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Nuclear Science User Facilities

IRRADIATION TOOLS FOR NSUF MATERIALS RESEARCH

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Test, Research and Training Reactors
San Diego, CA
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NSUF Nuclear Science User Facilities

INL/CON-17-42048

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Outline

NSUF Nuclear Science User Facilities

- **FY2017 Neutron Irradiation Requests & Activities**
- **Tools**
  - Reactor Position Tool
  - DPA Calculation Tool
  - Specimen Activation Tool
- **RTR ANS Session**

What is a User Facility?

- *Regional, national or international facility with **unique** experimental capabilities.*
- *Access is typically **cost-free** through a competitive proposal process.*
- *The goal is to connect the **best ideas** with the capability regardless of geographical separation.*

Advanced Photon Source (ANL)

Spallation Neutron Source (ORNL)

There are currently 50 DOE user facilities in the U.S.

– Advanced scientific computing research
– High flux synchrotron and neutron sources
– Electron beam characterization
– Nano-scale science
– Biological and environmental research
– High energy and nuclear physics
– Fusion energy science

……***But before 2007 there were no user facilities to address the unique challenges of nuclear energy.***

Then came the Advanced Test Reactor National Scientific User Facility!

Initial Vision for the (ATR) **NSUF**

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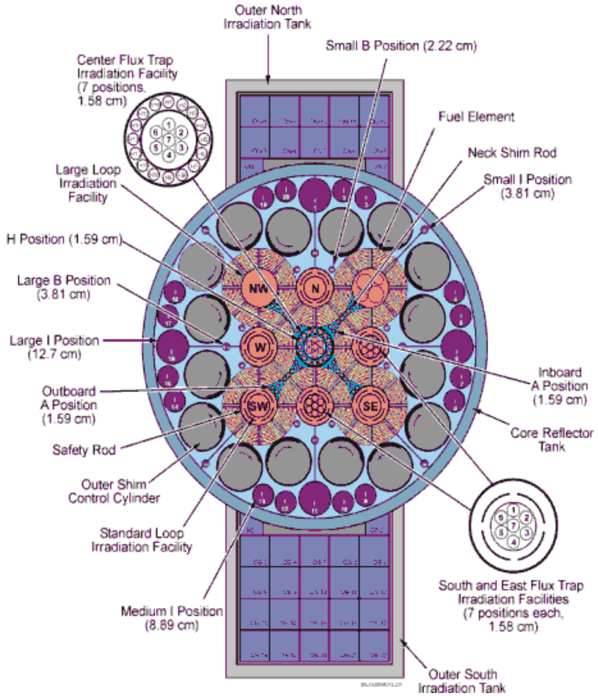
NSUF Nuclear Science User Facilities

Allow the research community access to test reactor space and existing post irradiation examination facilities

Advanced Test Reactor



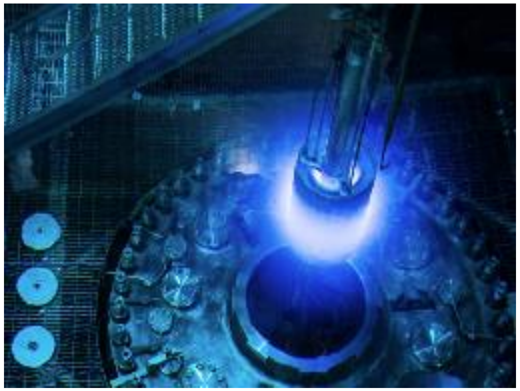
Post Irradiation Examination (PIE) Facilities at Materials & Fuels Complex (MFC @ INL)

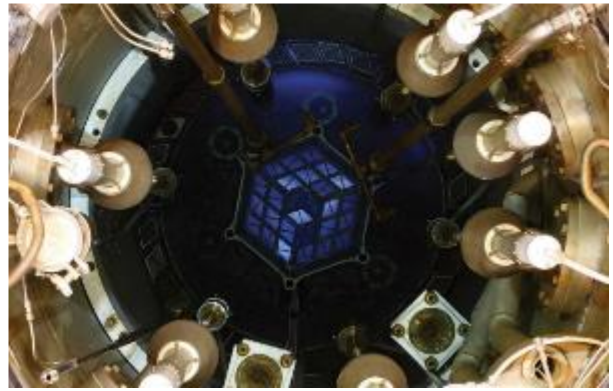
NSUF – a consortium

A group formed to undertake an enterprise beyond the resources of any one member

2007	2008	2009	2010	2011	2012	2013	2016	2017
INL Idaho National Laboratory	MIT Massachusetts Institute of Technology	CAES Center for Advanced Energy Studies	Oak Ridge National Laboratory	Cal	PNNL	Westinghouse	Argonne National Laboratory	Brookhaven National Laboratory
		125 Illinois Tech Since 1890			Purdue University			Sandia National Laboratories
		NC State University						Lawrence Livermore National Laboratory
		University of Michigan						Los Alamos National Laboratory Est. 1943
		UNLV University of Nevada Las Vegas						Ohio State
		Wisconsin University of Wisconsin-Madison						Texas A&M University
								University of Florida

NSUF Neutron Irradiation Capabilities





Accessing the NSUF

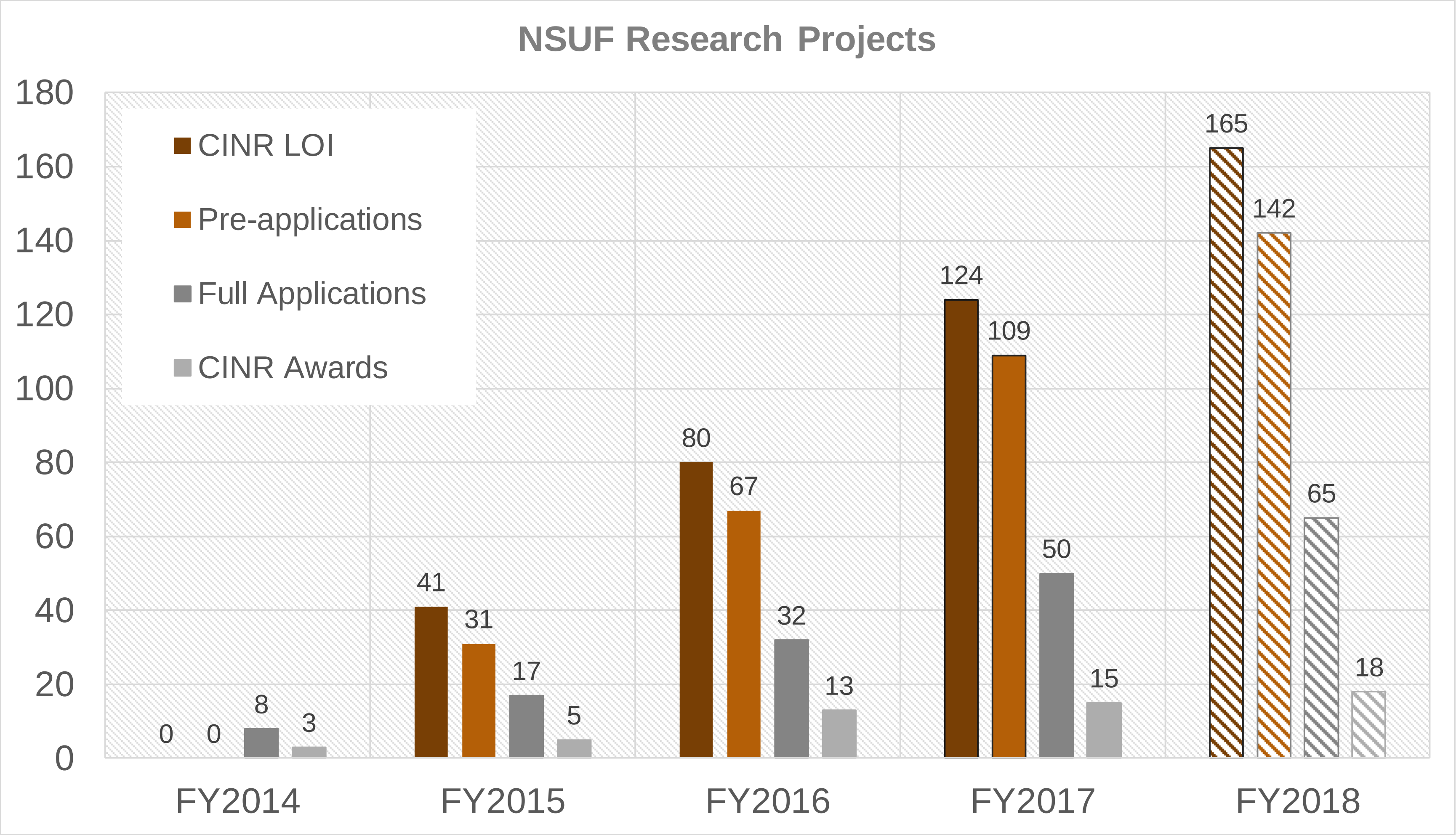
1. **Consolidated Innovative Nuclear Research FOA**
   - For full irradiation/PIE, PIE Only, or APS projects
   - Kickoff in August, awarded the following June
   - R&D support funding can be requested

