393	GE-Hitachi	Ronald Horn	Direct Metal Laser Melting (DMLM)	Tensile, CGR, fracture toughness for 316L SS & Alloy 718(PH)	ATR (B11)	• FDR comp. • Inserted 4Q17 • Done 3Q18
16-10584	Colorado School of Mines	Jeffrey King	Commercial SS and Inconel	Tensile, MPC for 316L SS & Alloy 718(PH)	ATR (B5)	• FDR comp. • Insert 2Q18 • Done 3Q18

Advanced Sensors

Number	Institution	PI	Purpose	Materials	Rx	Status
15-8389 ULTRA-2	Idaho National Laboratory	Joshua Daw	Sensor qualification: fission gas release, fission gas composition, and axial temp. meas.	INL- CEA pressure sensor, ultrasonic thermometer and fiber optics	MITR-II	Running through FY18
17-13073	Univ. of Pittsburgh	Kevin Chen	Multi-functional fiber optic sensors with AM components	3 types of silica FO as well as commercial sapphire fiber sensors	MITR-II	RTI 1Q19
17-12527	Boise State Univ. (MS&T)	Yanliang Zhang	AM thermal sensors for in-pile thermal conductivity measurement	Aerosol-jet printed thermal conductivity sensors (Pt printed on CeO_2)	NCSU(18) MITR(19)	NCSU irrad. done 4Q18
BR2-1	Idaho National Laboratory	Troy Unruh	Rx performance benchmarking and thermal modeling	SiC Temperature Monitors	BR2	Completed irrad. 4Q17
BR2-4	Idaho National Laboratory	Joshua Daw	Irradiation performance of adv. temp. sensors	ultrasonic thermometer and fiber optics	BR2	In design

Accident-Tolerant Materials

Number	Inst.	PI	Purpose	Materials	Rx	Status
16-10468	ORNL	Yutai Katoh	High-heat flux irradiations of SiC cladding	CVD SiC, composite SiC and coated SiC tubes	HFIR (rabbit)	• RTI 4Q 17 • Irradiation 2Q18
16-10784	ORNL	Tyler Gerczak	Radiation-Enhanced Diffusion of Ag, Ag-Pd, Eu, and Sr (TRISO)	Diffusion couples of Ion-implanted PyC/SiC	HFIR (rabbit)	• Thermal analysis done 4Q17 • Ion irrad. 2Q18 • RTI 3Q18
17-12573	General Atomics	Christian Deck	Performance of SiC-SiC cladding and endplug Joints under neutron irrad. & thermal gradient	tube-endplug and torsion joined specimens of SiC-SiC composites	HFIR (rabbit)	• Thermal analysis due 4Q18 • Irradiation FY19
17-13007	AREVA	Jacqueline Stevens	ATF Neutron Absorbers to replace Ag-In-Cd & B_4C	Hafnium Carbide, HfC w/< 3wt% MoSi2, Samarium Hafnate & Europium Hafnate	HFIR (rabbit)	• Thermal analysis due 1Q19 • Irradiation FY19-20

Nuclear Science User Facilities

SPECIMEN READINESS ISSUES AND SOLUTIONS

Specimen Readiness Issues

- INL-15-8389: Sensor qualification test
  - delay in shipment of CEA sensors

- ISU-16-10537: Nanostructured steels for rad. tolerance
  - delay in shipment of bulk material
  - difficulty in fabrication of specimens from bulk material

- CSM-16-10584: Commercial AM alloys
  - Difficulty in identifying material vendors

Changes to the CINR FOA

NOTE: Applicants must demonstrate readiness for NSUF access.

- In the NSUF Access Request, a summary of readiness is required.
- In the full application, a detailed description of readiness is required.
- Awarded projects that are found to not be ready for NSUF access may be cancelled.

