U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Nuclear Science User Facilities

UTILIZATION OF UNIVERSITY RESEARCH REACTORS TO SUPPORT IRRADIATION TESTING

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Albuquerque, NM
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NSUF Nuclear Science User Facilities

INL/CON-16-38605

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 48 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!***

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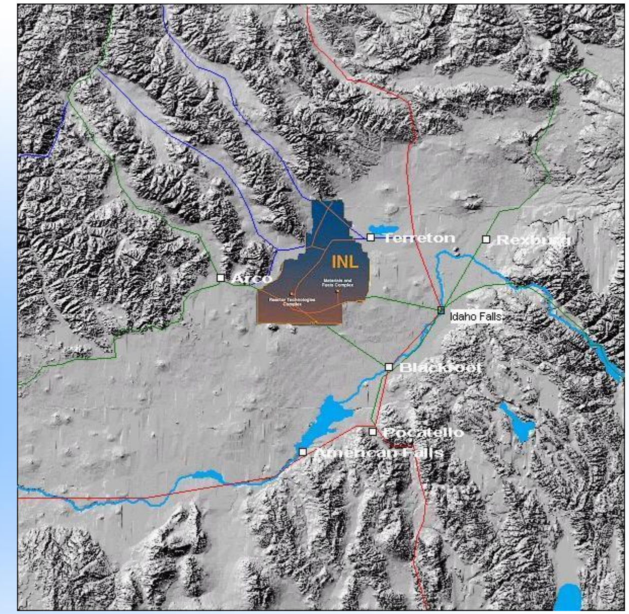
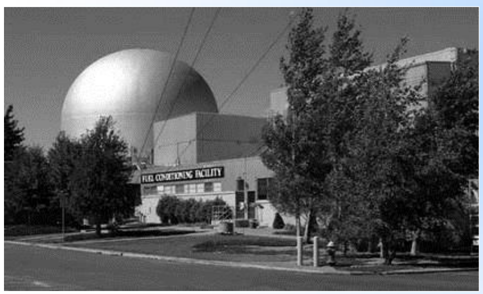
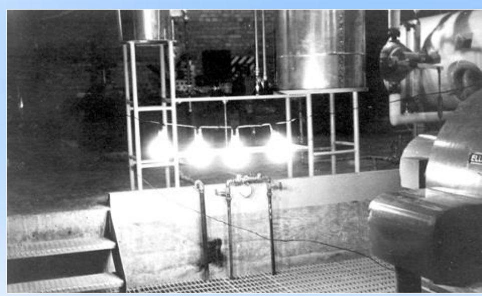
Idaho National Laboratory - History

Nuclear Science User Facilities

- Largest U.S. DOE National Laboratory over 890 square miles
- Designed and constructed 52 reactors
- Established in 1949 as the National Reactor Testing Station
- Currently managed and operated by Battelle Energy Alliance (BEA)

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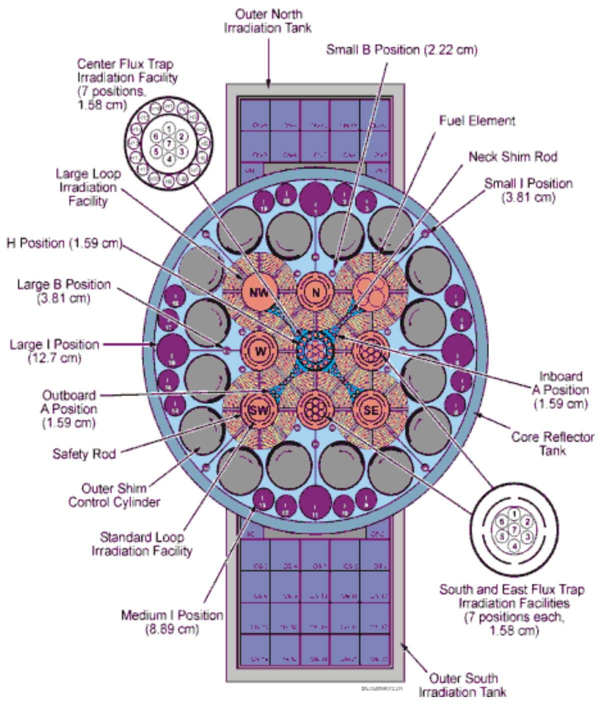
Initial Vision for the (ATR) **NSUF**

NSUF Nuclear Science User Facilities

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

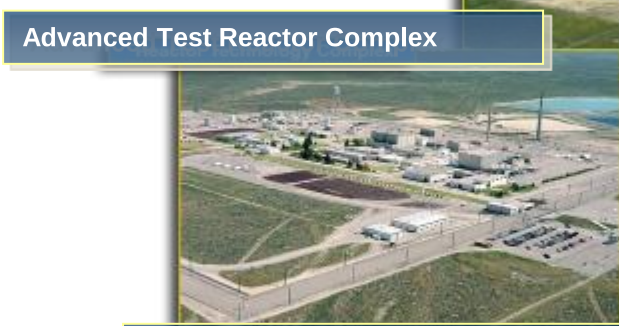
Advanced Test Reactor



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

INL's Main Campuses

891 sq. mi. complex



INL is the DOE Office of Nuclear Energy Lead Laboratory

NSUF – A consortium

- University of Michigan
- Idaho National Laboratory
- Massachusetts Institute of Technology
- Berkeley UNIVERSITY OF CALIFORNIA
- ILLINOIS INSTITUTE OF TECHNOLOGY
- THE UNIVERSITY of WISCONSIN MADISON
- CAES Center for Advanced Energy Studies
- OAK RIDGE National Laboratory
- NC State University Raleigh, NC
- UNLV UNIVERSITY OF NEVADA LAS VEGAS
- Westinghouse Westinghouse Electric Company LLC
- Pacific Northwest NATIONAL LABORATORY
- PURDUE UNIVERSITY
- Argonne NATIONAL LABORATORY
- BROOKHAVEN NATIONAL LABORATORY

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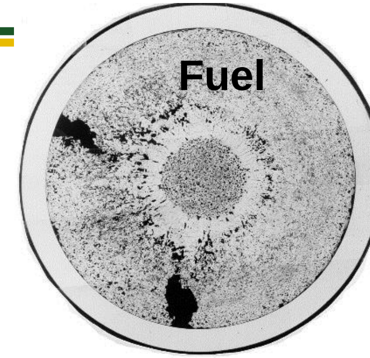
What does NSUF study?

Nuclear Science User Facilities

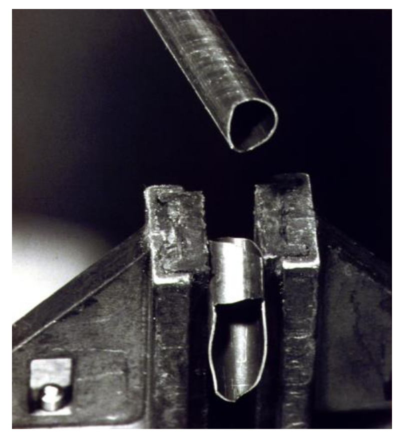
In-Reactor Degradation Behavior of Nuclear Fuels and Materials

- **Maintaining fleet of current reactors**
  - LWRS & ATF programs
- **Developing the next generation of safer more efficient reactor systems**
  - Materials resistant to high levels of radiation damage
  - RERTR/HPRR
  - AGCR program (TRISO)
- **Advanced In-Pile Instrumentation**
  - Adv. manufacturing technologies
  - Materials genomics program
  - Real-time data & transient testing

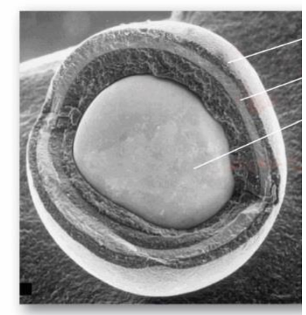
Restructuring in U-Pu-Zr Metallic Fuel



Radiation Damage Effects in Cladding and Structural Materials

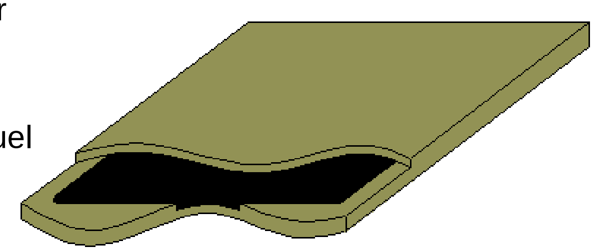


Austenitic Stainless Steel Following Irradiation in EBR II Fast Reactor



Gas Reactor Coated-Particle Fuel

U-Mo Plate Fuel



Courtesy of J. Cole

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What do the universities use? and where?

NSUF Nuclear Science User Facilities

Infrastructural Functional Areas	Internal Capabilities	External Capabilities	Desired Capabilities
Reactor & Neutron Sources	28%	40%	22%
Ion/Photon Beam Facility	21%	35%	19%
Materials Examination	17%	24%	15%
Thermal-Hydraulic	14%		7%
Radio-chemistry Laboratory	10%	2%	11%
Advanced Manufacturing	7%		4%
Advanced Instrumentation	3%		11%
Shipping Cask (UNF)			4%
Fuel Development			4%
NPP I&C			4%

Results from FY2015 RFI DE-SOL-0008318

Accessing the NSUF

- **Consolidated Innovative Nuclear Research FOA** (August 2016)
  - For full irradiation/PIE, PIE Only, or APS projects
  - Kickoff in August, Award the following June
  - R&D support funding can be requested
- **Rapid Turnaround Experiment / Beamline call**
  - For small examination or beamline projects
  - Three calls per year
  - No R&D support funding
  - XPD at NSLS-II, IVEM and MRCAT at APS are available
- **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

NSUF Awards and Publications

- **Historical data through FY 2015**
  - 134 Awarded Projects (274 proposals)
  - 26 Full irradiation / PIE
  - 11 Synchrotron irradiation
  - 97 Rapid Turnaround Experiments

- **FY 2016 Applications / Awards**
  - 63 CINR Pre-applications, 32 Full Applications
  - 30/39 Rapid Turnaround Experiment Awards/Proposals
  - 37 RTE Proposals in third call
- **Cooperative Projects**
  - Two CRADAs with EPRI, One CRADA with CNL
  - One WFO with NRC, One WFO with EPRI
- **Publications**
  - 255 Reported journal publications and conference proceedings through CY 2015