2. **Rapid Turnaround Experiment calls**
   - For small examination or beam-line projects
   - Three calls per year
   - No R&D support funding
   - XPD at NSLS-II, IVEM and MRCAT at APS are available

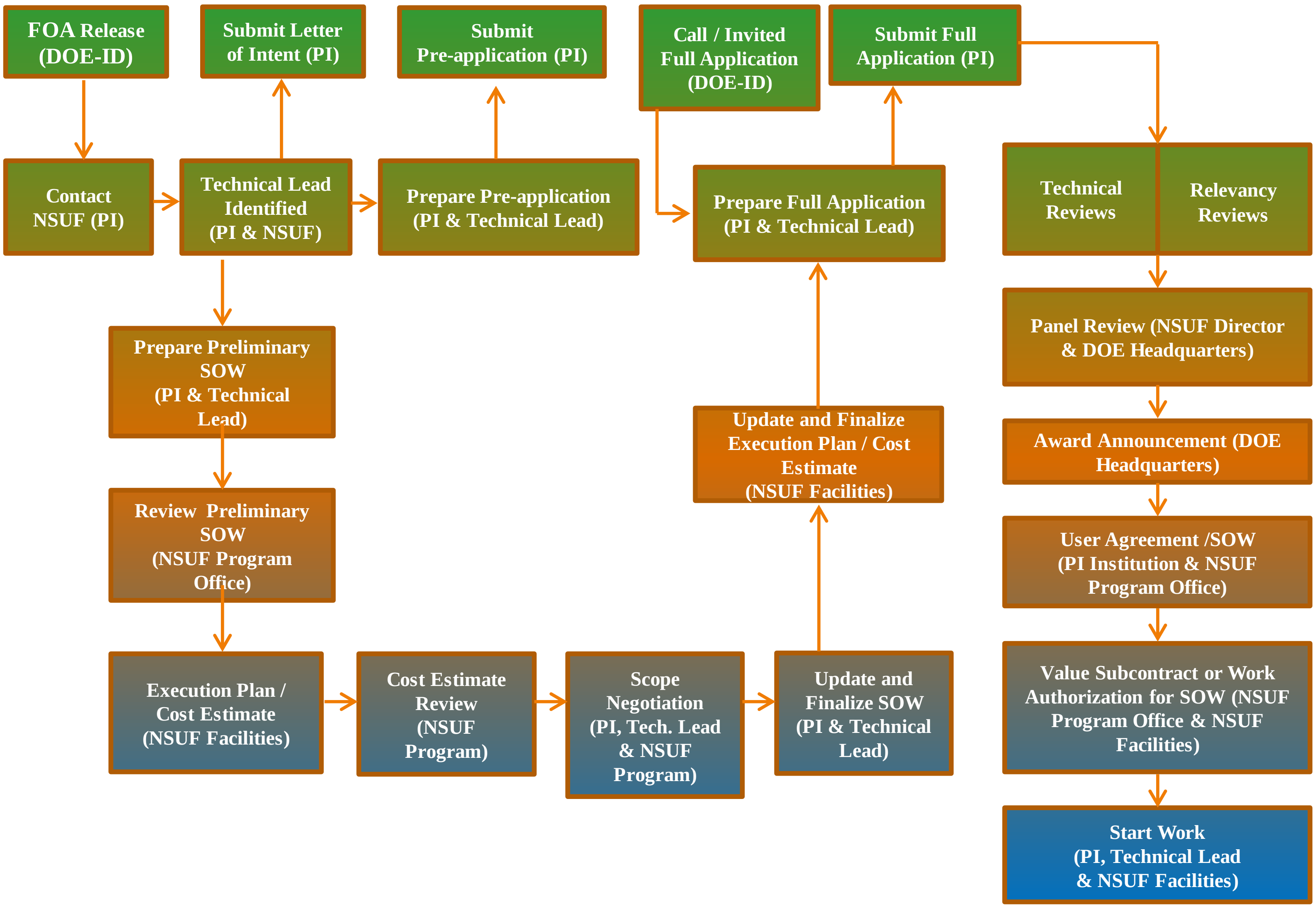
3. **CRADA and WFO (non-competitive)**
   - Cost shared non-proprietary research
   - Full cost recovery proprietary research
   - Utilized so far by industry and the Nuclear Regulatory Commission

4. **DOE-NE Infrastructure Programs**
   - Reactor Upgrades
   - General Scientific Infrastructure

Increasing Demand for NSUF resources



NSUF Access Process



NSUF Current Irradiation Projects

Institution	Reactor	Purpose
University of Central Florida	ATR	U-Zr and U-Mo (low Φ)
Boise State University (USU)		Uranium-silicide ATF
Boise State University (Purdue)		AM structural materials
General Electric-Hitachi		AM structural materials
Idaho State University		AM structural materials
Colorado School of Mines		AM structural materials
Oak Ridge National Laboratory	HFIR	TRISO Fuel
Oak Ridge National Laboratory		High heat flux SiC
Idaho National Laboratory	MITR	Sensor development

New Irradiation Projects (FY 2017 CINR)

Institution	Reactor	Purpose
EPRI	ATR & TREAT	Fuel testing
General Atomics	HFIR	SiC cladding
AREVA		ATF neutron absorbers
University of Pittsburgh	MITR	Sensor development
Boise State University	NCSU & MITR	Sensor development
University of Illinois	NCSU(β+)	Fe-Cr alloys
INL/SCK-CEN	BR-2	U-Zr and U-Mo (DISECT)
INL/SCK-CEN		Uranium-silicide ATF (ATTICUS)

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NSUF Irradiation Utilization (by CINR)