The following items must be completed prior to requesting access:

- Development and qualification of fabrication techniques, processes and methods
- Pre-irradiation characterization (physical, mechanical, thermal, chemical and other applicable properties)
- Material interaction studies (at irradiation conditions)
- Corrosion studies (at irradiation conditions)

NSUF/INL will arrange for fabrication of materials into specimens for the test reactor irradiations.

Changes to the CINR FOA

A plan for delivery with specific attention to the following:

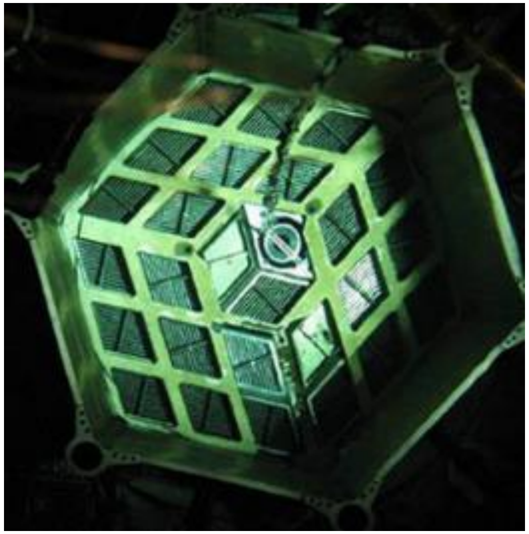
- Structural and cladding materials for neutron irradiation must be supplied to NSUF three months after project initiation..
- For previously irradiated fuels and materials not residing in the NFML, information that will be needed in order to ship and/or prepare the fuel or material for examination must be identified.
- Ownership of the materials
  - For any fuels or materials supplied for the purpose of neutron irradiation, the applicant must own and have full authority to transfer ownership to DOE.
  - For fuels or materials coming from other DOE programs (not NSUF), a statement of program commitment is required.

Usability Improvements

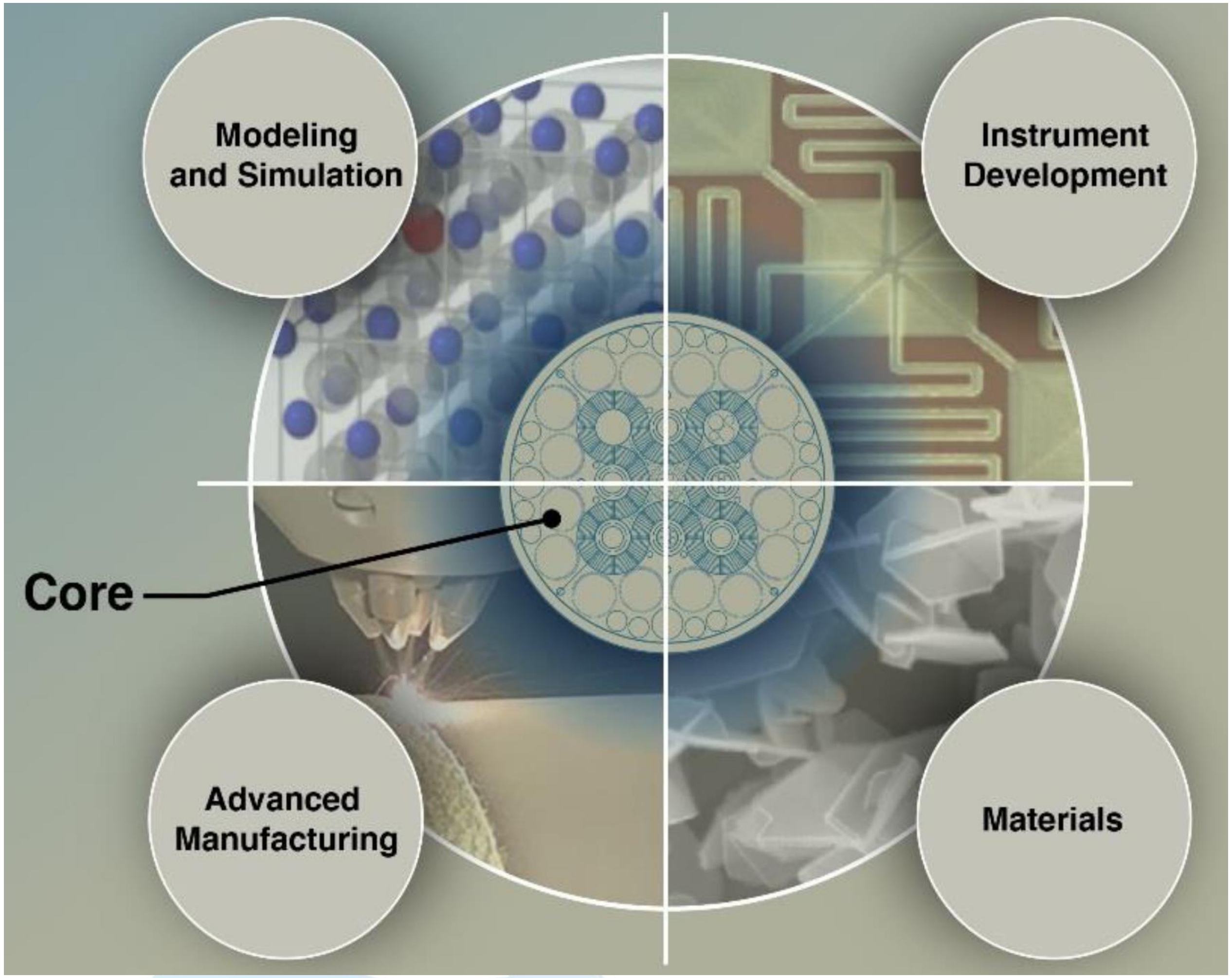
In order to better support the users of the NSUF access programs:

- Developing web-based tools to help users and NSUF Tech Leads:

1. **Irradiation resource selection**
   - Neutron flux and spectrum for NSUF reactors
     - Most efficient allocation of resources
   - Convert Neutron Fluence to DPA
     - Materials scientists request dpa
     - Reactor engineers think in terms of fluence
     - Compound materials can be difficult
2. **ATR Experiment Database**
   - Library of prior ATR irradiation experiment documentation
3. **Estimate sample activity following irradiation**
   - Estimate time to be able to ship samples
   - Determine facilities that can accept materials
   - Estimate dose from characterization procedures
   - Also for materials in the NFML



In-pile Instrumentation Initiative



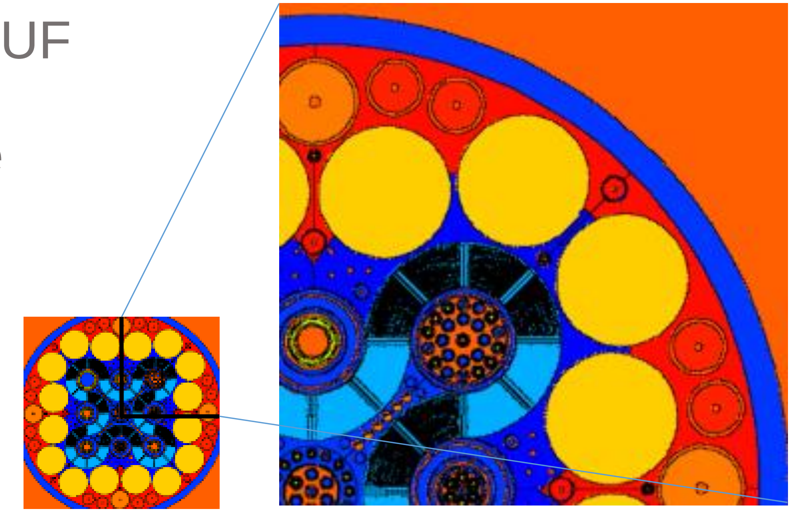
Testing Strategy for Novel Materials

Irradiation Testing Hierarchy

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

1. Irradiation resource selection tool

The goal of this project was a tool that NSUF users and technical project leads can use during the conceptual design phase of the proposal to select the irradiation location which is the most appropriate.