NSUF Neutron Irradiation

HIGH-FLUX REACTORS

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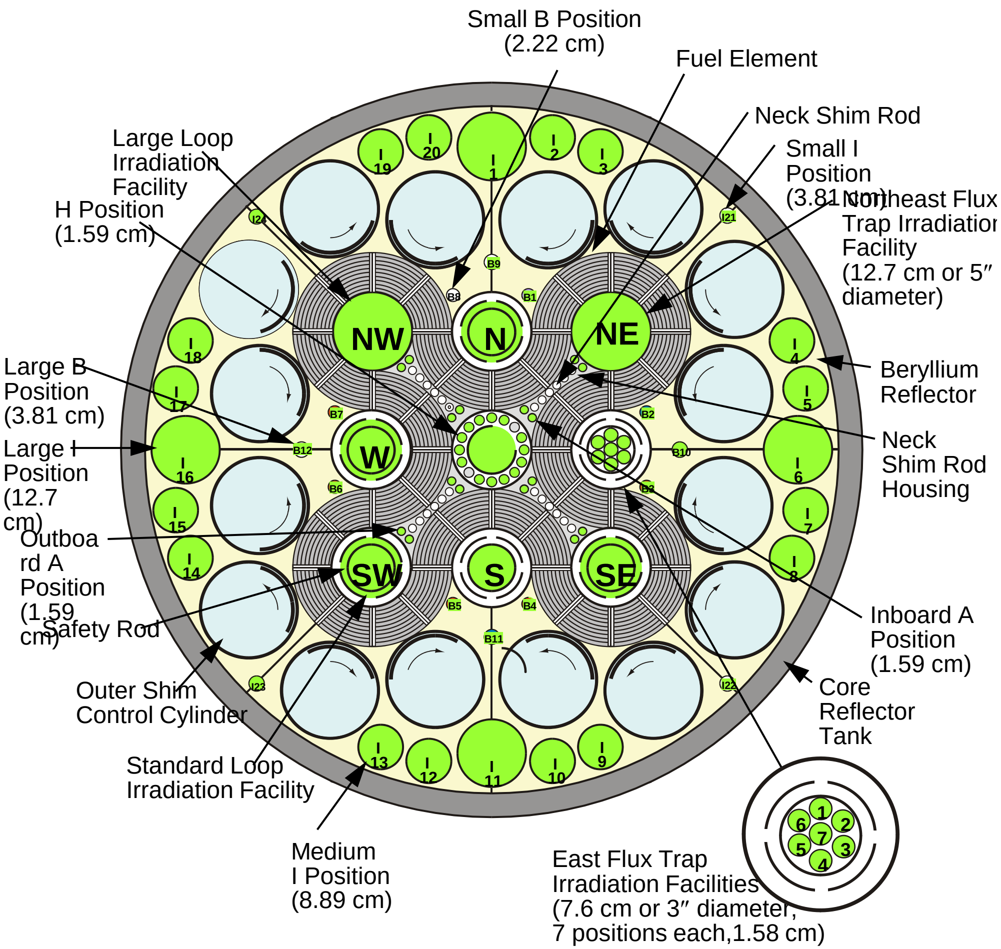
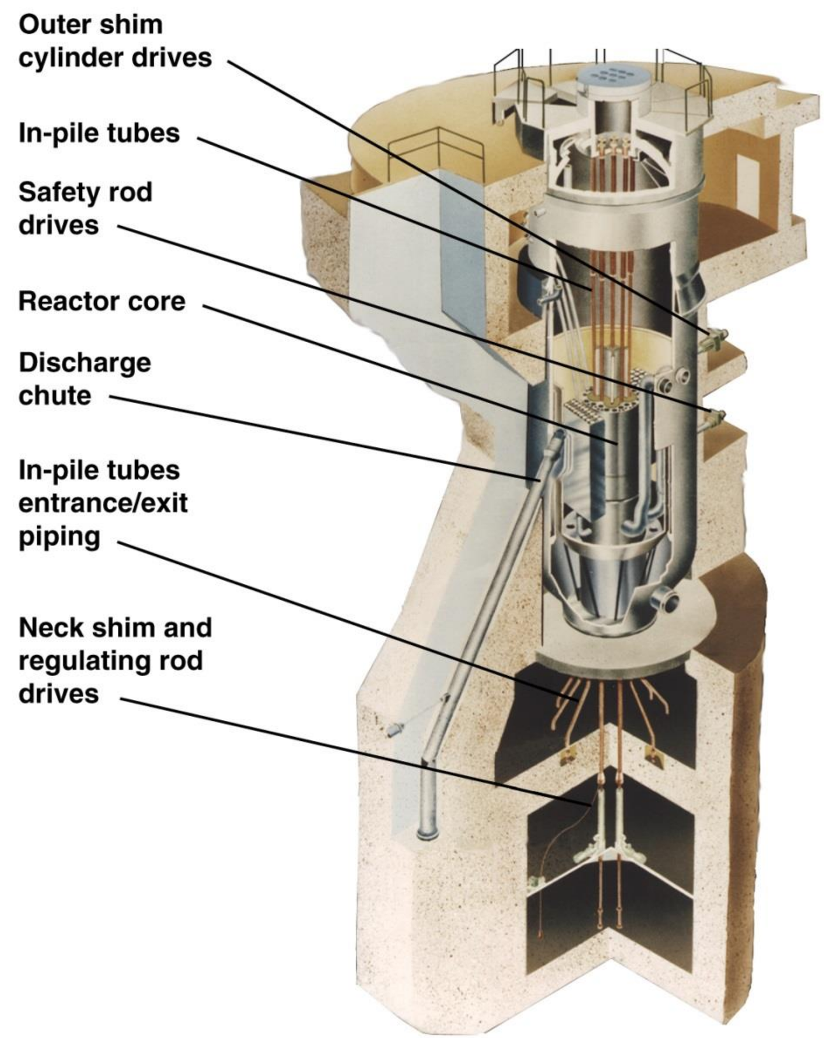
Advanced Test Reactor

Nuclear Science User Facilities





Test Reactor (ATR) Irradiation Types

Simple Static Capsules

- Reflector positions or flux traps
- Structural materials, isotopes, fuel specimens

Instrumented Lead Experiments

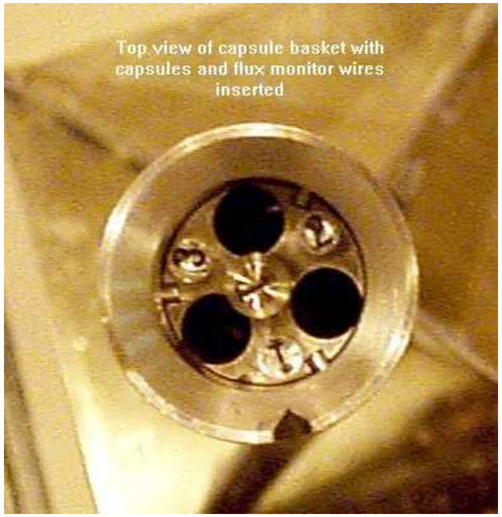
- On-line experiment measurements
- With or without temperature control
- Structural materials, cladding tubes, fuel pins

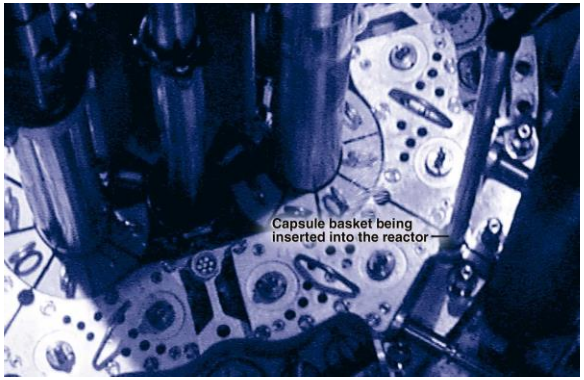
Pressurized Water Loops

- Five presently installed in flux traps
- Control pressure, temperature & chemistry
- Structural materials, cladding tubes, fuel assemblies

Hydraulic Shuttle Irradiation System

- ≤14 capsules in a set
- Inserted and removed during reactor operations





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High Flux Isotope Reactor (HFIR)