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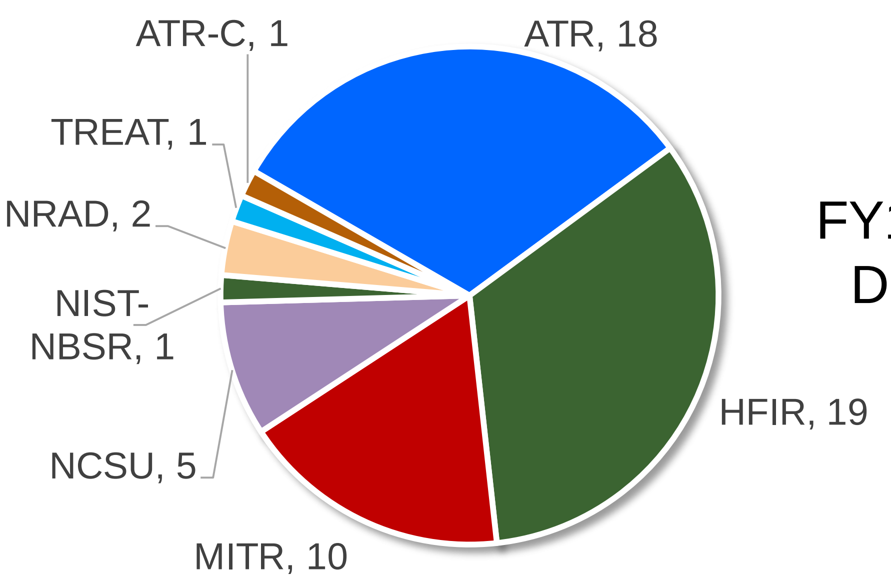
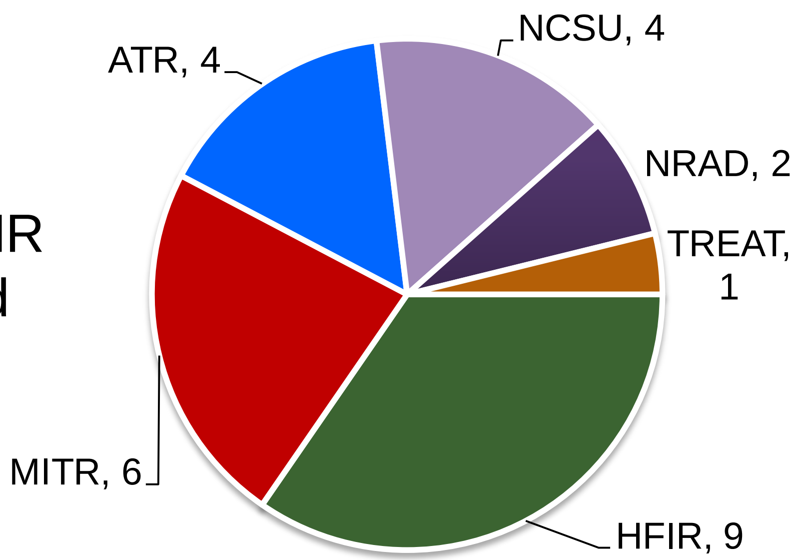
Reactor	FY15 FOA	FY16 FOA	FY17 FOA
ATR (INL)	1	3 + SAM1	1 + SAM2(?)
HFIR (ORNL)	0	2	2
MITR-II (MIT)	1	1	2
PULSTAR (NCSU)	0	1	2
BR-2 (SCK-CEN)	0	3	0



FY17 CINR Demand



Integrated Infrastructure Enhancement Project

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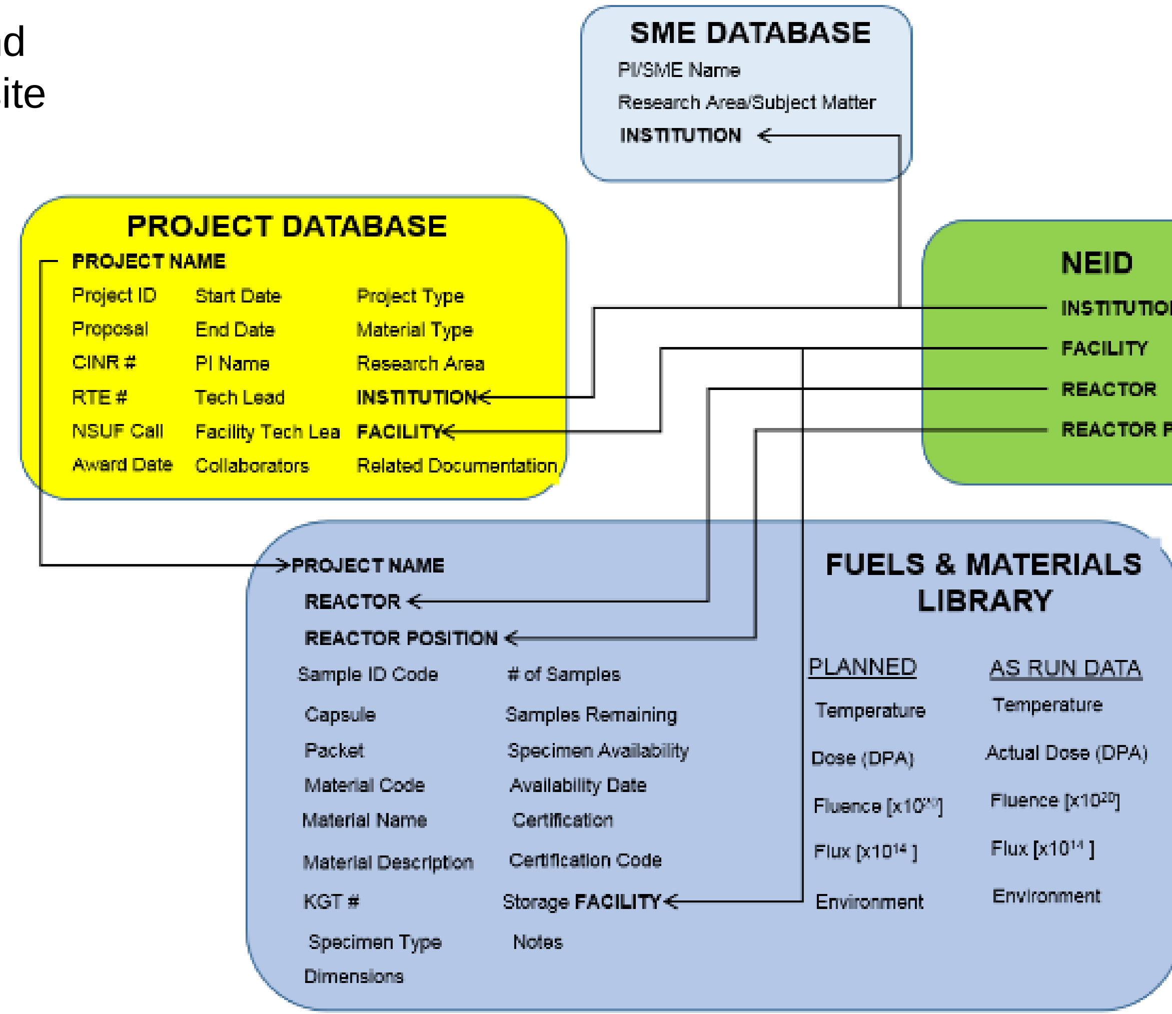
Linking of databases and tools to the NSUF website



NSUF "Storefront"

