INL/MIS-21-64923-Revision-0

Irradiation Capabilities at the Advanced Test Reactor

October 2021

Changing the World's Energy Future

Brenden J Heidrich

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

INL/MIS-21-64923-Revision-0

Irradiation Capabilities at the Advanced Test Reactor

Brenden J Heidrich

October 2021

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

November 9, 2021

Brenden Heidrich, PhD PE
NFMD Irradiation Testing Manager

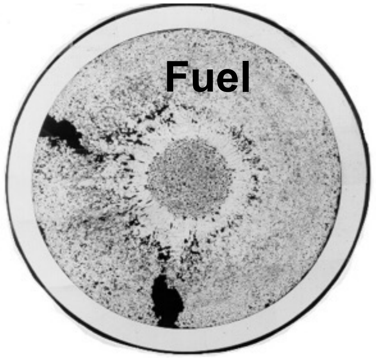
Irradiation Capabilities at the Advanced Test Reactor

Idaho National Laboratory

INL/MIS-21-64923

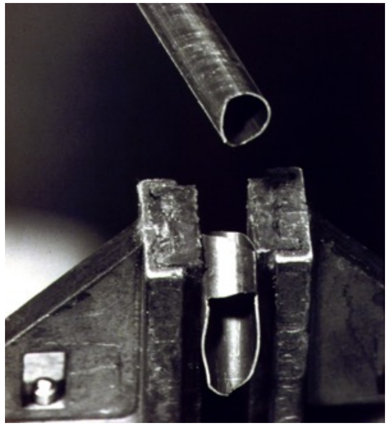
Importance of Understanding Materials Degradation Processes

- Neutron and gamma radiation can change material properties.
- A mechanistic understanding of radiation-induced degradation processes can aid in lifetime prediction of core components and guide inspection and replacement programs.
- Enable the development of mitigation strategies, such as hydrogen water chemistry, Zn injection, etc., used in current light water reactors.
- Lead to the development of more radiation-tolerant materials that can be used in advanced LWR and next generation nuclear power plants.

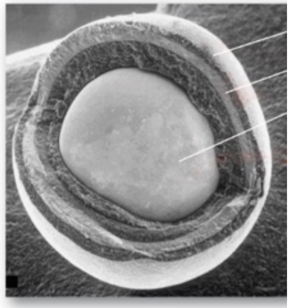


Restructuring in U-Pu-Zr Metallic Fuel

Radiation Damage Effects in Cladding and Structural Materials



Austenitic Stainless Steel Following Irradiation in EBR II Fast Reactor



Gas Reactor Coated-Particle Fuel

Utilization of Research and Test Reactors for Radiation Damage

Testing Strategy for Novel Materials

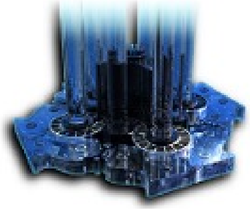
Irradiation Testing Hierarchy

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

THE UNIVERSITY of WISCONSIN MADISON

NC State University Raleigh, NC

Massachusetts Institute of Technology



Sandia National Laboratories

The ***Ion Beam Laboratory*** uses ion and electron accelerators to study and modify materials systems. The IBL is interested in pursuing a range of cutting edge studies, including controlled defects in materials, materials in radiation environments, and hostile environment performance. The building houses a Tandem and a Pelletron accelerator, an Implanter, a Nano-Implanter, an in-situ TEM and the Colutron. The Nano-Implanter is unique to the world, and the in-situ TEM is one of two in the U.S., putting the IBL on the forefront of developing technologies in radiation studies.

Technical Point of Contact: Khalid Hattar (khattar@sandia.gov or 505-845-9859)

LEARN MORE »

Texas A&M University

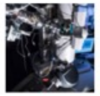
The ***Accelerator Laboratory*** is one of the largest university ion irradiation facilities in the U.S. A total of five accelerators are able to deliver virtually all ions in the elemental table with ion energy from a few hundred eV to a few MeVs. The lab provides unique capabilities to perform accelerator based irradiation studies on various nuclear materials. The key facilities in the lab include: a 10 kV ion accelerator (with a gas ion source); a 150 kV Ion Accelerator (with a universal ion source); a 200 kV ion accelerator (with a universal ion source); a 1 MV ionex tandetron accelerator (with a RF plasma source and a SNICS source); a 1.7 MV ionex tandetron accelerator (with a RF plasma source and a SNICS source); a high temperature vacuum furnace; a high temperature gas furnace; a four-point-probe resistivity measurement; and various heating and cooling systems for ion irradiations at different temperatures.

All five accelerators provide mass-analyzed ion beams of most of the elements of the periodic table. 1 MV and 1.7 MV ion accelerators are modified general ionex tandetron accelerators. Each of them has its own scanning systems, electrostatic deflectors, an injector and an analyzing magnet. The general purpose chamber has been equipped with numerous unique designs for various ion beam applications.