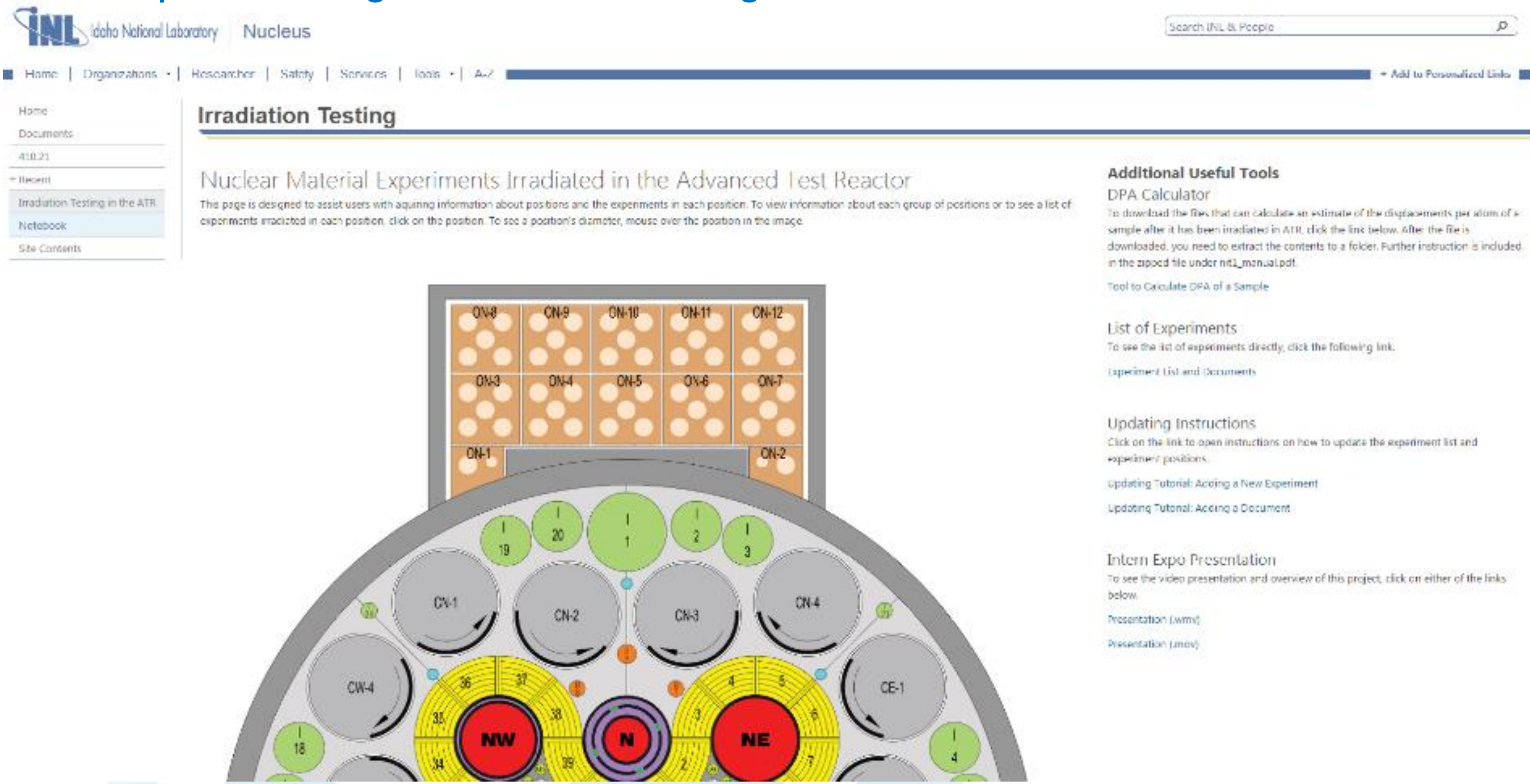


The tool has three main functions:

1) calculate displacements per atom (DPA) for multiple different materials,
2) calculate the time needed to reach the desired DPA, and
3) inform users what position in what reactor will give them the desired radiation damage the most effectively.