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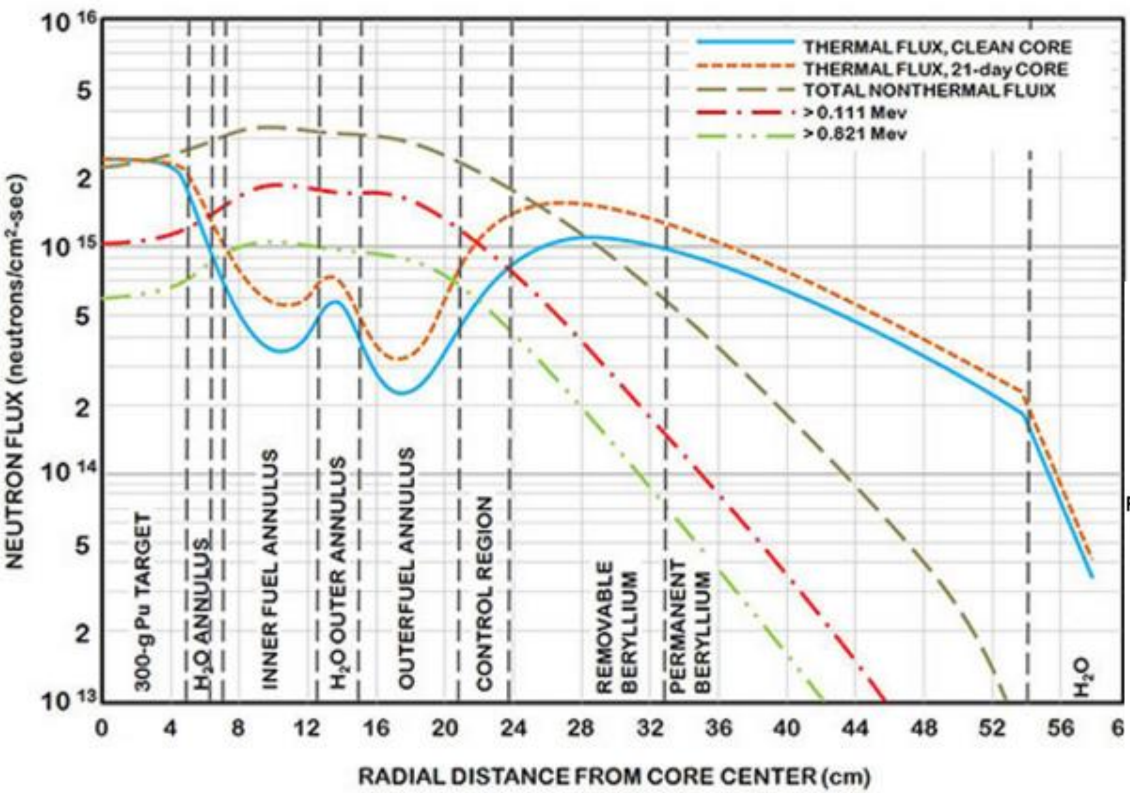
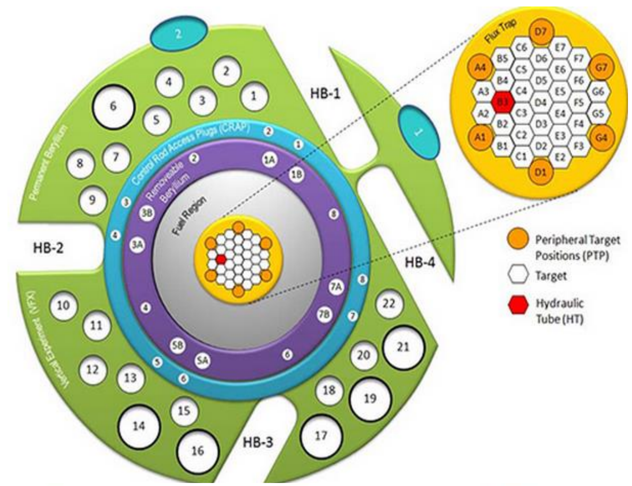
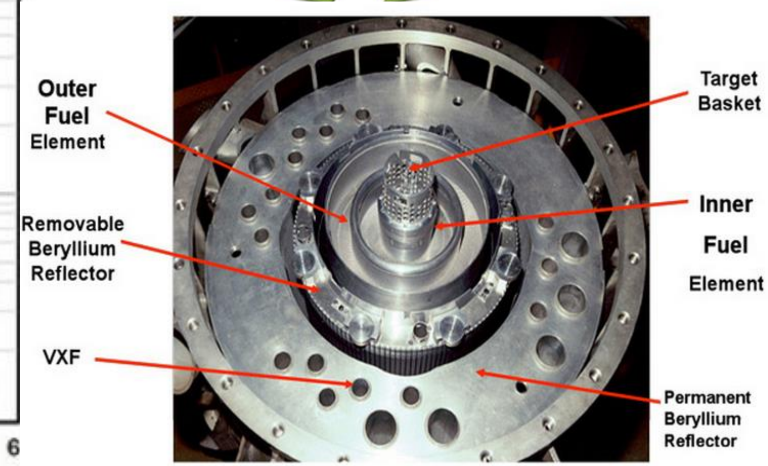
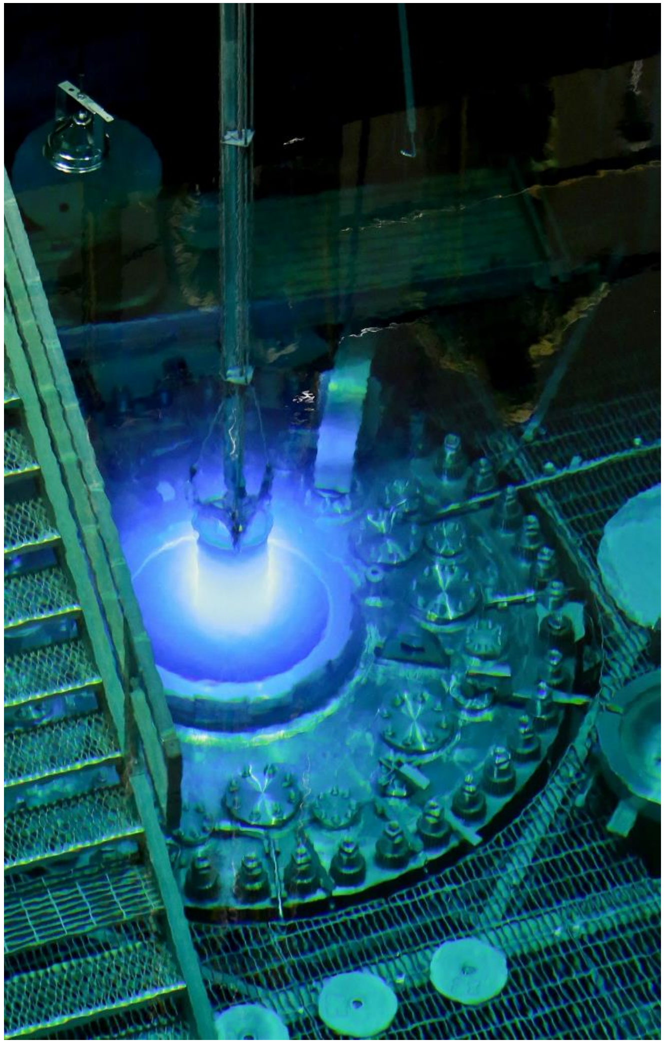
- 85MW, 468psig, 69°C, 6-7 cycles/year @ 25-days
- Main mission is to supply cold and thermal neutrons for neutron science.
- Secondary missions are isotope production and materials irradiations.







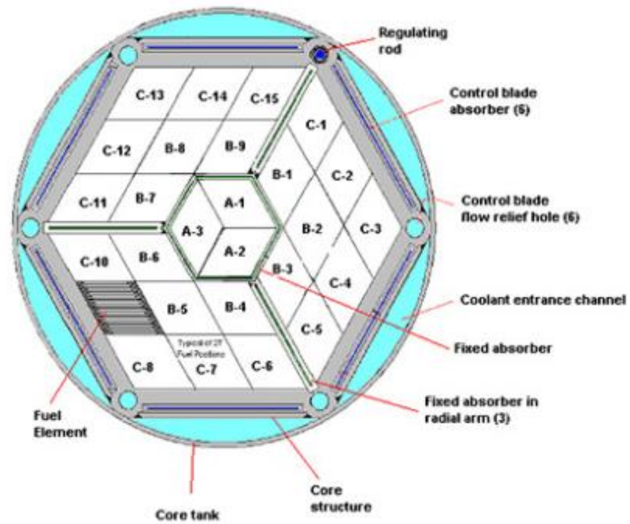
High Flux Isotope Reactor (HFIR)

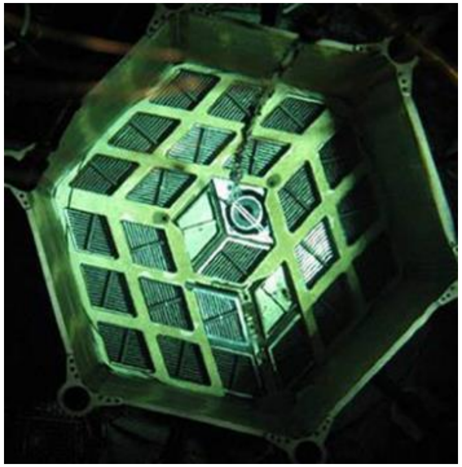


- Very high flux positions in the center flux trap (target basket)
  - Hydraulic Tube Facility (9 capsules).
- Instrumented Lead experiments or static capsules available.
- Pneumatic Tube Facilities (2) at edge of permanent reflector go to NAA laboratory w/ DN counting (10^{13}-10^{14}nv).
- Gamma Irradiation Facility in spent fuel pool. (≤100MR/hr.)
- PIE Support Facilities
  - Irradiated Fuels Examination Laboratory
  - Irradiated Materials Examination and Testing Laboratory
  - Radiochemical Engineering Development Center

MIT Nuclear Reactor Laboratory

- The MITR has the capability to perform a wide range of experiments in the reactor's core.
  - An inert gas-filled irradiation tube (ICSA) for sample capsule irradiation at $<900\ ^{\circ}C$ (instrumented or un-instrumented),
  - Forced-circulation coolant loops that replicate conditions in both pressurized and boiling water reactors,
  - High temperature ($>900\ ^{\circ}C$) irradiation facility for materials irradiations in inert gas (He/Ne mix)
  - Custom, dedicated facilities for irradiations in unique conditions (e.g., molten fluoride salts).
  - thermal flux **0.4×10^{14} n/cm^2-s**
  - fast flux (>0.1 MeV) 1**$.2 \times 10^{14}$ n/cm^2-s**





MIT Nuclear Reactor Laboratory

- **Hot cells and handling facilities**
  - larger cell - handling and disassembly of full-height in-core experiments
  - smaller cell - small, high activity components and experiments.
    - collimated gamma scan facility available
  - Shipping casks up to the GE2000 can be loaded dry or wet
- **Hot sample preparation facilities**
  - Standard metallurgical sample preparation (epoxy mounting, sectioning and polishing) can be carried out on activated samples
- **Electron microscopy facilities**
  - non-dedicated facilities can be used for hot sample microscopy at MIT

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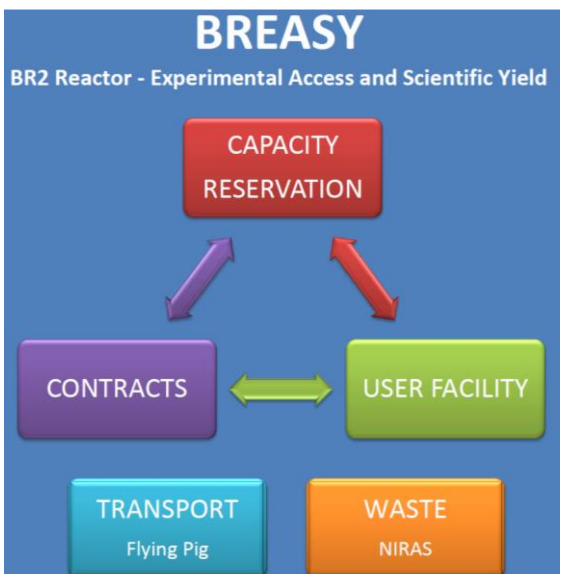
International Reactor Partner – BR-2 (Belgium)

Nuclear Science User Facilities

- Powerful European M.T.R. @ SCK-CEN site.
- Built 1961, major refurbishment in 2016 (Be reflector replacement), lifetime ≥2016.
- ~750 staff, >50% with academic degree + 70 PhD students
- annual budget ~ 200MM$; 40% gov. grant

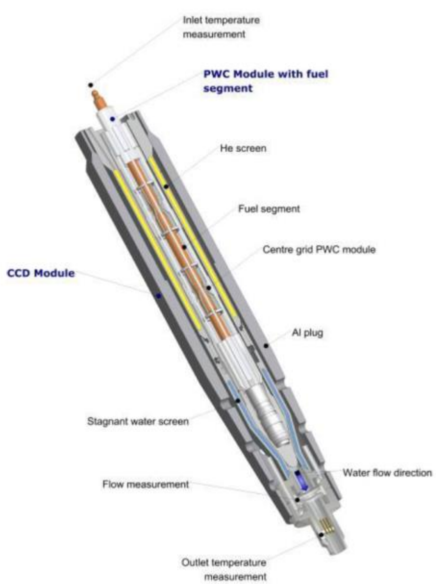


- **The BR2 reactor is mainly used for:**
  - Materials research
  - Nuclear fuel research
  - Production of doped silicon (25%W)
  - Production of radioisotopes (65%W)