Technical Point of Contact: Lin Shao (lshao@tamu.edu or 979-845-4107)

LEARN MORE »

University of Michigan



The ***Michigan Ion Beam Laboratory (MIBL)*** was established for the purpose of advancing our understanding of ion-solid interactions by providing unique and extensive facilities to support both research and development in the field and has developed extensive capabilities in the use of accelerators directed towards the study of radiation effects by emulating neutron damage in nuclear reactor materials. The laboratory also provides a wide range of capabilities for both surface modification and analysis including a 3 MV Pelletron Tandem accelerator, 1.7 MV Tandetron accelerator, 400 kV implanter, a Multi-Beam Chamber (MBC), dedicated beamline and corrosion cell to perform in situ irradiation-corrosion of samples in contact with liquid environments, and a 400 kV accelerator and a 30 kV He source are interfaced with a 300 kV Tecnai G2 F30 transmission electron microscope.

Technical Point of Contact: Gary Was (gsw@umich.edu or 734-763-4675)

LEARN MORE »

University of Wisconsin

The ***Ion Beam Laboratory (IBL)*** at the University of Wisconsin, Madison houses a NEC 1.7 MV tandem accelerator. The accelerator is actively used for research aimed at advancing the science of radiation damage of materials including alloys, ceramics, and coatings. The accelerator is equipped with TORVIS and SNICS ion sources for enhanced capabilities and the samples temperature is monitored by thermocouples and IR camera. The system can presently accommodate two types of sample geometries: 3 mm TEM samples and bar samples; with irradiation area between 1.45 and 2.3 sq. cm. the facility is continually improved to meet the research needs of the scientific community involved in research on radiation damage of materials and other fundamental materials science research areas involving ion irradiation.

Technical Point of Contact: Adrien Couet (couet@wisc.edu or 608-265-7655)

LEARN MORE »

Massachusetts Institute of Technology Reactor

The ***Massachusetts Institute of Technology Reactor (MITR)*** is a 6 MW tank-type research reactor. It has three positions available for in-core materials, fuel and instrumentation irradiation experiments over a wide range of conditions. Water loops at pressurized water reactor/boiling water reactor (PWR/BWR) conditions, static and lead-out capsule experiments in inert gas environment at temperatures up to 850°C, custom designed high-temperature irradiation facility up to 1400°C and nuclear fuel irradiation experiments with fissile materials up to 100 gm U-235 or equivalent. A variety of instrumentation, support facilities, pneumatic tubes, beam ports, neutron activation analysis laboratory, hot cells, and non-destructive post irradiation examination facilities are also available. Fast and thermal neutron fluxes are up to 1.2e14 and 6e13 n/cm2 s at 6 MW.

Technical Point of Contact: Gordon Khose (kohse@mit.edu or 617-253-4298)

LEARN MORE »

North Carolina State University

The ***PULSTAR reactor*** is a 1 MW pool-type nuclear research reactor located in NCSU's Burlington Engineering Laboratories. The reactor, one of two PULSTAR reactors built and the only one still in operation, uses 4% enriched, pin-type fuel consisting of uranium dioxide pellets in zircaloy cladding. The fuel provides response characteristics that are very similar to commercial light water power reactors. These characteristics allow teaching experiments to measure moderator temperature and power reactivity coefficients including Doppler feedback. In 2007, the PULSTAR reactor produced the most intense low-energy positron beam with the highest positron rate of any comparable facility worldwide.

Technical Point of Contact: Ayman Hawari (ayman.hawari@ncsu.edu or 919-515-4598)

LEARN MORE »

Oak Ridge National Laboratory

The ***High-Flux Isotope Reactor (HFIR)*** is a versatile 85 MW research reactor offering the highest steady-state neutron flux in the western world. With a peak thermal flux of 2.5x1015 n/cm2-s and a peak fast flux of 1.1x1015 n/cm2-s, HFIR is able to quickly generate isotopes that require multiple neutron captures and perform materials irradiations that simulate lifetimes of power reactor use in a fraction of the time. HFIR typically operates 7 cycles per year, each cycle lasting between 23 and 26 days. Associated irradiation processing facilities include the Hydraulic Tube Facility, Pneumatic Tube Facilities for Neutron Activation Analysis (NAA), and Gamma Irradiation Facility.

Technical Point of Contact: Kory Linton (kory.linton@inl.gov or 865-228-3193)

LEARN MORE »

Ohio State University

The ***Ohio State University Nuclear Reactor Laboratory (OSU-NRL)*** offers the unique capability of reactor irradiations in external large-experiment dry tubes for the OSU Research Reactor (OSURR). In the next-to-core position in which either a 6.5-in I.D. or a 9.5-in I.D. external dry tube can be located, irradiations can be performed in a neutron flux up to 1012 n/cm2/s. Among the possibilities for use are experiments involving instrumented, high-temperature irradiations of prototype instrumentation for next-generation reactors, sensors and sensor materials, and optical fibers designed for up to 1600 C. In addition to the external large-experiment dry tubes, the reactor also has two 2.5-in I.D. in-core dry tubes that also support instrumented experiments, but at ambient temperature.