Type of experiment

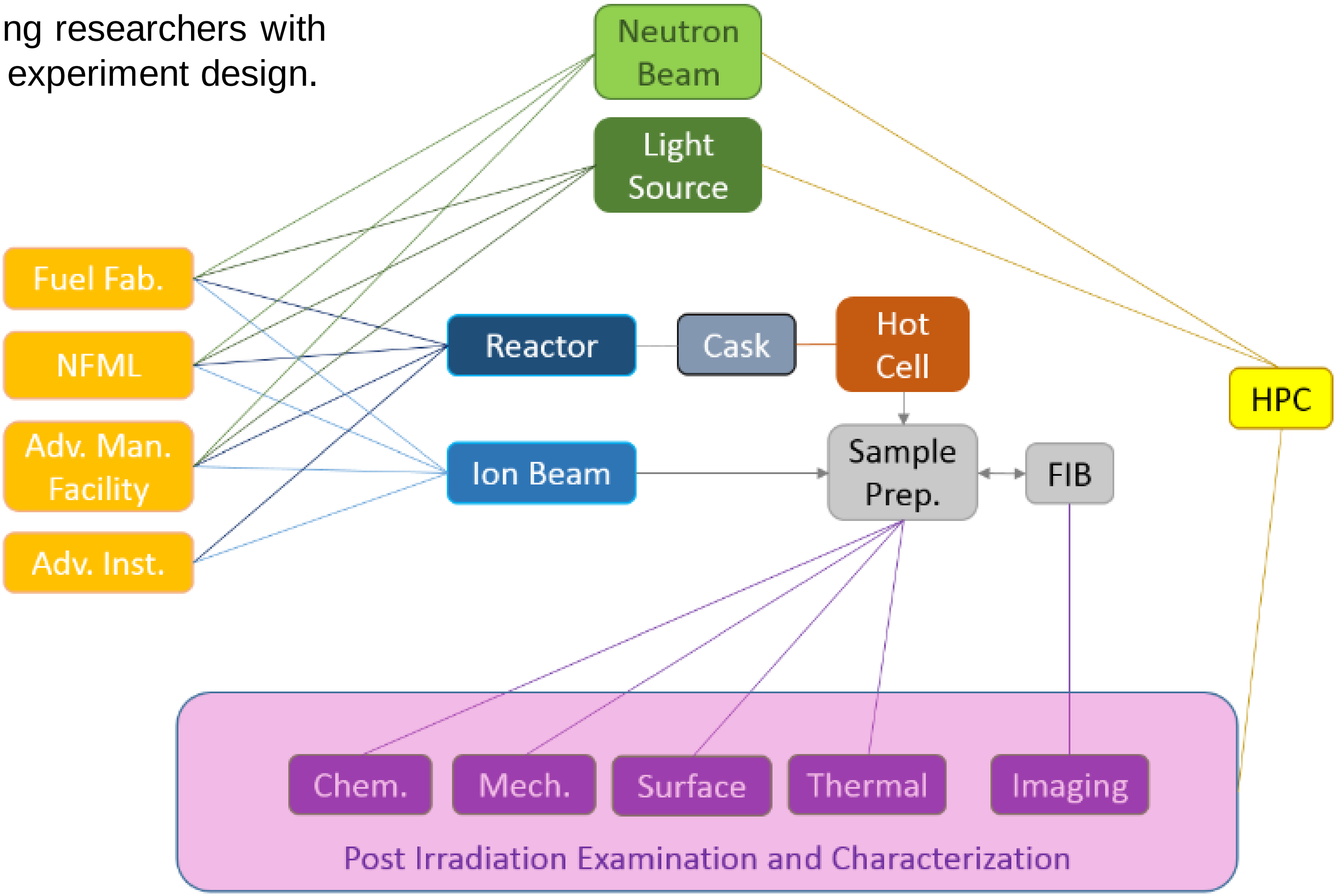
1. Neutron irradiation & PIE
2. Ion beam irradiation & PIE
3. PIE only (NFML specimens), includes neutron and x-ray beams

Based on choice, tool provides the required stages and links to the NEID entries for the available NSUF partner facilities.

1. Specimen materials and fabrication
2. Pre-irradiation characterization
3. Irradiation (neutron)
4. Capsule shipment & disassembly
5. Non-destructive PIE
6. Sample preparation
7. Destructive PIE
8. Disposal or NFML transfer

Deployment of NSUF Experiment Storefront

Assisting researchers with NSUF experiment design.



Nuclear Science User Facilities

IRRADIATION TOOLKIT

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Usability Improvements

NSUF Nuclear Science User Facilities

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

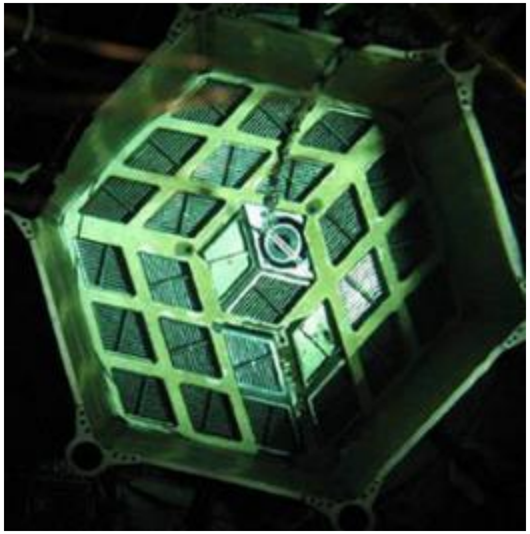
- Neutron flux and spectrum for NSUF reactors
  - Most efficient allocation of resources
- Convert Neutron Fluence to DPA
  - Materials scientists request dpa
  - Reactor engineers think in terms of fluence
  - Compound materials can be difficult

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



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**
   - 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)

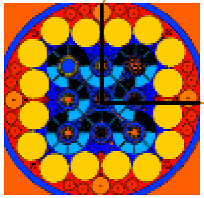
THE UNIVERSITY of WISCONSIN MADISON

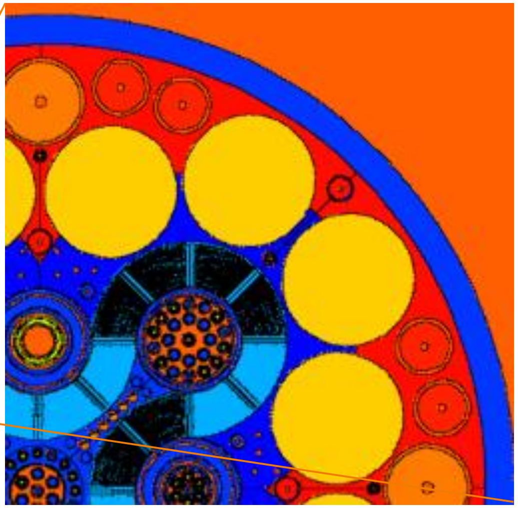
NC State University Raleigh, NC

Massachusetts Institute of Technology

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.

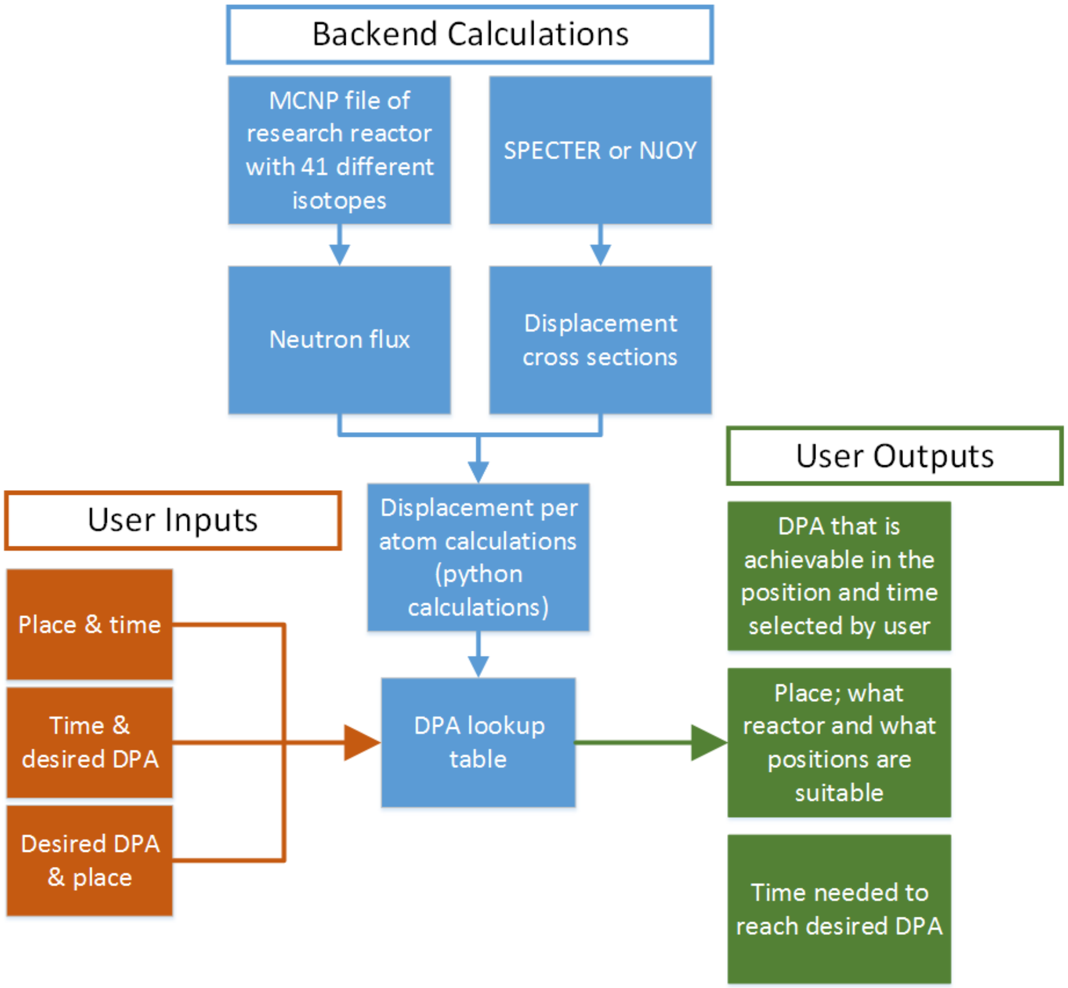




The tool has three main functions:

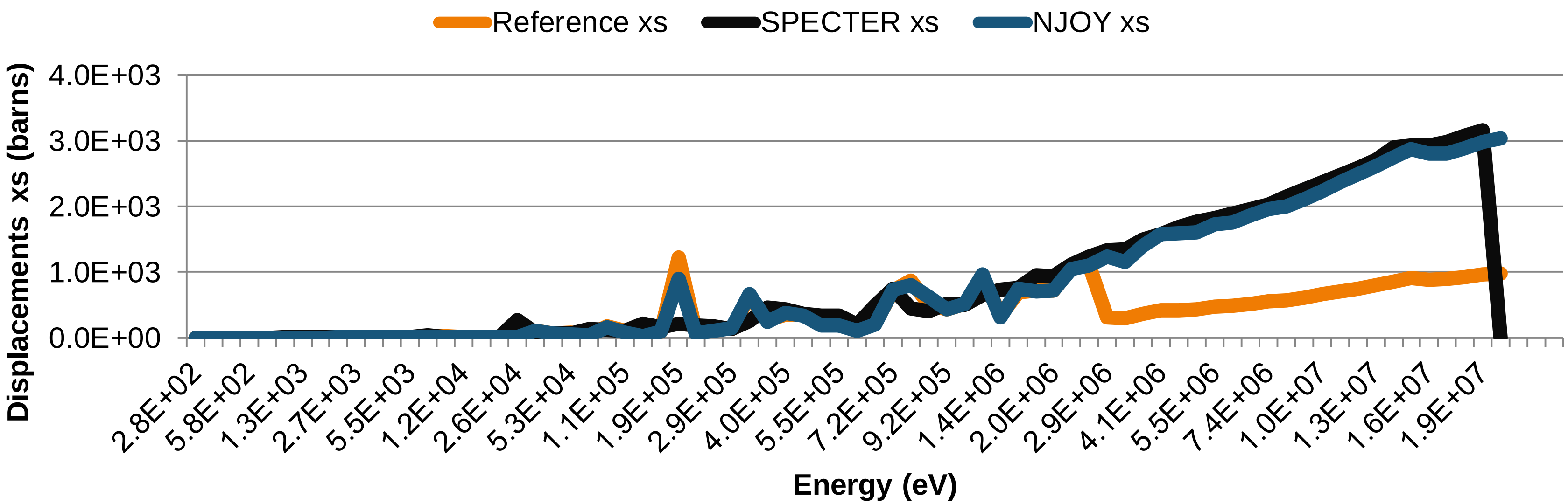
1) calculate displacements per atom (DPA) for multiple different materials,
2) calculate the time needed to reach the desired DPA, and
3) inform users what position in what reactor will give them the desired radiation damage the most effectively.

1. Process Diagram



1. DPA to Fluence calculator

- **Displacements per atom (DPA)** is used to estimate the amount of radiation damage incurred by materials**.**
- **Two existing tools are NJOY and SPECTER.**
  - NJOY uses data from the ENDF cross section library files to calculate the energy available for lattice damage (HEATR module).
  - SPECTER can calculate the neutron spectrum averaged DPA, but also provides the displacement cross sections of 41 isotopes.



1. DPA Calculator

- Calculation of DPA uses the **Norgett-Robinson-Torrens (NRT)** method.
- NJOY outputs the available energy (E_a) and the displacement threshold energy (E_d) is taken from tables provided in the SPECTER manual.
- To find the DPA, the displacement cross sections are then multiplied by the neutron flux and integrated over the energy spectrum.

$$\sigma_{disp} = \frac{0.8}{2E_d} * E_a$$

$$DPA = \int_{E_{min}}^{E_{max}} \sigma_{disp}(E) \frac{d\phi(E)}{dE} dE$$

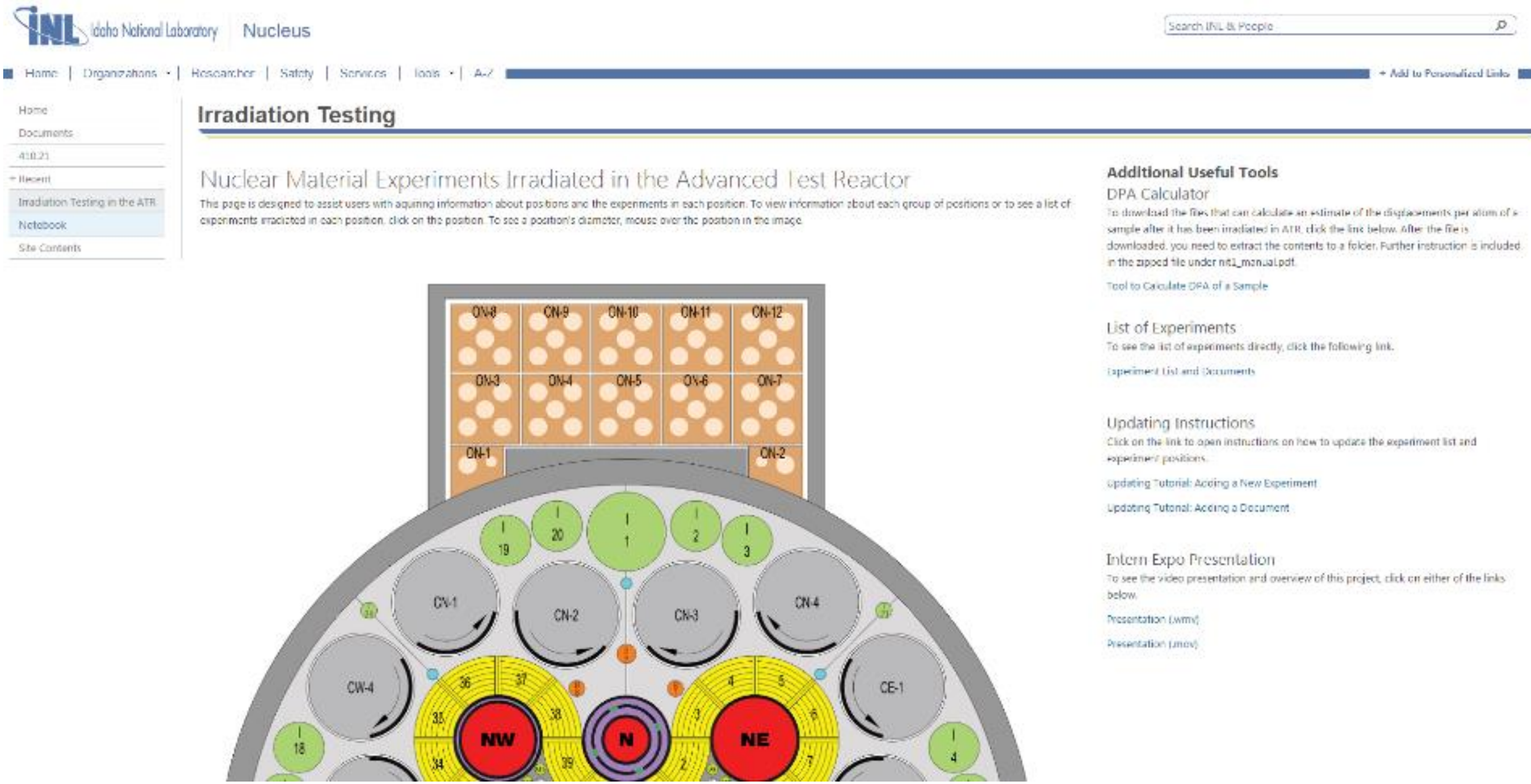
1. DPA Calculator

- The completed work for this project includes:
  - automating the MCNP models for 41 isotopes,
  - calculating the flux for each material, and collecting NJOY data for iron.