BR 2 @ your service

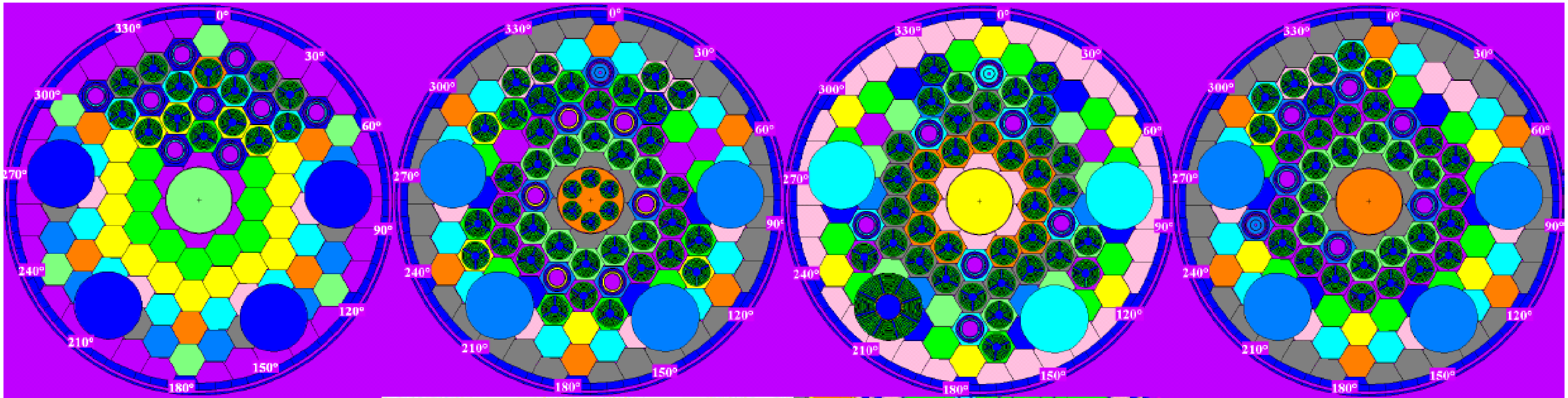
SCK • CEN
STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ÉTUDE DE L'ÉNERGIE NUCLÉAIRE

BR-2 Research Reactor



Mission-configurable core design.

- 3D MCNP model of core
- Multiple experiment vehicles
  - Static Capsules & Instrumented Leads
  - Pressurized water capsules for fuel tests (PWC)
  - PWR loop (CALLISTO)
  - Sodium loop (IPSL)
- Steady state and transient tests
  - SS: 600w/cm^2 & 100 W/cm/min up to 750 W/cm

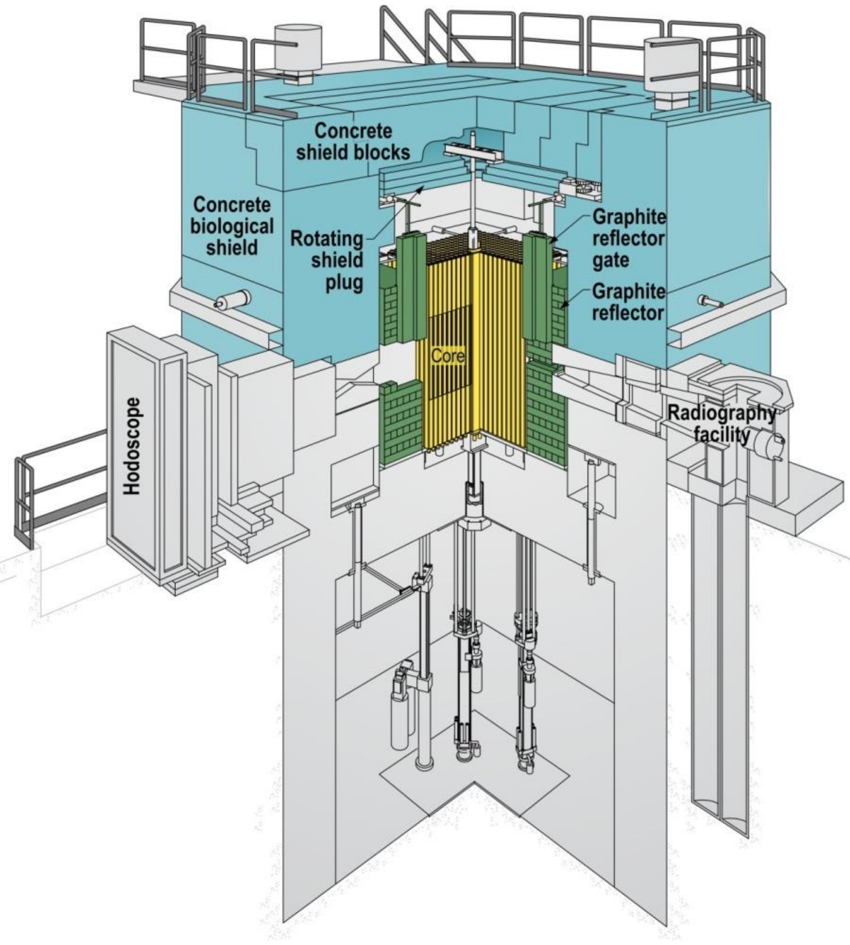


NSUF Neutron Irradiation

TRANSIENT TESTING

Transient Reactor Test Facility (TREAT)

TREAT was specifically built to conduct transient reactor tests where the test material Is subjected to neutron pulses that can simulate conditions ranging from mild upsets to severe reactor accidents.



TREAT was designed to:

- **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.**

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SERTA and Multi-SERTA Test Vehicles

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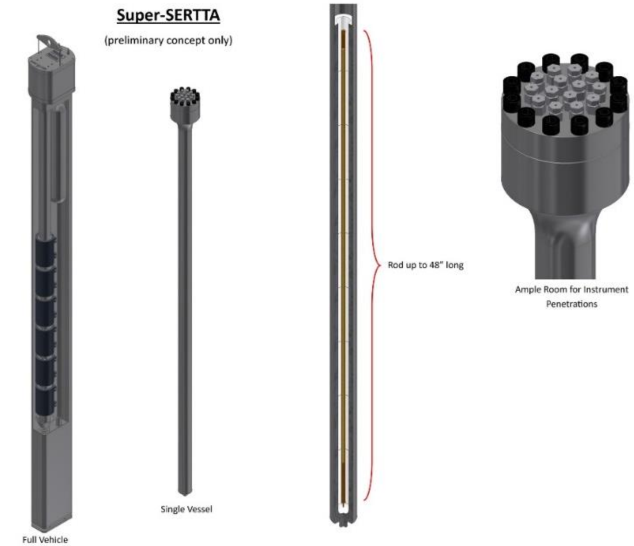
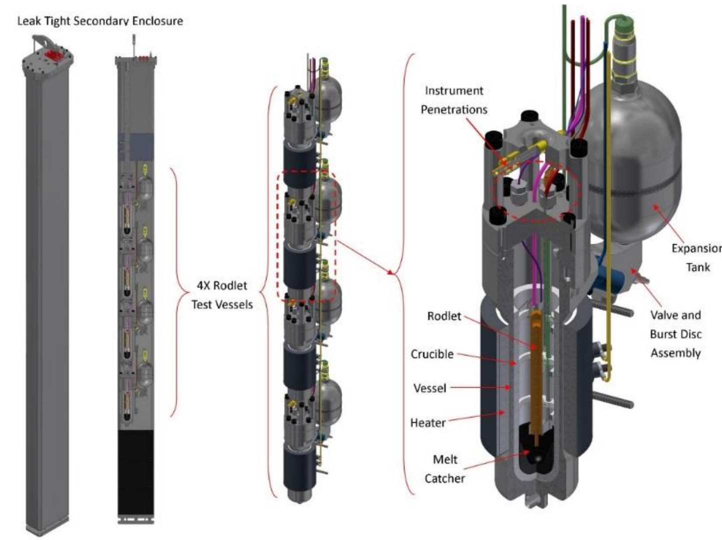
Static Environment Rodlet Transient Test Apparatus (SERTTA)

- General purpose device <u>without</u> forced convection
- **Pre-pressurized and electrically heated**
  - Liquid water up to PWR condition
    - 320°C & 16 MPa
  - Inert gas or steam and liquid sodium capability
- **Super-SERTTA**
  - Up to 1.2m active fuel length with additional capacity for instrumentation
  - Scaled up phenomena demonstration, foundational for large-scale water loop testing and LOCA analysis
- **Multi-SERTTA**
  - Up to four little rodlets, each isolated from each other for post test gas/water analysis





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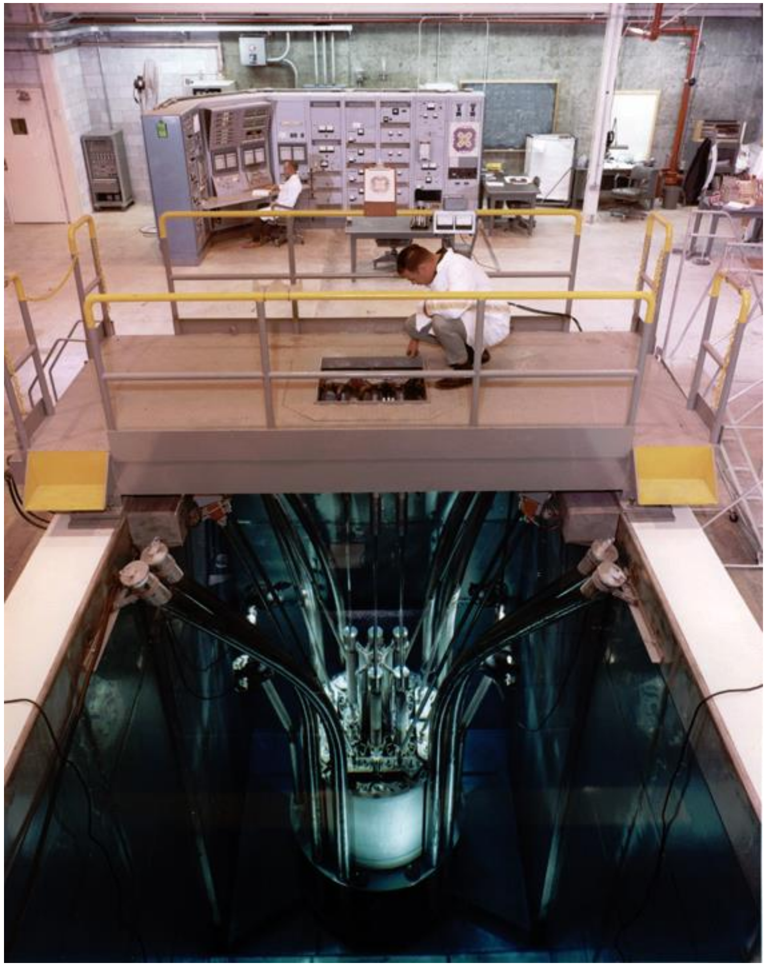
NSUF Neutron Irradiation

LOWER-FLUX REACTORS

What is the (potential) role of RTRs?