Technical Point of Contact: Raymond Cao (cao.152@osu.edu or 614-547-8701)

LEARN MORE »

ATR Historical Perspective

Materials Test Reactor (MTR)
- 1952 through the early 1970s
- First of its kind to study material behavior in a radiation field.

Engineering Test Reactor (ETR)
- 1958 through the early 1980s
- Studied fuel performance and reactor components, including experiments.

Advanced Test Reactor (ATR)
- Initial operation in 1967 – continuous operation until present
- Fuels and materials development for the Naval Nuclear Propulsion Program, the Department of Energy, and others.

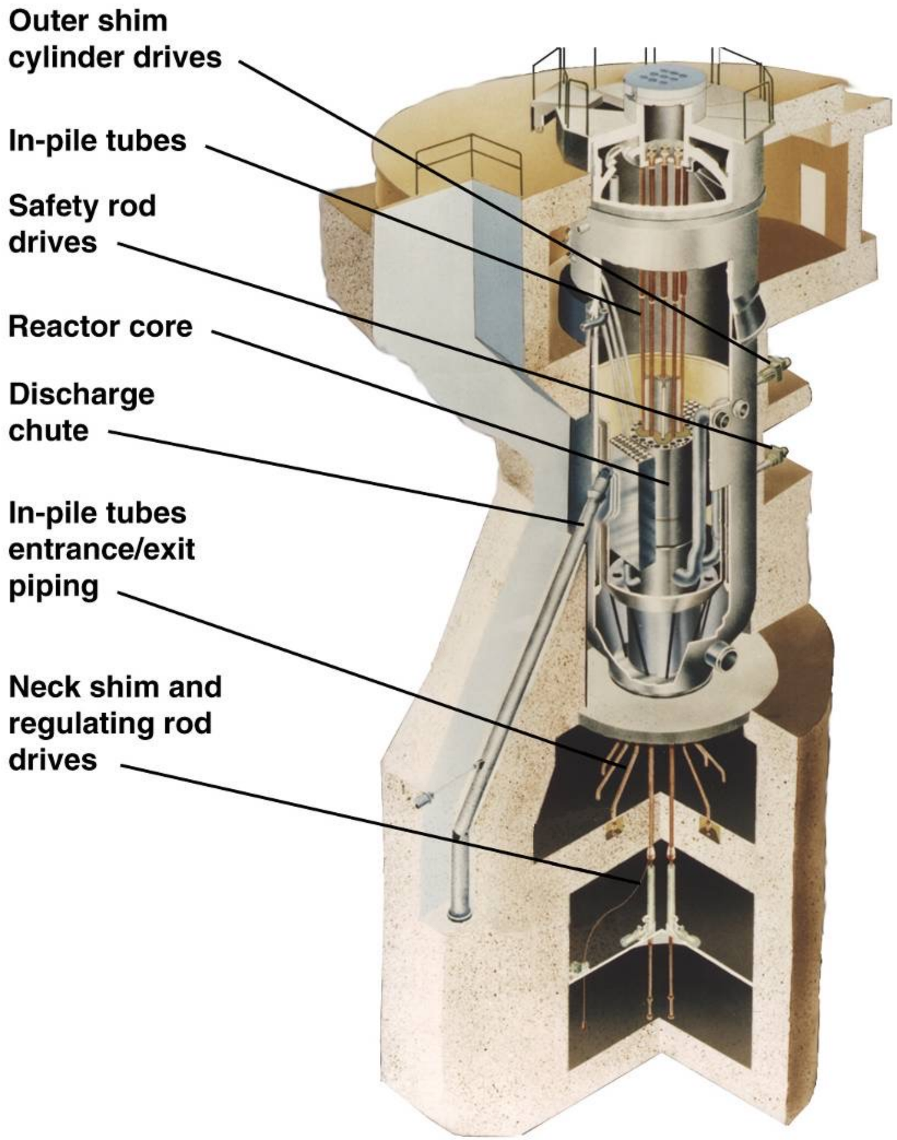
ATR Description

Reactor Type
Pressurized, light-water moderated and cooled; beryllium reflector
250MWt design

Reactor Vessel
12 ft (3.65 m) diameter cylinder,
36 ft (10.67 m) high stainless steel