2. ATR Irradiation Testing Tool

- https://nst.inl.gov/irradiationtesting



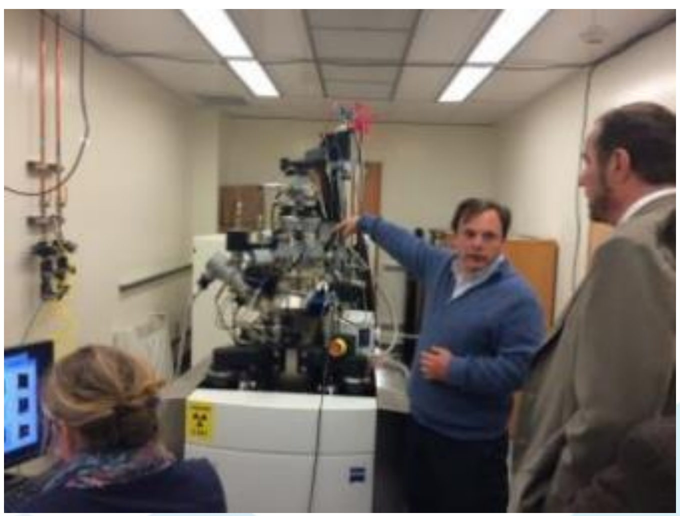
3. Sample Activation Tool

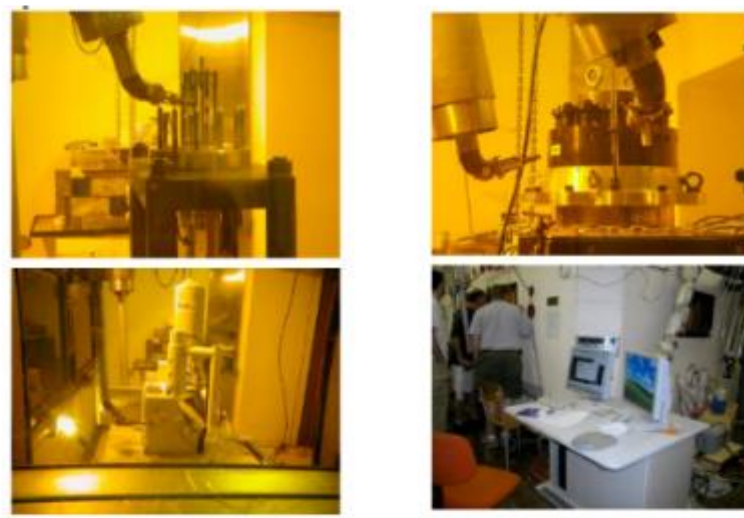
Estimating the radioactivity of a sample before it is ever irradiated will:

(1) increase awareness for worker safety,

(2) improve efficiency by planning the examination work at the appropriate facility, and reducing shipping costs

(3) inform researchers of project delays due waiting for decay.





3. Small Specimen Tensile Testing Challenge

- Tensile testing has long been an important method for determining the material properties of different structural steel components.

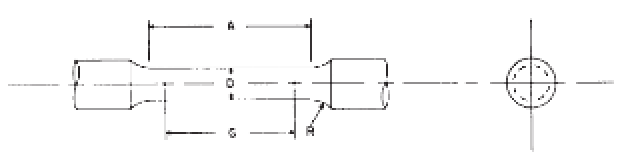
- The effect of irradiation on these steel components is of particular interest to the nuclear power industry.

- The large (E8) specimens typically used are not efficient for test reactor irradiations. They also usually require a hot cell for performing post-irradiation examination.