1. **Steady-State Irradiations**
   - First 1% and 10% testing
   - Instrumentation development
   - Neutron radiography & activation analysis
   - Experiment modeling & validation efforts
2. **Transient Testing**
   - Instrumentation development for TREAT
   - Code validation efforts
3. **RTR advantages:**
   - Ease of use
   - Lower cost
   - Expertise in handling and shipping/receiving RAM
   - Co-located with Hot Cell facilities (sample preparation)

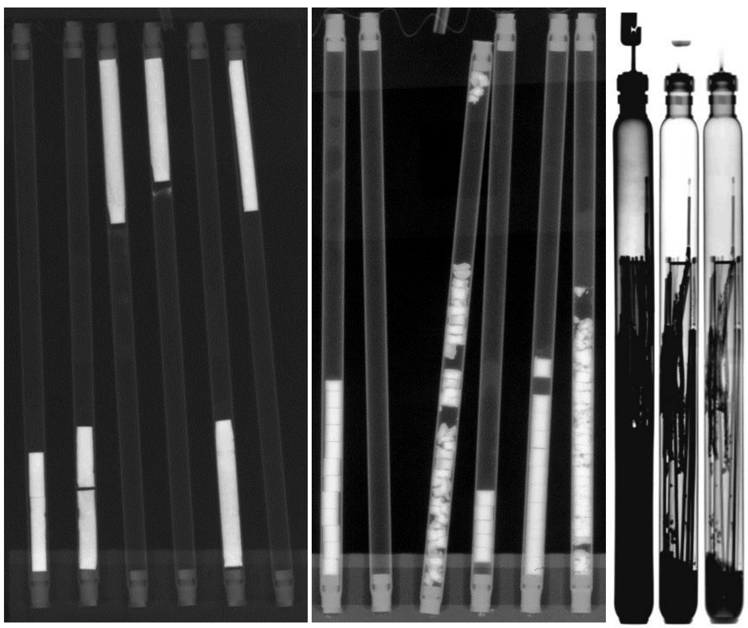
ATR Critical Facility

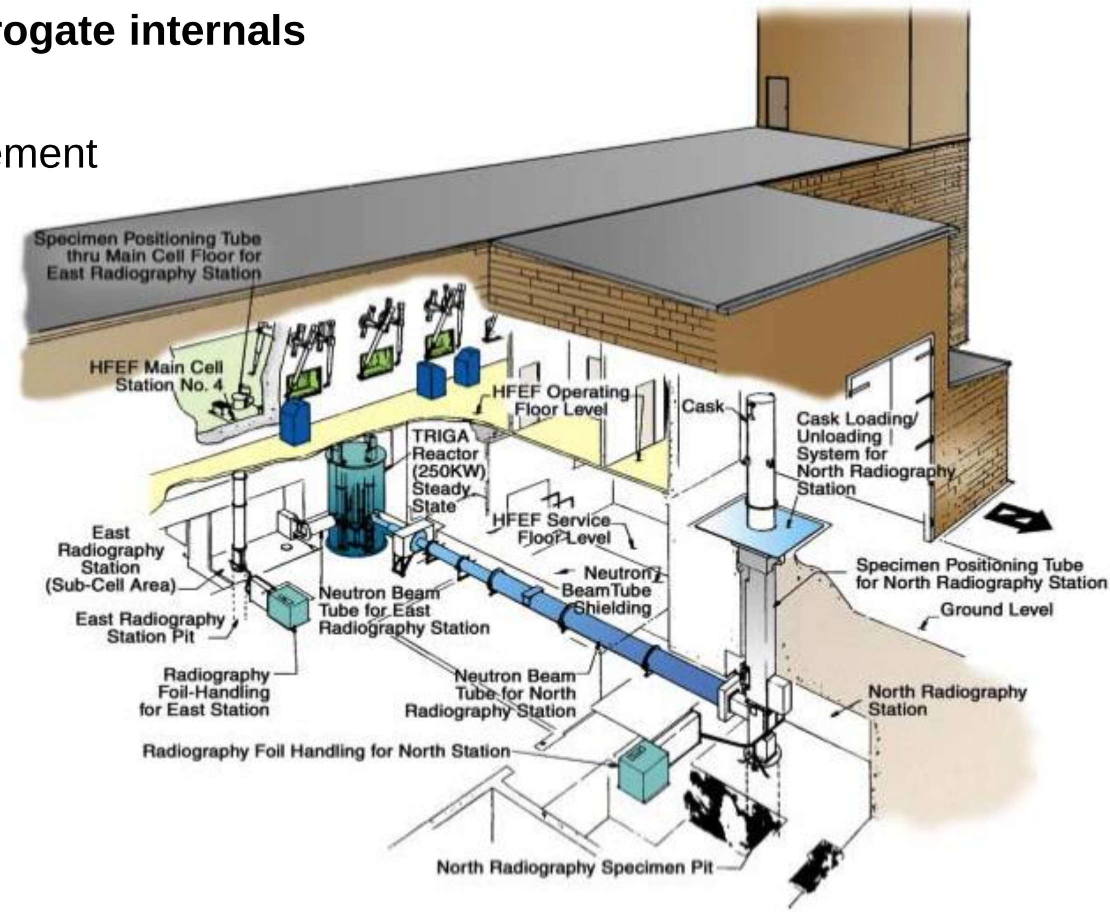


- **0.1kW (typical) 5 kW_{th} (max)**
  - Thermal Flux $2.3x10^{10}$ $n/cm^2/s$
  - Fast Flux $7.0x10^{9}$ $n/cm^2/s$
- ATR-C can provide physics data useful for evaluating the following:
  - worth and calibration of control elements,
  - excess reactivities and charge lifetimes,
  - thermal and fast neutron distributions,
  - gamma heat generation rates,
  - fuel loading requirements,
  - effects of inserting and removing experiments and experiment void reactivities, and
  - temperature and void reactivity coefficients
- **High-fidelity MCNP models of ATR-C**

Neutron Radiography Reactor (NRAD)

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





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North Carolina State PULSTAR Reactor

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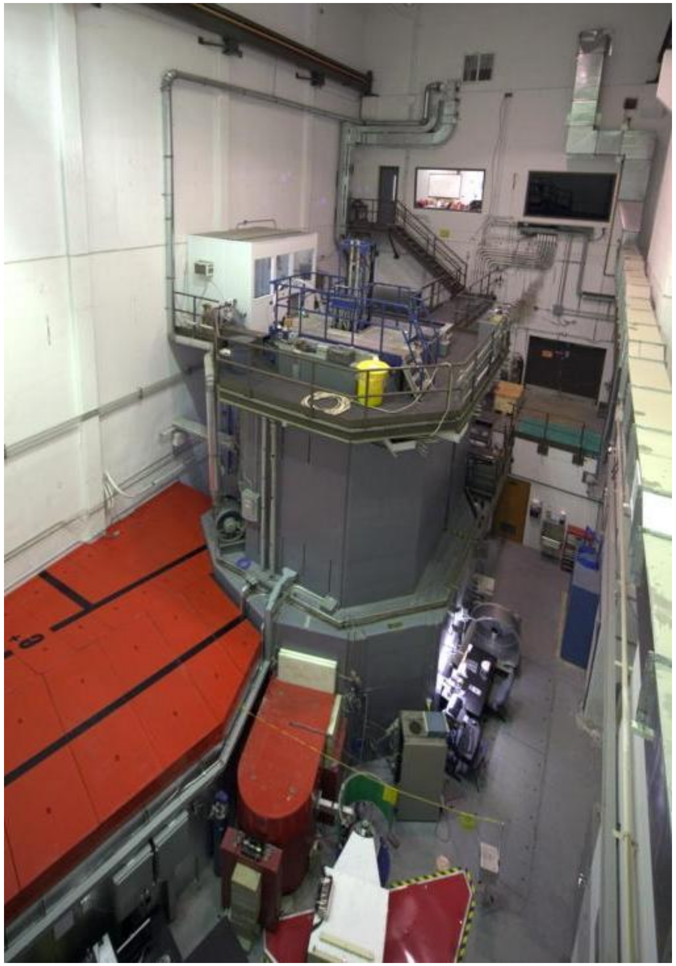
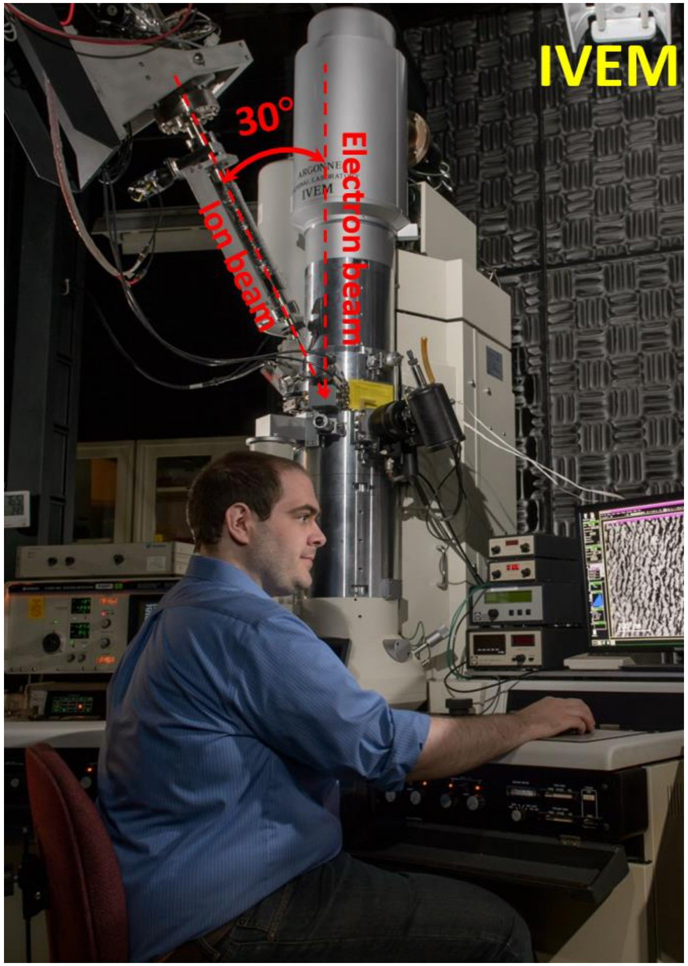


- 1 MW_{th} Light Water Reactor
- Pin type, 4% enriched pellets with Zircaloy-2 cladding
- Active fuel rod height 60.96 cm
- Sample sizes range 3.175–8.89 cm
- Thermal Flux range 10^{12}-10^{13} n/cm^2/s
- Fast Flux range 5x10^9–10^{12} n/cm^2/s
- Capabilities
  - Positron intense beam facility,
  - neutron powder diffraction facility,
  - neutron imaging facility,
  - ultra-cold neutron source