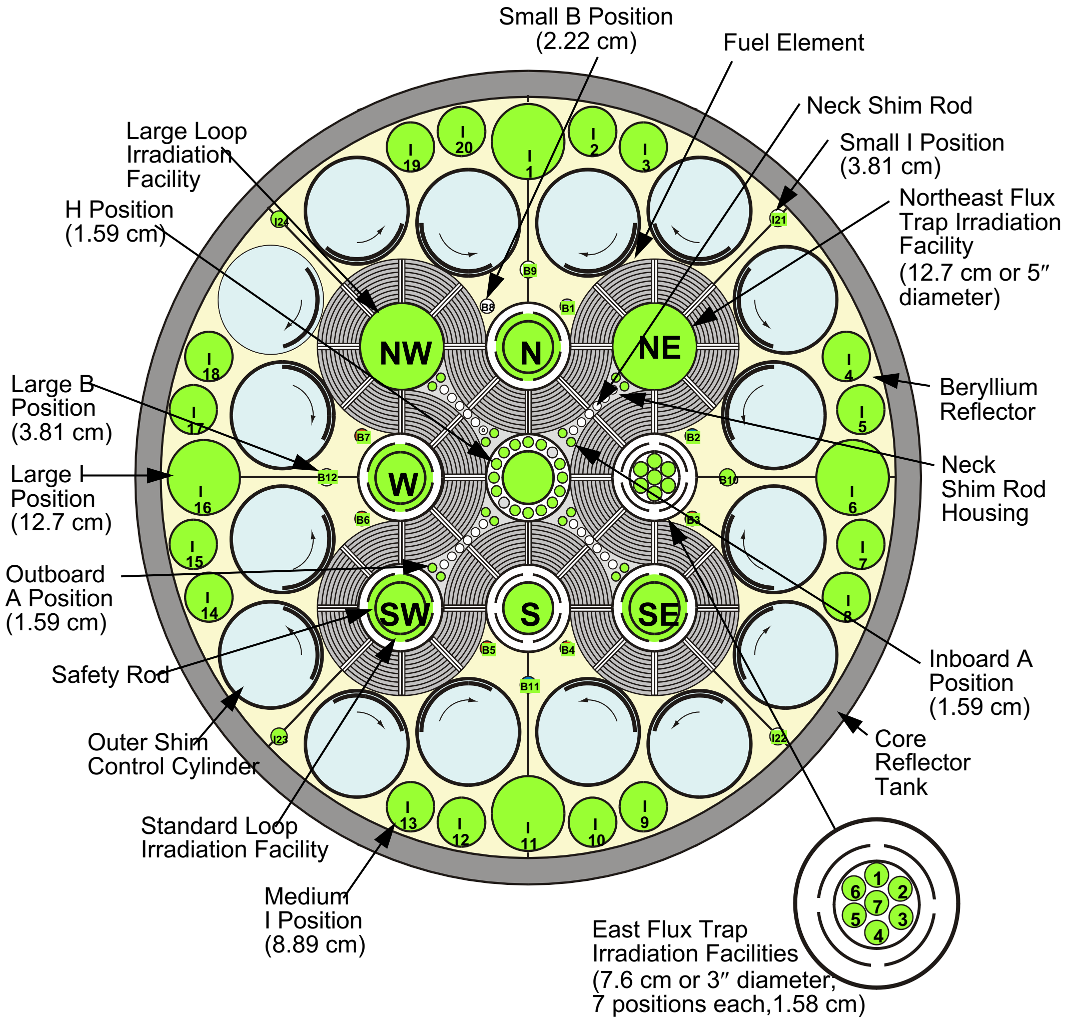
Maximum Flux, at 250 MW
1.0×10^{15} n/cm^2-sec thermal
0.5×10^{15} n/cm^2-sec fast

Reactor Core
40 fuel assemblies
U-Al plates – 19/assembly



ATR Operations

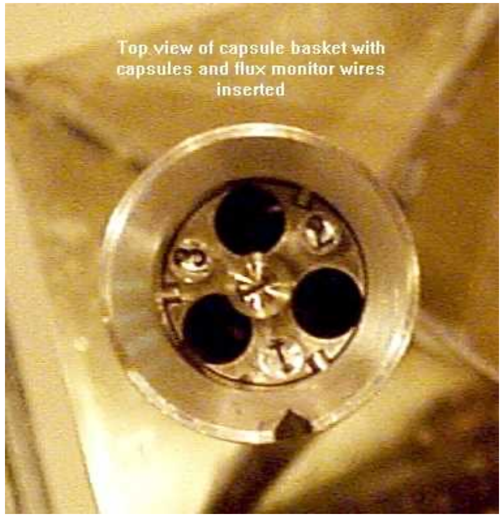
- 77 Irradiation Positions
  - 48” length, 0.5” to 5.0” diameter
- Rotating Hafnium Control Cylinders – symmetrical axial flux
- Power/Flux Adjustments (“Tilt”) across the Core – ≤3:1 ratio
- Operating Cycles
  - Standard operating cycle is 60 days
  - Occasionally short high-power cycles of 2 weeks
  - Typical reactor outages are three weeks
  - Operations for approximately 200 days per year
- Core Internals Change-out (CIC), every ~10 years