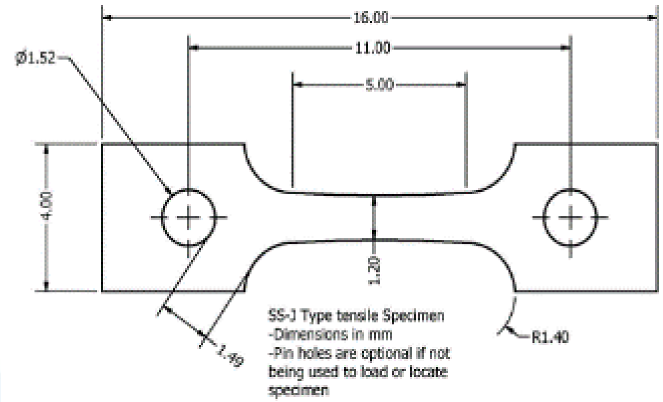
- Research into using small-scale tensile specimens has been of great interest in the nuclear industry for quite some time.

Alloy	Dose Rate		6 dpa
	T=0	T=365	
SA 508	112	97	R/hr @ 30cm
625	75	28	
718	6.2	0.13	
690	1.5	0.10	
316L	3.8	0.10	
Grade 91	2.3	0.09	
304L	3.8	0.09	

E 8M – 04



	Dimensions, mm				
	Standard Specimen	Small Size Specimens Proportional To Standard			
	12.5	9	6	4	2.5
G—Gage length	62.5 ± 0.1	45.0 ± 0.1	30.0 ± 0.1	20.0 ± 0.1	12.5 ± 0.1
D—Diameter (Note 1)	12.5 ± 0.2	9.0 ± 0.1	6.0 ± 0.1	4.0 ± 0.1	2.5 ± 0.1
R—Radius of fillet, min	10	8	6	4	2
A—Length of reduced section, min (Note 2)	75	54	36	24	20



Future Work

1. Couple the Irradiation Selection Tool with the Activation Tool
   - IST calculates irradiation time from spectrum and power and feeds fluence and time data to AT.
   - AcT uses the 100-energy group flux to calculate activation of specimen
2. Integrate these tools into the NSUF Storefront.
   - Reactor selection is limited by “reasonable” irradiation times, nothing too big or too small.
   - Shipping and PIE facility choices are informed by specimen radiation levels.
3. Verify results with MCNP-ORIGEN calculations

Special Session at Summer 2018 ANS Meeting, Philadelphia, PA

"Applications of DOE-NE Infrastructure Support for University Research Reactors"

- University research reactors have formed a cornerstone of nuclear engineering research and education since the first reactor was deployed in 1954 at the NCSU.
  - The population grew to a high of ~80 in 1970, but has dropped to 24 in 2017.
- DOE-NE has supported the remaining reactors through fuel and infrastructure support.
  - Since 2009, DOE-NE has awarded 208 proposals totaling over $56 million for research reactor infrastructure not including fuel support.
- This session is intended to highlight the unique and innovative applications that have been funded through the DOE-NE RRI program that have helped to keep these reactors viable into the 21st century.
- IRD wants this to be a recurring session, alternating RRU & GSI

Contact Information for NSUF

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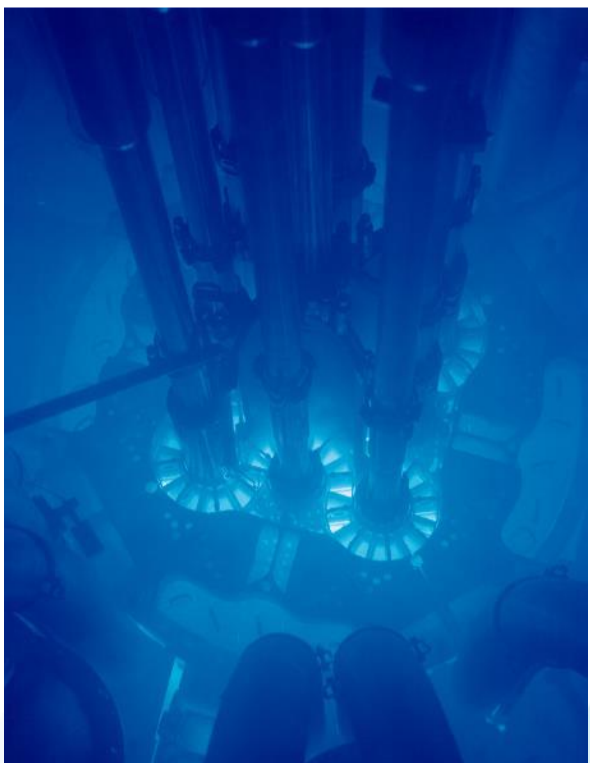