Nuclear Science User Facilities

ION IRRADIATION PARTNERS

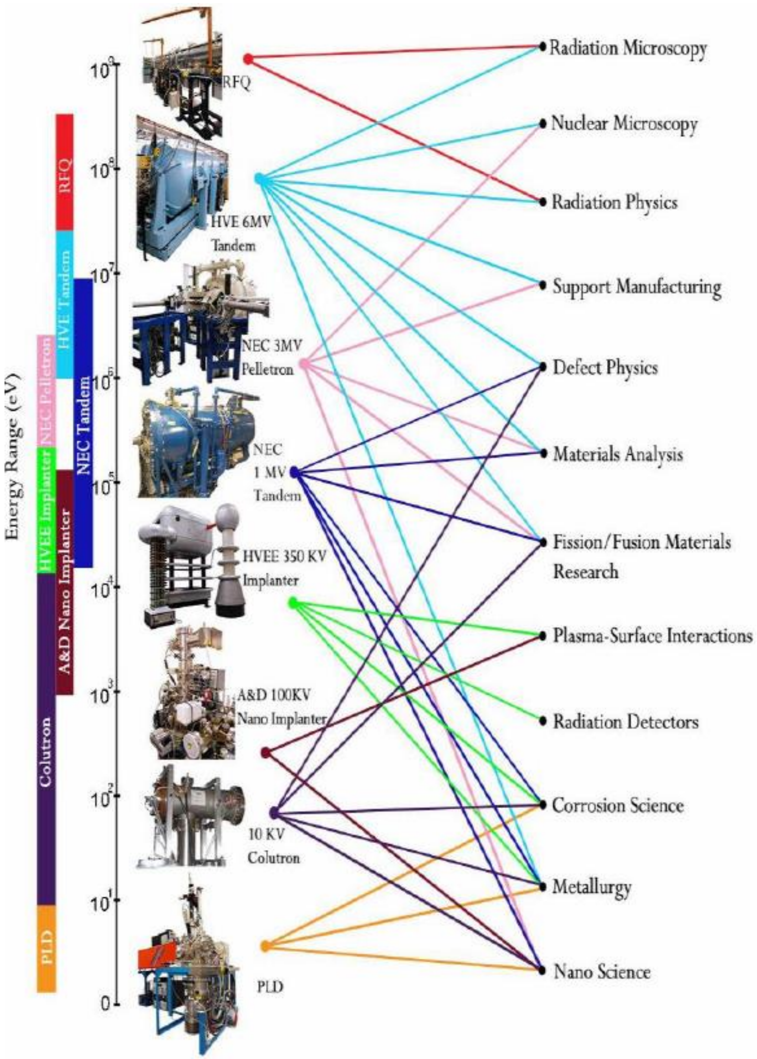
Argonne National Laboratory IVEM Tandem User Facility



- In-situ examination of ion irradiation using TEM
- Adding a second beam to TEM in FY2017
- Triple-beam irradiation available at ATLAS.
- Radioactive material handling, sample preparation and shipping at the Irradiated Material Laboratory.

Sandia National Laboratory

I^{3}TEM @ the Ion Beam Laboratory



- **Seven ion beams that cover the range of energies.**
- **Triple-beam irradiation in TEM**
  - 10kV Colutron, 200kV TEM, 6MV Tandem
  - In situ
    - Heating up to 1,000°C
    - Quantitative and bulk straining & fatigue
    - Two-port microfluidic cell-corrosion
    - Gas flow/heating stage
    - Electron tomography
    - Precession Electron Diffraction
  - Developing <u>Ion Beam Induced Luminescence (IBIL)</u> capability
    - Elemental information and
    - **Chemical bond structure**

University of Michigan Ion Beam Laboratory

- **Irradiation Damage, Ion Implantation and Ion Beam Analysis**
- **Light ion high dose irradiation damage, heavy ion high dose irradiation damage, surface analysis (RBS, NRA, PIXE, ERD)**
- **Accelerators:**
  - 3 MV Tandem (Pelletron)(Wolverine)
  - 1.7 MV Tandem (Tandetron)(Maize)
  - 0.4 MV implanter (Blue)

- **Single Ion Irradiations**
  - Proton irradiation to moderate dose
  - Self-ion irradiation to high dose
  - In-situ corrosion
- **Dual Beam Irradiations**
- **Triple Beam Irradiations**
- **Dual Beam In-situ TEM (in progress)**

- **Ion Beam Analysis**
  - Rutherford backscattering spectroscopy (RBS)
  - Nuclear Reaction Analysis (NRA)
  - Particle Induced X-ray Emission (PIXE)
  - Elastic Recoil Detection (ERD)
  - Ion channeling

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University of Wisconsin

Tandem Accelerator Ion Beam

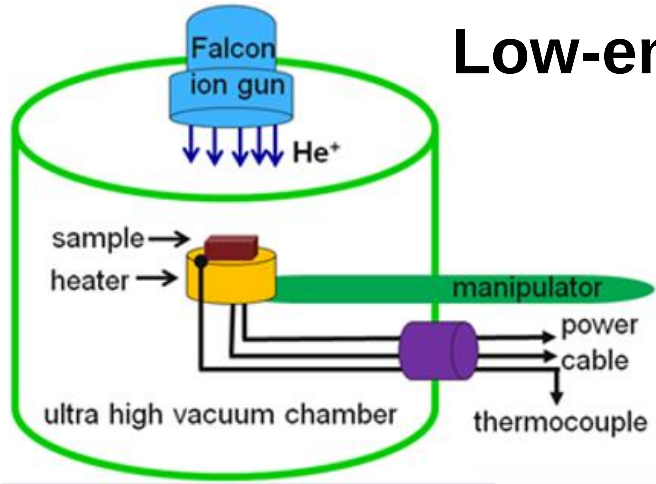
NSUF Nuclear Science User Facilities

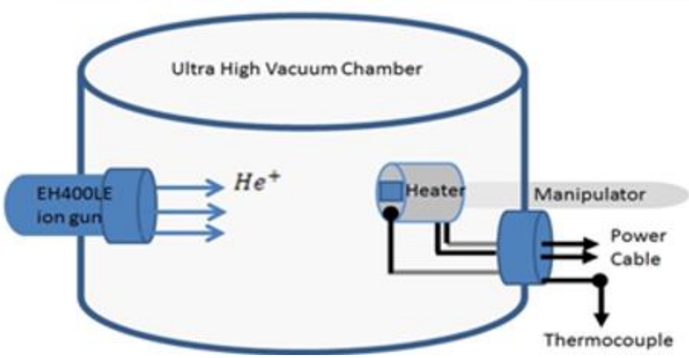
Characterization Laboratory for Irradiated Materials (CLIM)

- **400-800 hours of irradiation per year, 10-20% NSUF**
- **Radioactive sample capability:**
  - 10 mCi storage, 100 mR/hr. unshielded on contact, no transuranic products

- **1.7 MV tandem accelerator (NEC)**
- **Torvis and SNICS ion sources**
  - Protons: 1×10^{11}-2×10^{15} p/cm²/s
  - Ions: 4×10^{10}-6×10^{14} ions/cm²/s
- **-150-800°C, 900°C flash controlled by TCs and IR camera**
- **Sample preparation capability**
- **Analysis techniques:**
  - In-situ:
    - IBA: RBD, NRA and PIXE
  - Ex situ at the MSC:
    - SEM with EDS and EBSD
    - TEM, XRD, AFM, etc.
  - Planning for TEM integration, triple-beam station and corrosion stage.

Low-energy/high-flux ion irradiation facility





Falcon ion source gun

- 650-2000eV
- Inert gases,
- Reactive gases (H_2, CH_4, N_2,O_2)
- 1.0×10^{17} ions/cm^2/sec

eH-400 LE ion source gun

- 70-300eV
- Inert gases
- O^+,N^+,H^+
- 1.15×10^{17} ions/cm^2/sec

Analytical techniques: x-ray photoelectron, Auger electron, ultraviolet photoelectron and low-energy ion scattering spectroscopy available.

Nuclear Science User Facilities

FUELS & MATERIALS LIBRARY

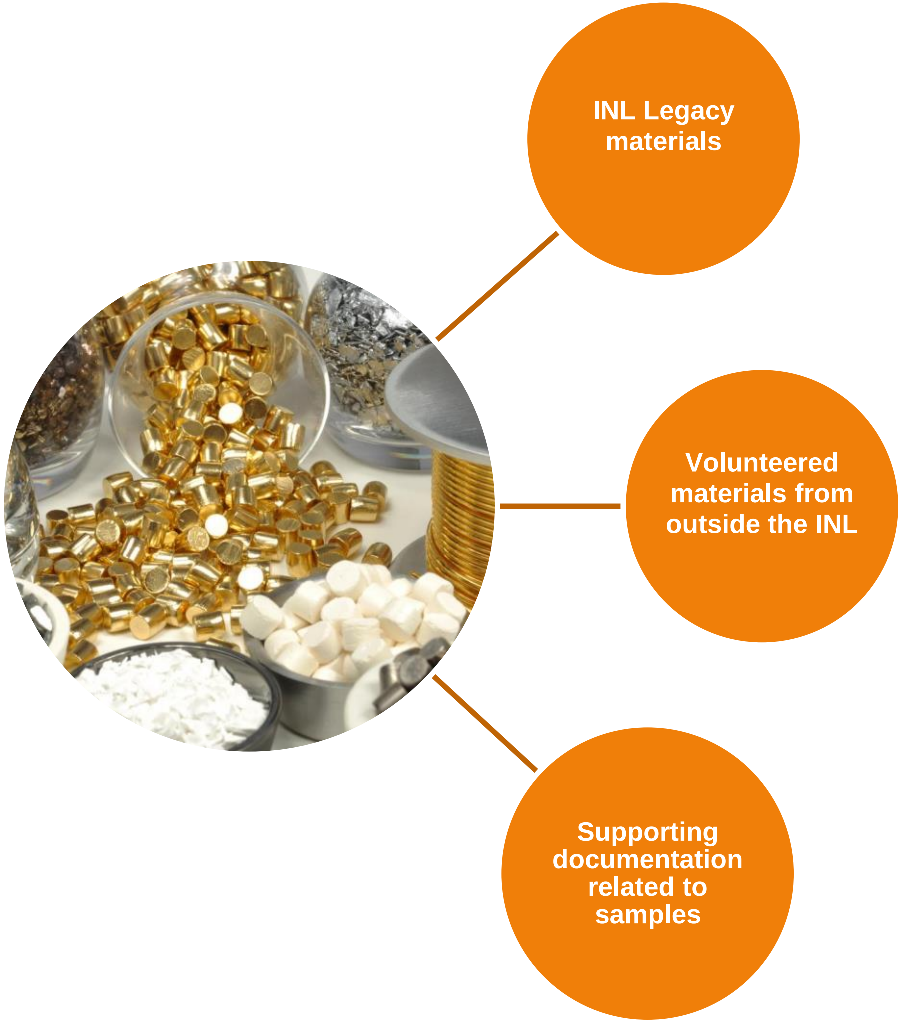
NSUF Fuels and Materials Library

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**



NSUF Fuels and Materials Library

- **Most samples in the library have been neutron irradiated in:**
  - **EBR-II** (Idaho National Laboratory)
  - **ATR** (Idaho National Laboratory)
  - **HFIR** (Oak Ridge National Laboratory)
  - **FFTF** (Hanford Site / Pacific Northwest National Laboratory)
  - José Cabrera Nuclear Power Station