Advanced Test Reactor Irradiation Types

Simple Static Capsules

- Designed for a single temperature
- Instrumented with flux and melt wires



Instrumented Lead Experiments

- Online experiment measurements
- With or w/o temperature control

Pressurized-Water Loops

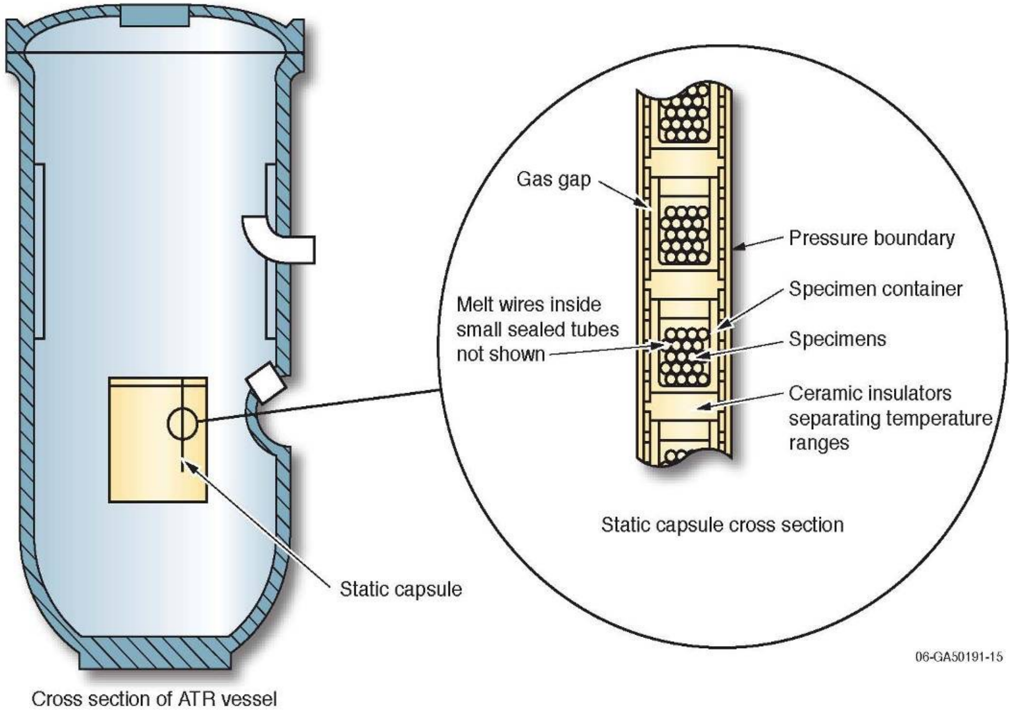
- Five loops installed in flux traps
- Control pressure, temperature, chemistry

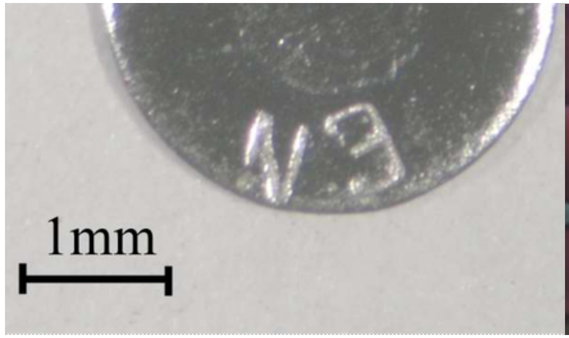
~~**Hydraulic Shuttle Irradiation System**~~

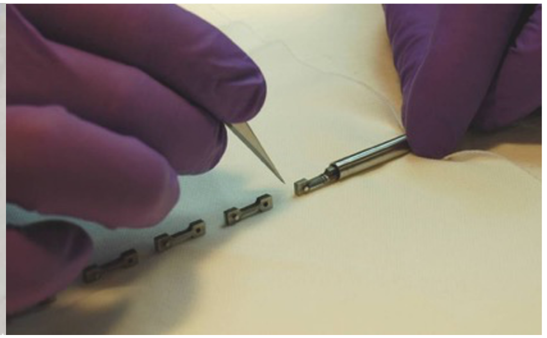
- ~~Inserted and removed during reactor ops~~

Simple Static Capsule Experiments

- Passive instrumentation (flux wires, melt wires)
- Enclosed in sealed tube, or fuel plates
- Temperature target controlled by varying gas mixture in conduction gap and with material selection
- Lengths up to 48”
- Diameter 0.5-5.0”
- Used for isotope production and fuel and material testing