- Future work includes:
  1. Collecting NJOY data for all 41 isotopes to calculate the DPA
  2. DPA calculations will be completed once the displacement cross section data is compiled.
  3. Once the DPA is known the information can be placed on the NSUF website for users.
  4. Extending the tool to the entire fleet of NSUF partner reactors.

2. ATR Irradiation Testing Tool

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



2. Experiments in ATR Positions

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Large I Positions

Click on each experiment to view the associated documents.

Experiment Positions

✓	Cycle		I-1	I-6	I-11	I-16
	160A-1	...				
	159A-1	...				
	158B-1	...				
	158A-1	...				
	157D-1	...				
	157C-1	...				
	157A-1	...				
	156A-1	...				
	155B	...				
	155A	...				
	154B	...				
	154A	...				
	153B	...				
	153A	...				
	152B	...				
	152A	...				
	151B-2	...				
	151B-1	...				
	151A	...				
	150B	...				
	150A	...				
	149B	...				

General Information

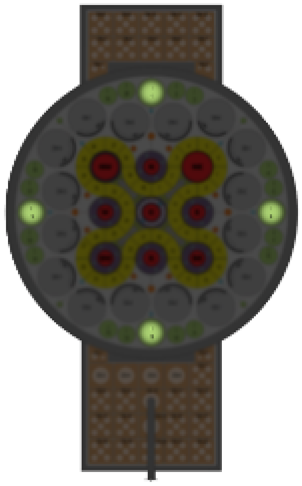
Information for total power average of 110 MW_{th}, 22 MW_{th} in each lobe

Location	Diameter (inches)	Thermal Flux (n/cm^2-s)	Fast Flux (n/cm^2-s)
North Flux Trap	3.250	4.4E+14	9.7E+13
West Flux Trap	3.250	4.4E+14	9.7E+13
East Flux Trap	3.250	4.4E+14	9.7E+13
South Flux Trap	3.250	4.4E+14	9.7E+13
Center Flux Trap	3.160	4.4E+14	9.7E+13
Northwest Flux Trap	5.375	4.4E+14	2.2E+14
Northeast Flux Trap	5.375	4.4E+14	2.2E+14
Southwest Flux Trap	3.250	4.4E+14	9.7E+13
Southeast Flux Trap	3.250	4.4E+14	9.7E+13
Small B-Position	0.875	2.5E+14	8.1E+13
Large B-Position	1.500	1.1E+14	1.6E+13
Inner-A Position	0.625	1.9E+14	1.7E+14
Outer-A Position	0.500/0.625	2.0E+14	2.3E+14
H-Hole	0.625	1.9E+14	1.7E+14
Small I-Position	1.500	8.4E+13	3.2E+12
Medium I-Position	3.250	3.4E+13	1.3E+12
Large I-Position	**5.000**	**1.7E+13**	**1.3E+12**

Position Elevation Drawing

Back to Experiment Positions in the Advanced Test Reactor

Click on the image to return to the previous page.



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2. ATR Experiment Documentation

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Irradiation Testing

Experiment Documents

All Items 2A-C-BU AECL ••• Find an item

✓ Experiment Name	Experiment Document	Document Type

Experiment Name : 2A-C-BU (12)
- Document Type : DP (1)
- Document Type : Drawing (6)
- Document Type : ECAR (3)
- Document Type : ESAP (1)
- Document Type : TEV (1)

Experiment Name : AECL (7)
- Document Type : Drawing (4)
- Document Type : ECAR (2)
- Document Type : TEV (1)

- Experiment Name : **2A-C-BU** (12)
- Experiment Name : **AECL** (7)
- Experiment Name : **AFC-1D** (19)
- Experiment Name : **AFC-1G** (26)
- Experiment Name : **AFC-1H** (28)
- Experiment Name : **AFC-2A** (18)
- Experiment Name : **AFC-2B** (19)
- Experiment Name : **AFC-2C** (16)
- Experiment Name : **AFC-2D** (16)
- Experiment Name : **AFC-2E** (12)
- Experiment Name : **AFC-3A** (18)
- Experiment Name : **AFC-3B** (18)
- Experiment Name : **AFC-3C** (16)
- Experiment Name : **AFC-3D** (18)
- Experiment Name : **AFC-3F** (19)
- Experiment Name : **AFC-4A** (13)
- Experiment Name : **AFC-4B** (36)
- Experiment Name : **AFC-4C** (12)
- Experiment Name : **AFIP-1** (8)
- Experiment Name : **AFIP-2** (12)
- Experiment Name : **AFIP-3** (9)
- Experiment Name : **AFIP-4** (12)
- Experiment Name : **AFIP-6** (25)

- Experiment Name : **AFIP-7** (23)
- Experiment Name : **AGC-1** (27)
- Experiment Name : **AGC-2** (17)
- Experiment Name : **AGC-3** (14)
- Experiment Name : **AGC-4** (10)
- Experiment Name : **AGR-1** (42)
- Experiment Name : **AGR-2** (25)
- Experiment Name : **AGR-3/4** (30)
- Experiment Name : **ATF 1** (31)
- Experiment Name : **ATF-2** (1)
- Experiment Name : **DREXEL** (29)
- Experiment Name : **EPRI-1** (16)
- Experiment Name : **EPRI-2** (15)
- Experiment Name : **EPRI-3** (15)
- Experiment Name : **EPRI-ZG** (17)
- Experiment Name : **GD** (7)
- Experiment Name : **GFR-F1-2** (11)
- Experiment Name : **GTL** (17)
- Experiment Name : **HAFNIUM** (7)
- Experiment Name : **ISORAY** (8)
- Experiment Name : **JNC** (8)
- Experiment Name : **KJRR** (13)
- Experiment Name : **LACE** (3)
- Experiment Name : **LSA COBALT** (8)
- Experiment Name : **LUNA** (11)
- Experiment Name : **MANTRA-1** (11)

- Experiment Name : **MANTRA-2** (11)
- Experiment Name : **MANTRA-3** (10)
- Experiment Name : **NCSU** (16)
- Experiment Name : **NEW HSA COBALT**
- Experiment Name : **OLD HSA COBALT I**
- Experiment Name : **OLD HSA COBALT I**
- Experiment Name : **RERTR-10** (21)
- Experiment Name : **RERTR-12** (26)
- Experiment Name : **RERTR-13** (21)
- Experiment Name : **RERTR-6** (19)
- Experiment Name : **RERTR-7** (25)
- Experiment Name : **RERTR-8** (22)
- Experiment Name : **RERTR-9** (24)
- Experiment Name : **SAM-1** (8)
- Experiment Name : **TMIST-1** (16)
- Experiment Name : **TMIST-2** (20)
- Experiment Name : **TMIST-3** (26)
- Experiment Name : **UCF-1** (15)
- Experiment Name : **UCF-3** (1)
- Experiment Name : **UCSB-1** (11)
- Experiment Name : **UCSB-2** (17)
- Experiment Name : **UF** (12)
- Experiment Name : **UI** (18)
- Experiment Name : **USU** (10)
- Experiment Name : **UW** (14)