- **A smaller number were proton irradiated at:**
  - LANSCE (Los Alamos National Laboratory)

NSUF Fuels and Materials Library

Steels	
17-4 PH SS	Fe-Cr Alloys
304 SS	HCM12-A
304 SS welds	HT-9
Super 304H	MA-956
316 SS	MA-957
347 SS	MAR-2008
416 SS	Mo-ODS
420 SS	nCr-YWT
9Cr ODS	NF616
Borated Steel	NF709
Carbon Steel	PM2000
Cast ASS	T-91
D9 ASS	Tool Steel T-1
Eurofer 97	XM-19
F82H-IEA	various model alloys

Other Alloys	Ceramics	Pure Materials
Al_3Hf	Al_2O_3	Copper
Al-1100	MgO	Iron
Al-6061	$MgO-ZrO_2$	Ni/Cu/Nb (DC)
Aluminum Bronze	Mg_2-SnO_4	Nickel
Berylco #25	$Mg0_{1.5}Al_2O_3$	Niobium
C276 Hasteloy	$MgTiO_3$	Silver
Incoloy 800H	$Nd_2Zr_2O_7$	Tantalum
Inconel X/X-750	SiC	Tungsten
Stellite	Ti_2AlC	Zirconium
	Ti_3AlC_2	
	Ti_2AlN	
	TiO_2	
	Ti_3SiC_2	

Small amounts of purified actinides and fission products in liquid form.

What is the (potential) role of RTRs?

1. **Steady-State Irradiations**
   - First 1% and 10% testing
   - Instrumentation development
   - Neutron radiography & activation analysis
   - Experiment modeling & code validation efforts
2. **Transient Testing**
   - Instrumentation development for TREAT
   - Transient code validation efforts
3. **RTR advantages:**
   - Ease of access/use (speed of access)
   - Lower cost
   - Expertise in handling and shipping/receiving RAM
   - Co-located with Hot Cell facilities (sample preparation)

Nuclear Science User Facilities

INFRASTRUCTURE MANAGEMENT PROGRAM

U.S. DEPARTMENT OF ENERGY

Nuclear Energy

Infrastructure Management Program

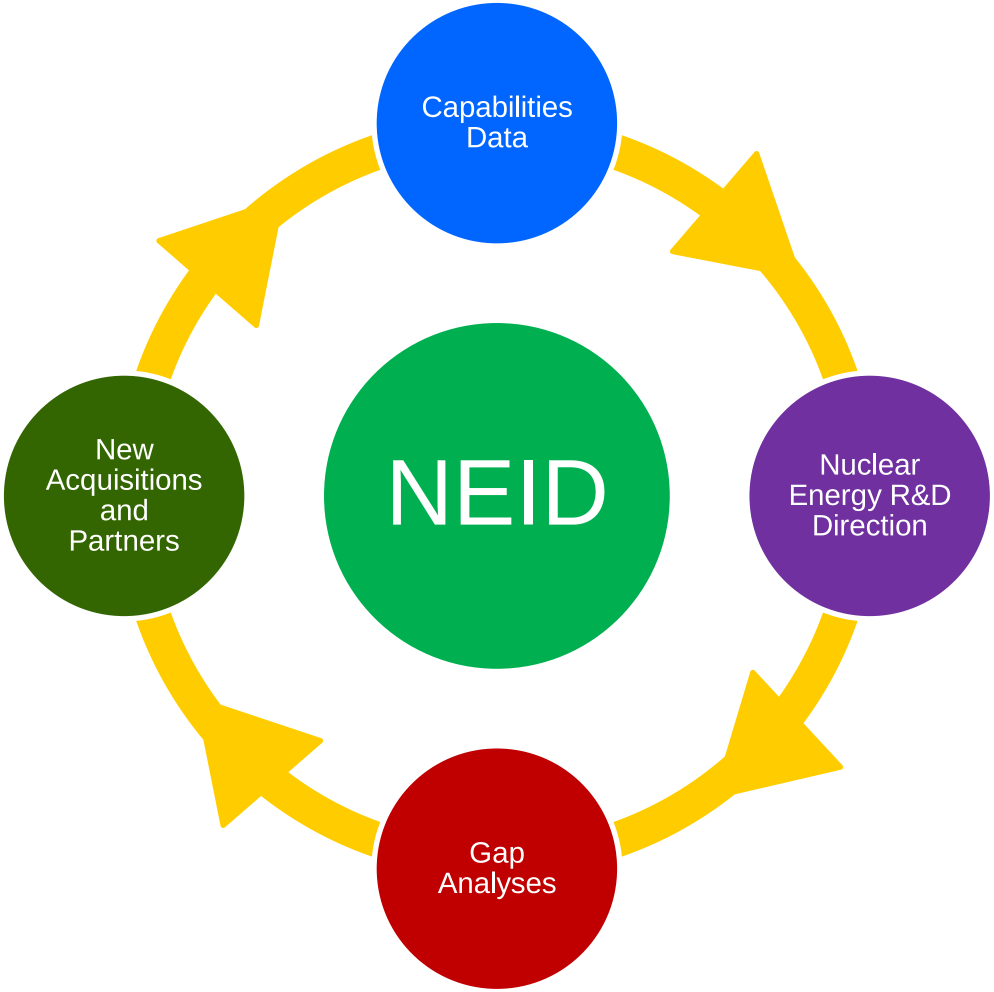
NSUF Nuclear Science User Facilities

1. Gather Data on Nuclear Energy R&D Capabilities

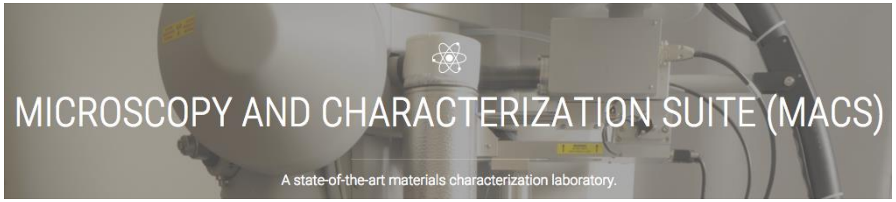
2. Estimate Near, Mid and Long-term R&D Directions

3. Use these to perform gap analyses for Nuclear Energy R&D.

4. Assist funding decisions and incorporate the results into the NEID.



NEID Organization



FEI Quanta 3D FEG
Focused Ion Beam
SEM Microscope

Institutions

Facilities

Instruments

U.S. DEPARTMENT OF ENERGY

Nuclear Energy

Database Characteristics

Nuclear Science User Facilities

Data

124 Institutions

445 Facilities

804 Instruments

Users

61 Federal Government & National Laboratories

32 Universities & NGOs

15 Nuclear Energy Industry

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Database Categories (“fields”)

NSUF Nuclear Science User Facilities

Facility Information	Facility Conditions	Facility Utilization	Data Sources
Facility/Instrument Name	Commissioning Date	User Facility or Contract?	Contact information
Abbreviation	Recent Major Upgrade	Cost to Use	Email Address
Owner Type	Material Condition	Cost to Maintain	Web Site
Institution	Mission Upgradable?	Cost to Replace	Source(s) of Data
State	Supporting Physical Plant	Funding Sources	Date of Data
Region	Regulating Agency	NSUF Partner?	
Country	License End Date	DOE-NE Use [%]	
Primary Capability		NE Objectives [1,2,3,4]	**Reactor Type**
Secondary Capability		Utilization [%]	Thermal Power
Tertiary Capability		# of users	Pulse Power
Core Capability		# of staff	Thermal Flux
Unique Capability			Fast Flux
Radiological Limits			In-core locations
Hot Work Facilities			Ex-core locations
Support Equipment			Pneumatic Transfer System
Sample Encapsulation			Flow Loops
Atmosphere/environment			Beam Ports