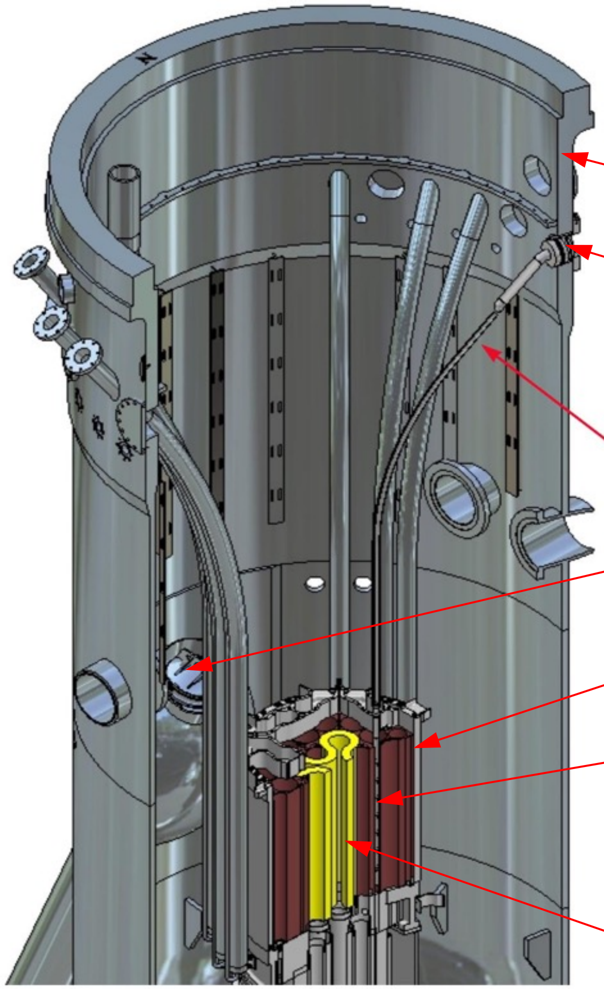






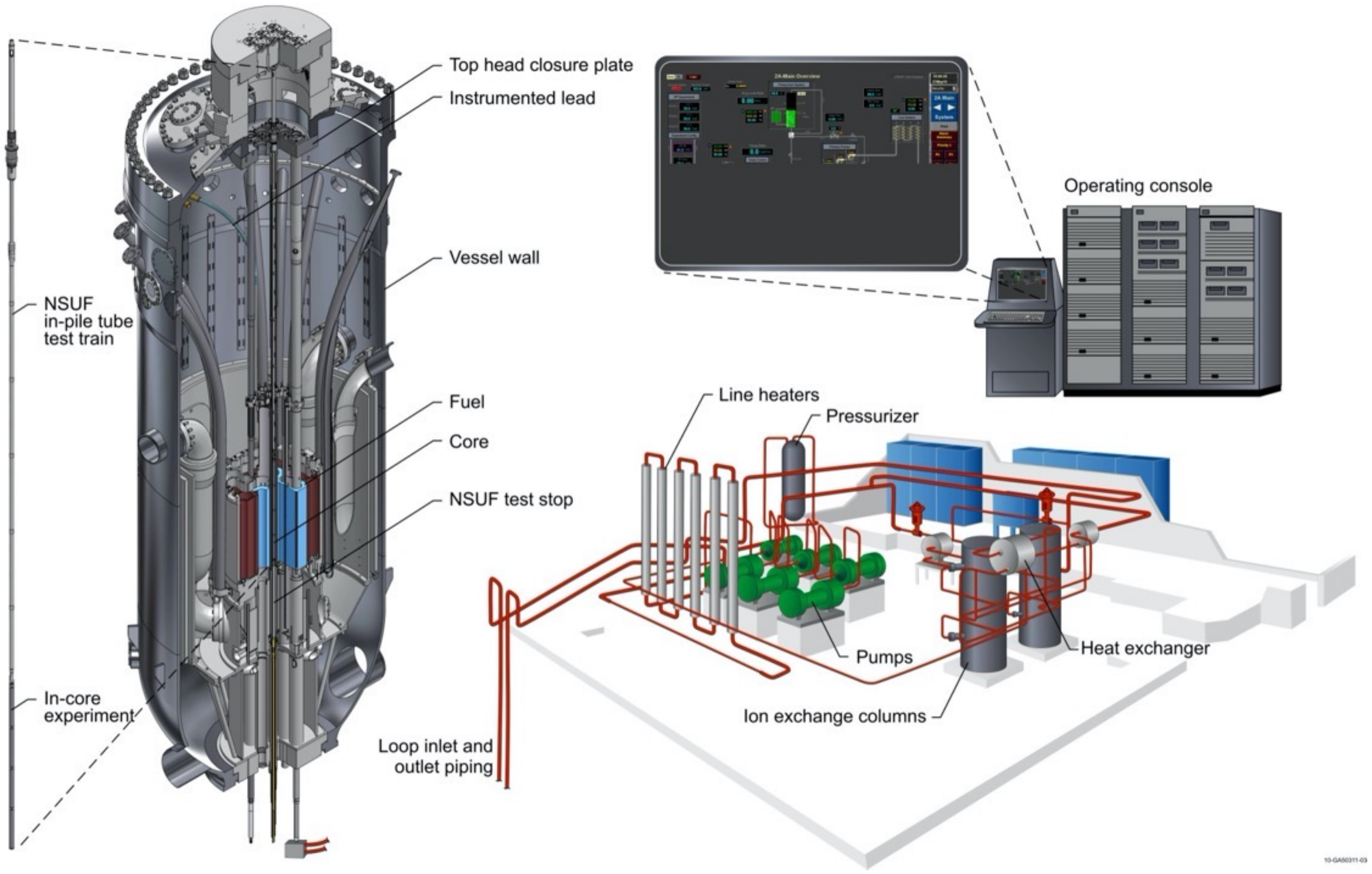
Instrumented Lead Experiments

- Online experiment measurements
- Temperature control range 250-1200°C, ±5°C
- Monitoring of temperature control exhaust gases for experiment performance (e.g., gasses, fission products, leaking materials, etc.)
- Specialized gas environments (oxidized, inert, etc.)



Pressurized-Water Loop Tests

- Six flux trap positions currently have pressurized-water in-pile loop tests (1 large diameter, 5 small diameter)
- Separate from ATR primary coolant system
- Each loop has its own temperature, pressure, flow, and chemistry control systems – can exceed current reactor operating conditions
- Transient testing capabilities (cycle/seconds)
- Potentially feasible to simulate boiling-water reactor void conditions
- 2A-Center available for experiments



INLs Other Steady-State Reactors