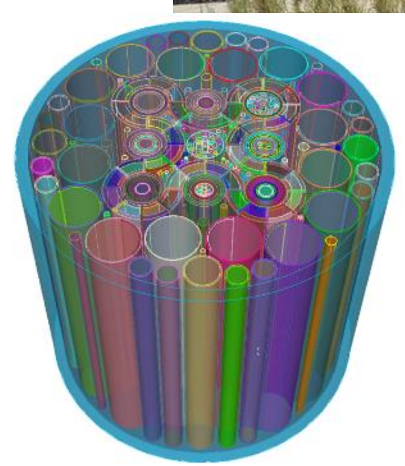

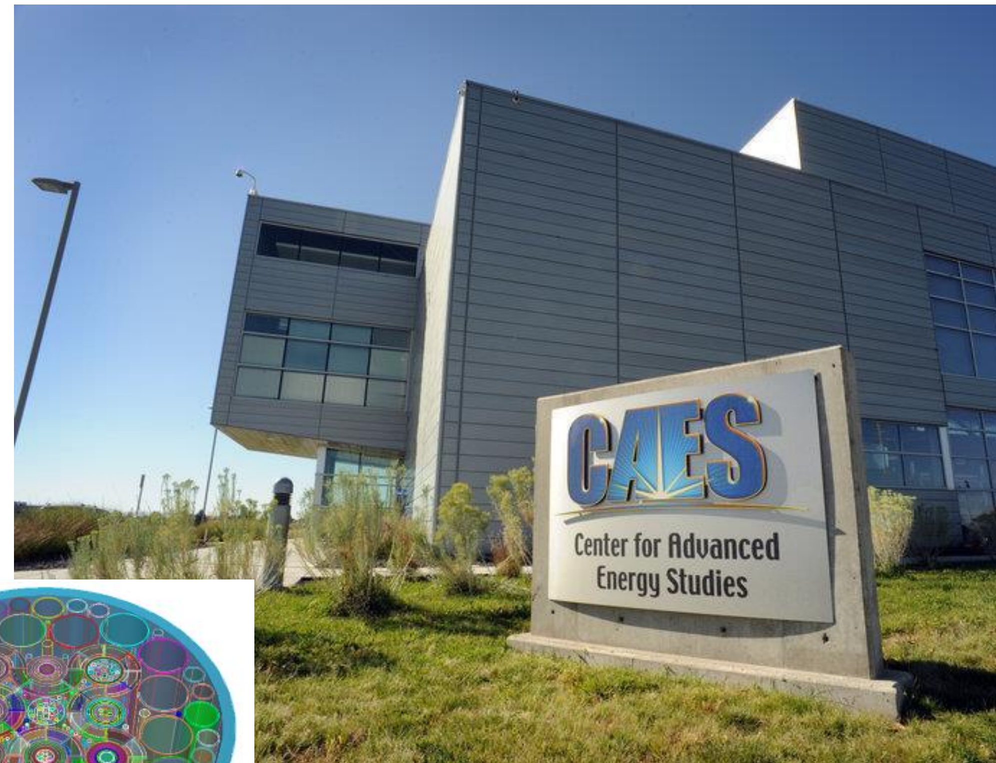

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