40 common database fields for all entries

5-20 fields specific to facility/instrument type

Additional Usability Improvements

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

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

1. **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 FMSL

2. **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

GAIN

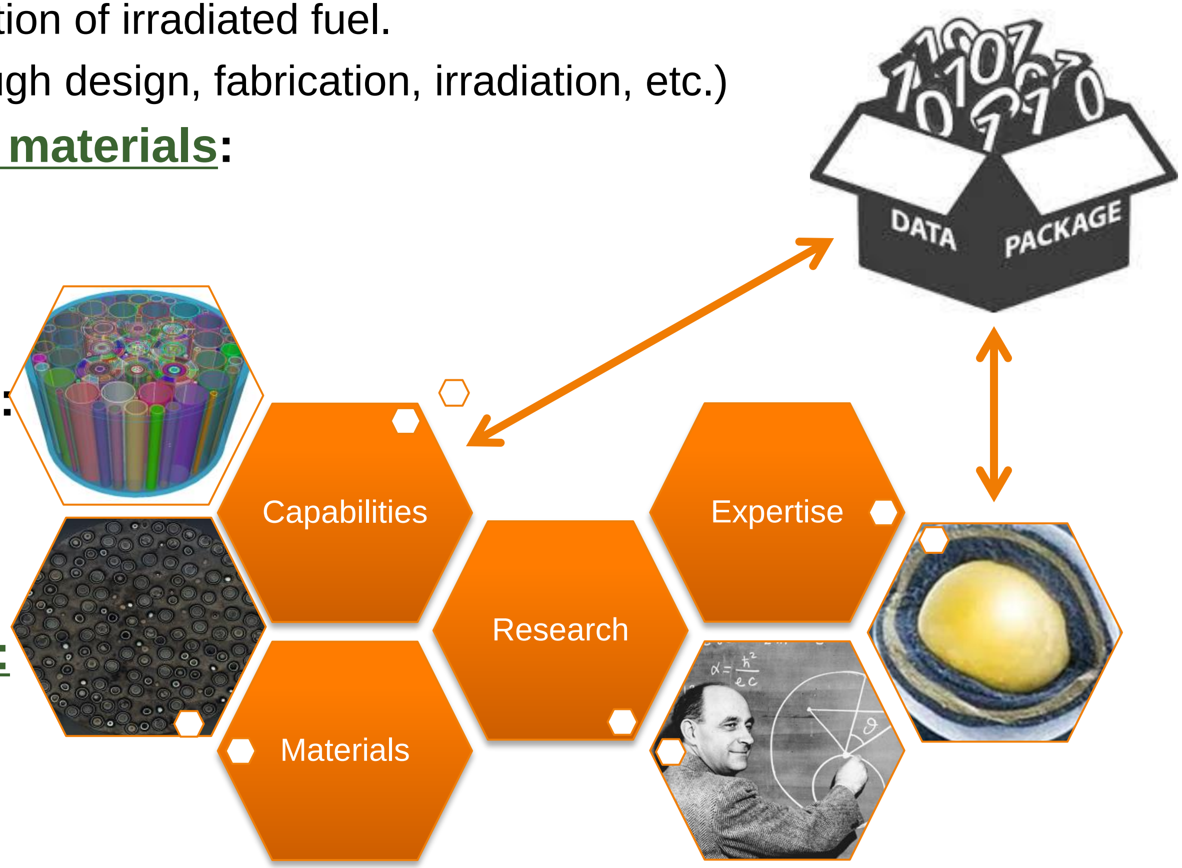
NSUF Nuclear Science User Facilities

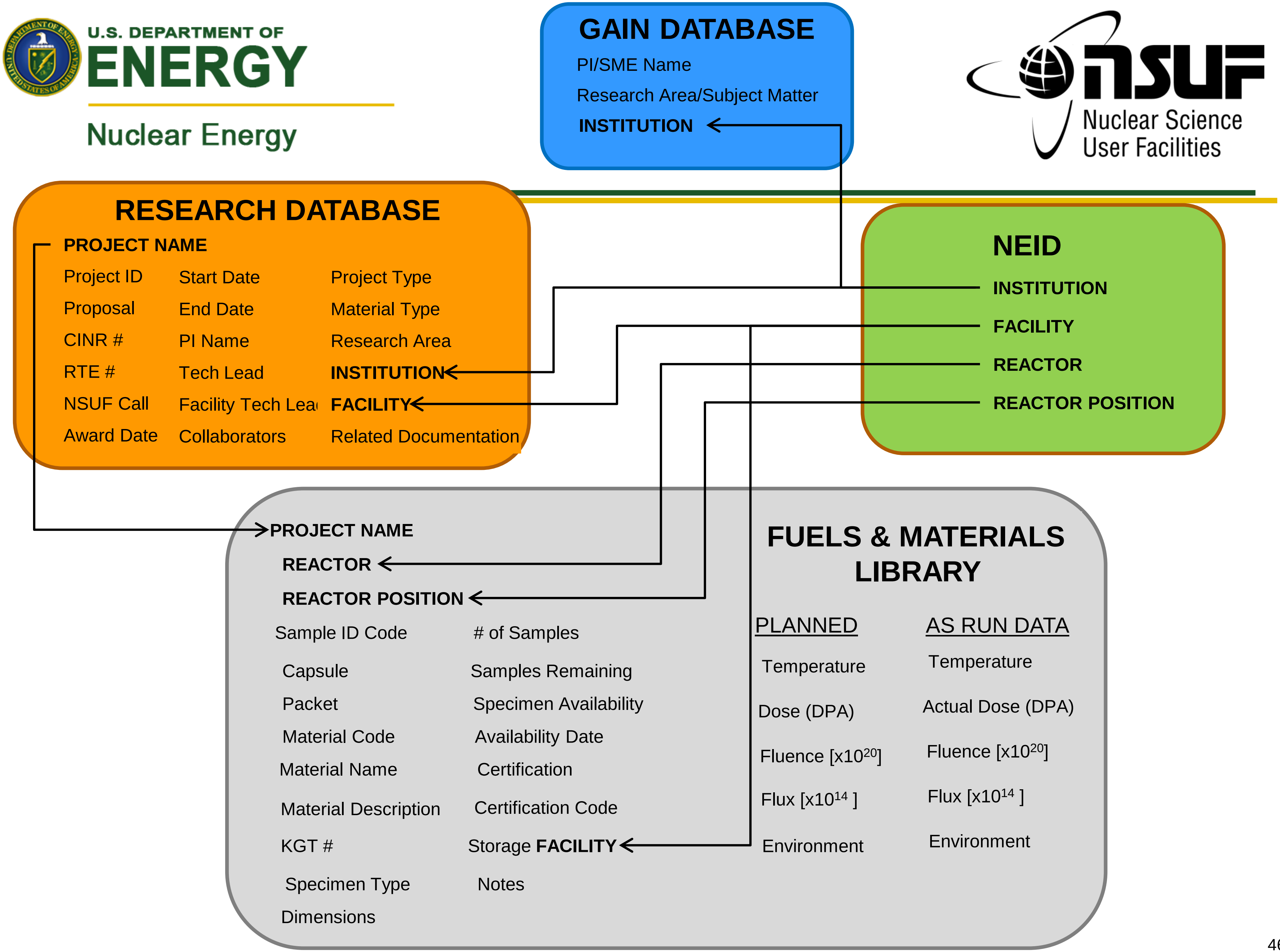
Small Business Vouchers Pilot

What can we build from NSUF Data?

1. **We can connect facilities and instruments as parts of a process to accomplish a research method or process, such as:**
   - Microstructural characterization of irradiated fuel.
   - Irradiation experiment (through design, fabrication, irradiation, etc.)
2. **We can include fuels and materials:**
   - Fuels and Materials Library
   - Link to facilities utilized
   - Link to researchers
3. **We can connect research:**
   - Subject matter
   - Facilities utilized
   - PIs & collaborators
4. **We can include expertise:**
   - Support for **GAIN**

What's missing?




U.S. DEPARTMENT OF ENERGY
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GAIN DATABASE
PI/SME Name
Research Area/Subject Matter
INSTITUTION
NSUF
Nuclear Science User Facilities
RESEARCH DATABASE
PROJECT NAME
Project ID
Start Date
Project Type
Proposal
End Date
Material Type
CINR #
PI Name
Research Area
RTE #
Tech Lead
INSTITUTION
NSUF Call
Facility Tech Lea
FACILITY
Award Date
Collaborators
Related Documentation
NEID
INSTITUTION
FACILITY
REACTOR
REACTOR POSITION
PROJECT NAME
REACTOR
REACTOR POSITION
Sample ID Code
# of Samples
Capsule
Samples Remaining
Packet
Specimen Availability
Material Code
Availability Date
Material Name
Certification
Material Description
Certification Code
KGT #
Storage FACILITY
Specimen Type
Notes
Dimensions
FUELS & MATERIALS LIBRARY
PLANNED
AS RUN DATA
Temperature
Temperature
Dose (DPA)
Actual Dose (DPA)
Fluence [x10^20]
Fluence [x10^20]
Flux [x10^14]
Flux [x10^14]
Environment
Environment

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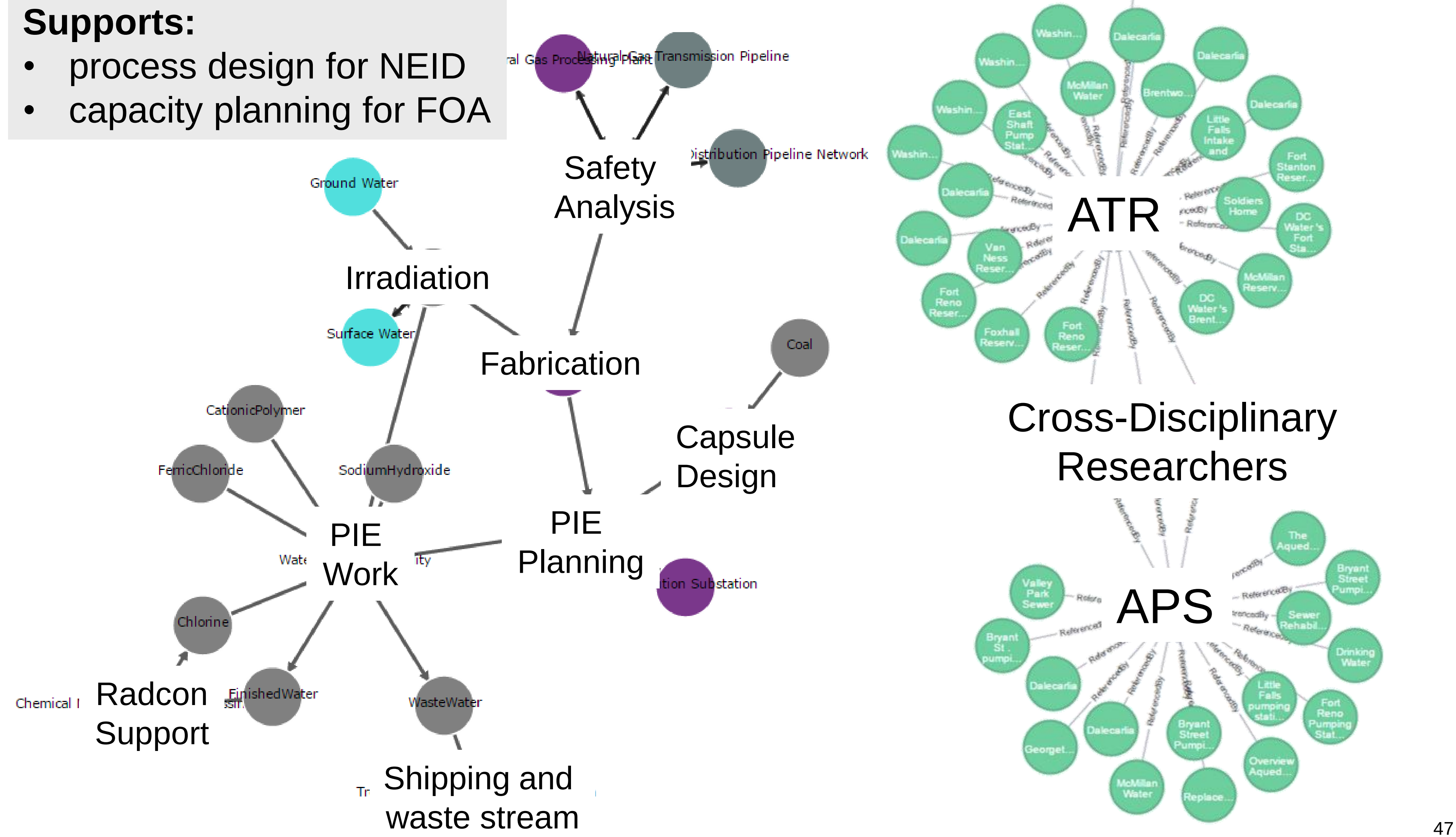
Graph (Social) Network Dependency Models

Nuclear Science User Facilities

Supports:
- process design for NEID
- capacity planning for FOA



NSUF
Nuclear Science
User Facilities

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