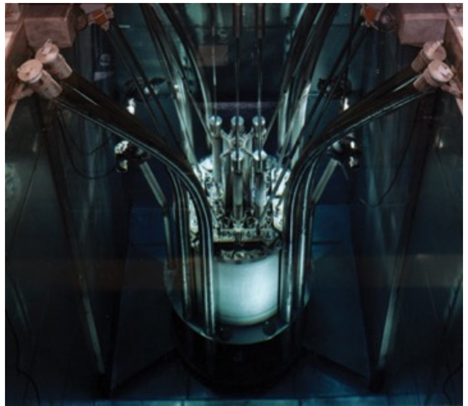
ATR Critical Facility (ATRC)

Low Power version of ATR

- Same size and geometry as ATR
- Pool reactor connected to ATR canal
- Power <5 KW, typically ~600 W
- Primarily utilized to verify ATR core change (experiments) effects
- Limited availability for other types of experiments including instrumentation testing.

Nuclear Radiography Reactor (NRAD)

- 250kW TRIGA reactor
- The reactor room is located beneath the Hot Fuel Examination Facility (HFEF) main cell.
- Two beamlines provide radiography capabilities.
- Objects can be lowered into the north beam line from a truck lock capable of handling casks and larger materials.
- A water hole provides in-core irradiation capability.



Reactor Activation and Damage Calculator

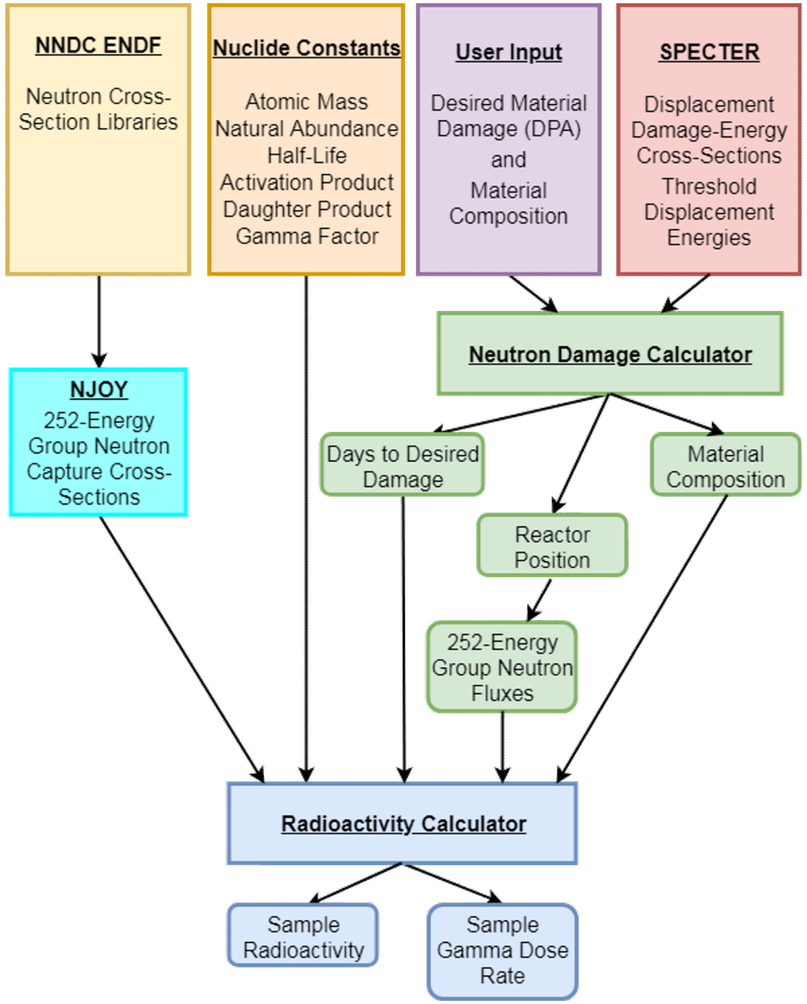
Designed to aid in selection of possible reactor positions and post-irradiation examination facilities based on nuclear constraints