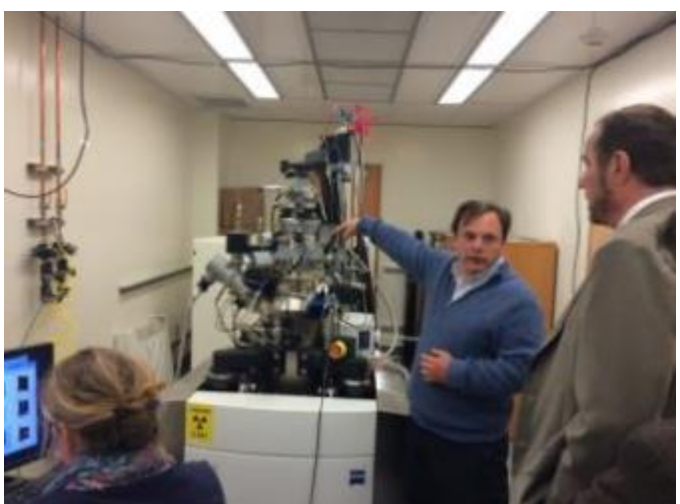
3. Sample Activation Tool

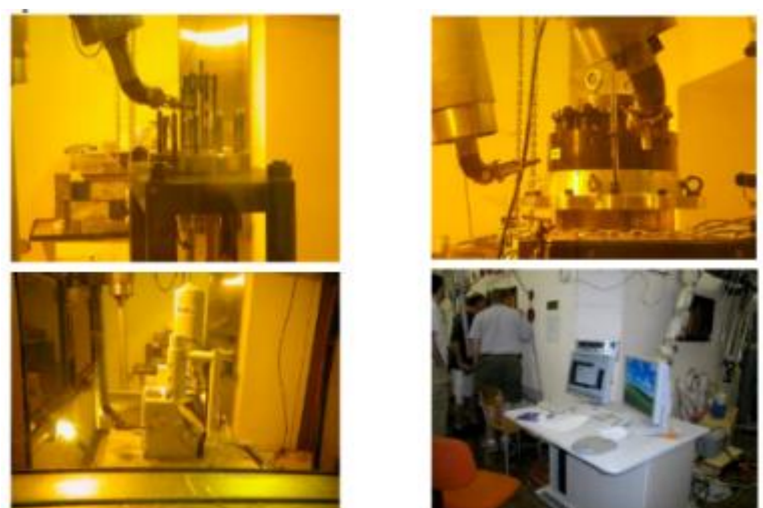
Estimating the radioactivity of a sample before it is ever irradiated will:

(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.





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3. Small Specimen Tensile Testing Challenge

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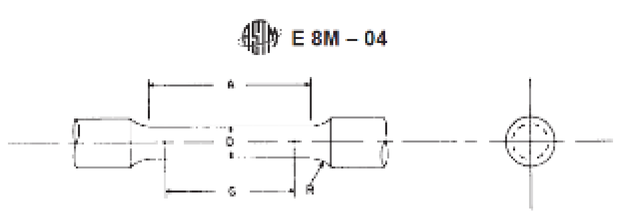
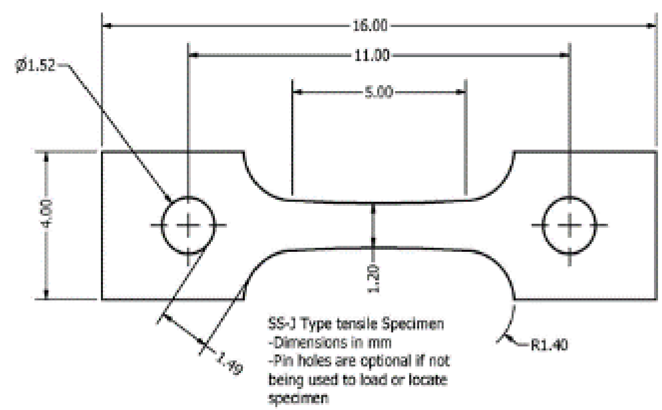
- Tensile testing has long been an important method for determining the material properties of different structural steel components.
- The effect of irradiation on these steel components is of particular interest to the nuclear power industry.
- The large (E8) specimens typically used are not efficient 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	



	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



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3. Sample Activation Tool

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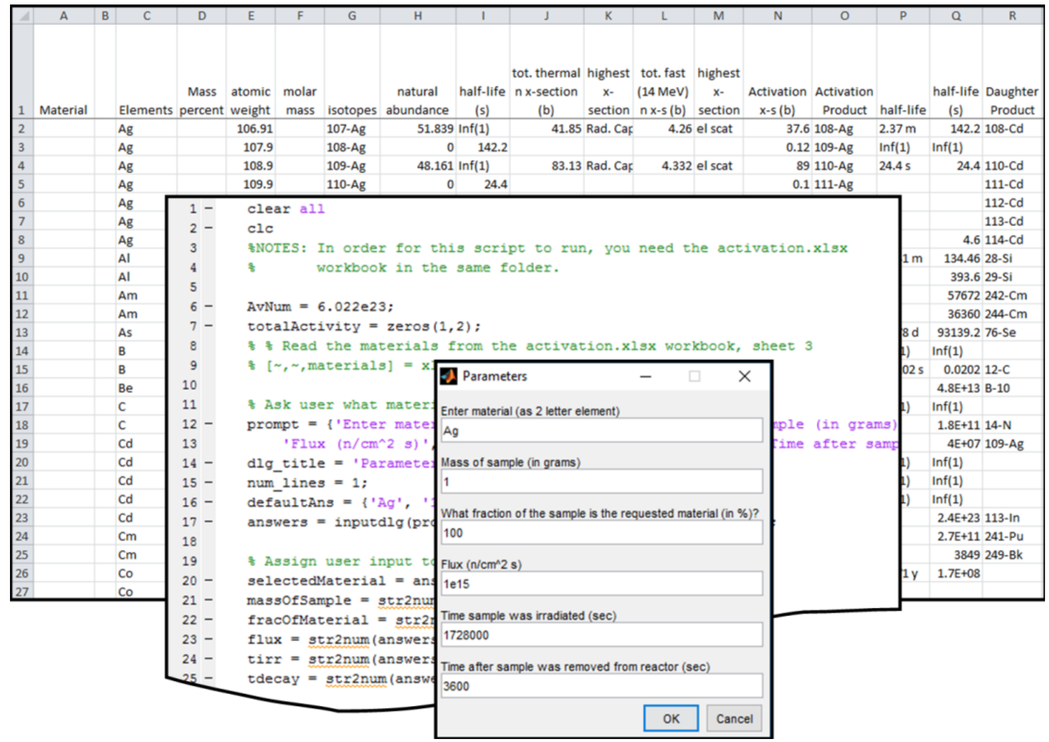
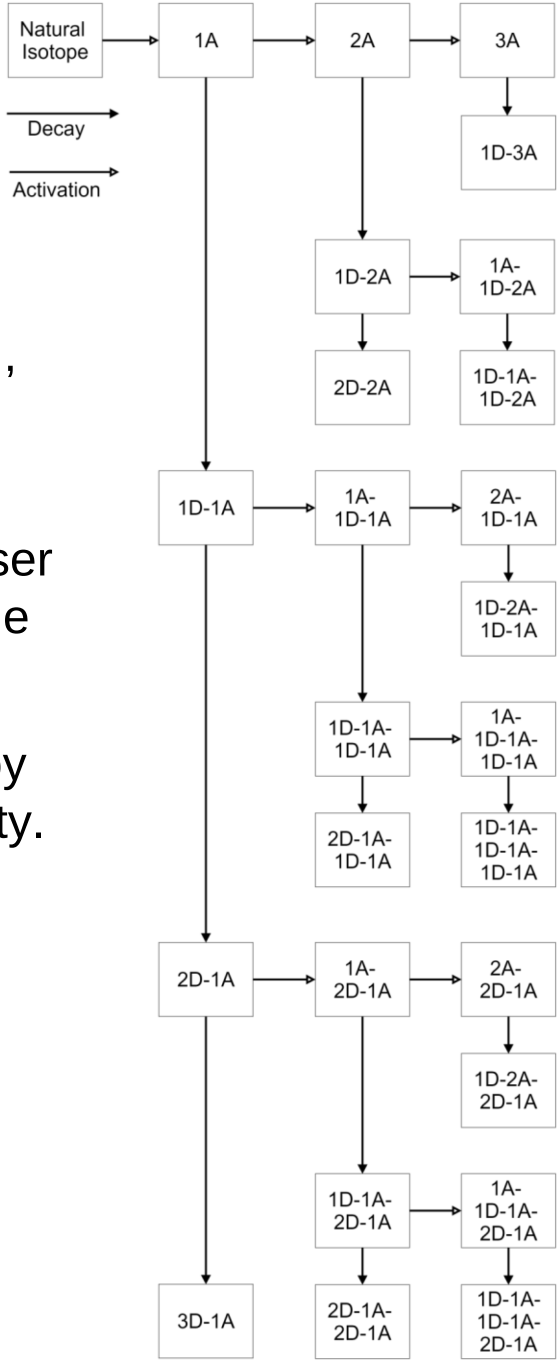
Several online radioactivity calculators exist, but they only consider the radioactivity from the first activation stage.

Due to the high flux and long run times of most ATR experiments, these calculators are insufficient.



While INL experimental analysts use the ORIGEN code to estimate activities, the radioactivity calculator designed for this project is intended to be an easily accessible tool for NSUF users during the <u>conceptual design phase</u> of their experiments.

3. Method of Solution



For each naturally occurring isotope in the sample material, the radioactivity calculator will determine up to 25 isotopes resulting from three stages of activation and decays.

The radioactivity (A) for each isotope is calculated using user specified neutron flux and irradiation time and by solving the differential equation for the number density (N).

The solution of this differential equation is then multiplied by the appropriate decay constant (λ) to obtain the radioactivity.

$$\frac{dN_2}{dt} = N_1\sigma_1\varphi - \lambda_2 N_2 - N_2\sigma_2\varphi$$

$$N_2 = \frac{N_1\sigma_1\varphi}{\lambda_2 + \sigma_2\varphi}\left[1 - e^{-(\lambda_2+\sigma_2\varphi)t}\right]$$

$$A_2 = \lambda_2 N_2$$

3. ^{60}Co Example

Five activation-decay chains are shown here, each begin with a naturally occurring isotope which can be found within typical stainless steel.

$$^{59}Co \overset{\sigma}{\Rightarrow} {}^{60}Co$$

$$^{58}Ni \overset{\sigma}{\Rightarrow} {}^{59}Ni \overset{\lambda}{\Rightarrow} {}^{59}Co \overset{\sigma}{\Rightarrow} {}^{60}Co$$

$$^{58}Fe \overset{\sigma}{\Rightarrow} {}^{59}Fe \overset{\lambda}{\Rightarrow} {}^{59}Co \overset{\sigma}{\Rightarrow} {}^{60}Co$$

$$^{58}Fe \overset{\sigma}{\Rightarrow} {}^{59}Fe \overset{\sigma}{\Rightarrow} {}^{60}Fe \overset{\lambda}{\Rightarrow} {}^{60}Co$$

$$^{57}Fe \overset{\sigma}{\Rightarrow} {}^{58}Fe \overset{\sigma}{\Rightarrow} {}^{59}Fe \overset{\sigma}{\Rightarrow} {}^{60}Fe \overset{\lambda}{\Rightarrow} {}^{60}Co$$

If only the first activation stage is considered, only one of the five activation-decay chains results in cobalt-60.

If multiple activations (σ) and decays (λ) are considered, all five result in cobalt-60.

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NSUF Fuels and Materials Library

Nuclear Science User Facilities

Provides irradiated samples for users to access and conduct research through a competitively reviewed proposal process.

The library includes over 3500 specimens as part of the NSUF awarded research.

<u>Materials Include:</u>

- **Steels**
- **Other alloys**
- **Ceramics**
- **Pure materials**
- **Actinides**
- **Fission products**

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.

Special Session at June 2018 ANS Meeting

"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 of URR 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.**

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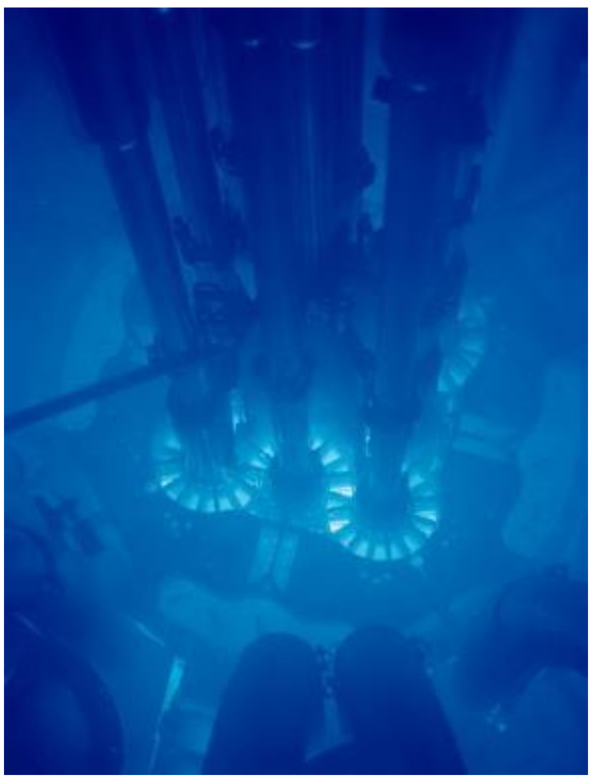

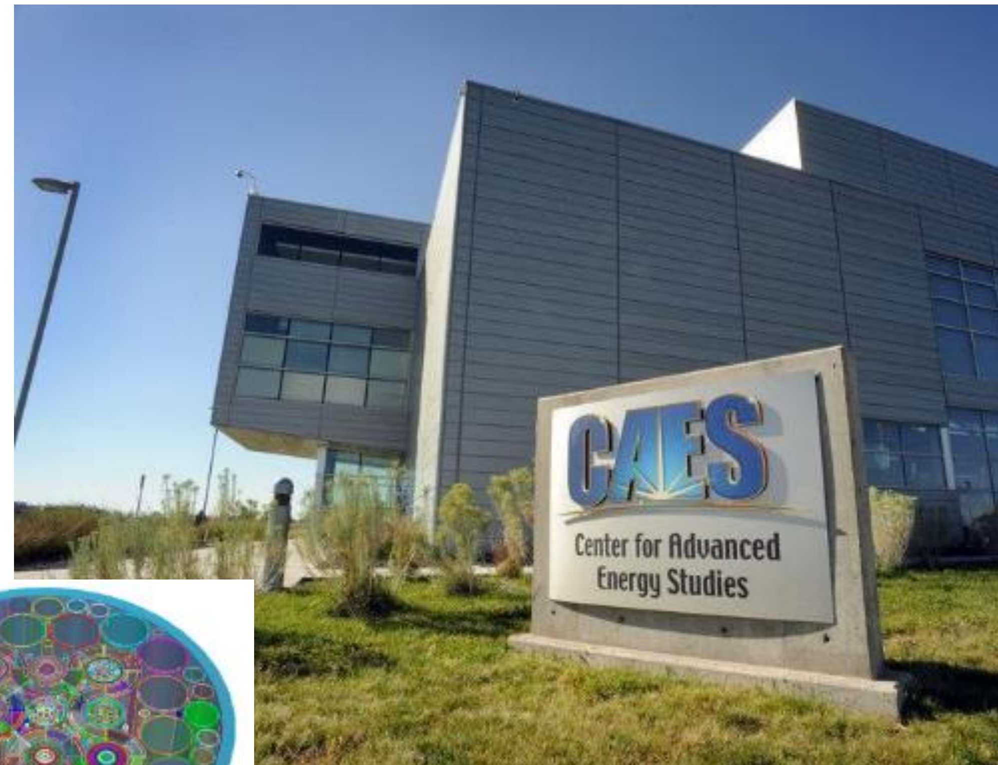

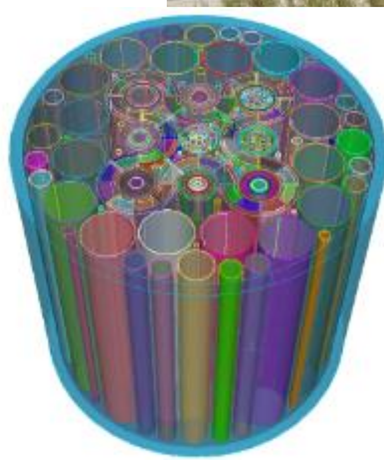

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