1. **Neutron Damage Calculator**
   - Calculates time to reach desired DPA or amount of DPA accumulated over desired time for reactor positions available to NSUF users
2. **Radioactivity Calculator**
   - Calculates activity and gamma dose rate for chosen position 30-180 days after irradiation

Includes 83 starting elements in user-specified composition and 794 isotopes of 94 elements for activation/decay calculations

Available at the NSUF website

- https://nsuf-infrastructure.inl.gov/Calculator
- Registration is required



Graphic courtesy of KaeCee Holden

Reactor Activation & Damage Calculator

Calculation Type

DAY

Desired Days

60

Material Composition

Fe-17Cr-12Ni-3Mo-2Mn-1C-1Si

Calculate

Select	Reactor	Position	Diameter (cm)	DPA	Days	Cycles	Years	Thermal Fluence (n/cm^2)	Fast Fluence (n/cm^2)
	ATR	A1	1.6	1.656	60	1.1	0.3	3.28e+020	2.72e+020
	ATR	A13	1.6	1.469	60	1.1	0.3	2.73e+020	2.24e+020
	ATR	B1	2.2	0.718	60	1.1	0.3	2.94e+020	1.53e+020
	ATR	B9	3.8	0.212	60	1.1	0.3	1.24e+020	5.69e+019
	ATR	EFT	7.6	0.954	60	1.1	0.3	5.96e+020	4.99e+020
	ATR	I1	12.7	0.007	60	1.1	0.3	9.42e+018	3.12e+018
	ATR	I21	3.8	0.024	60	1.1	0.3	3.55e+019	3.87e+018
	ATR	I3	8.3	0.008	60	1.1	0.3	1.28e+019	2.81e+018
	ATR	I5	8.3	0.005	60	1.1	0.3	1.07e+019	1.99e+018
	HFIR	PTP	1.1	4.098	60	2.2	0.3	5.18e+021	5.70e+021
	HFIR	RB5B	4.6	0.729	60	2.2	0.3	7.68e+020	4.68e+020
	HFIR	VXF12	4	0.036	60	2.2	0.3	1.75e+020	2.19e+019
	HFIR	VXF14	7.2	0.041	60	2.2	0.3	9.01e+019	1.69e+019
	MITR	ICSA	4.1	0.308	60	1	0	1.00e+020	1.17e+021
	MITR	WATF	5.1	0.339	60	1	0	1.80e+020	1.39e+021
	PULSTAR	REP	6.4	0.007	60	12	0	3.22e+019	4.64e+018

Feedback

RAD Calculator

Calculation Type

DAY

Desired Days

60

Material Compositic

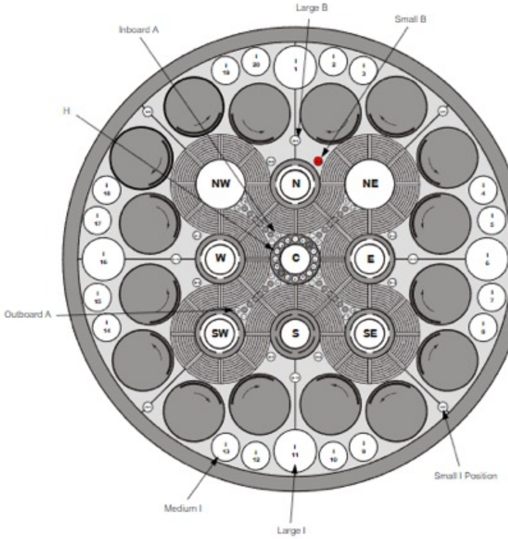
Fe-17Cr-12Ni-3

Calculate

Your sample contains **Fe-17Cr-12Ni-3Mo-2Mn-1C-1Si**

ATR

Position	B1
Diameter (cm)	2.2
DPA	0.497
Days	60
Cycle	1.1
Years	0.3
Thermal Fluence (n/cm^2)	2.94e+020
Fast Fluence (n/cm^2)	1.53e+020



After irradiation, the activity and effective gamma dose rate at 30 cm per gram of your sample is:

Duration	**Activity**		**Effective γ dose**
Days	Bq/g	Ci/g	mrem/hr/g
30	9.01E+09	0.243	97
60	4.61E+09	0.125	53.7
90	2.52E+09	0.0682	31.2
180	8.05E+08	0.0218	8.9

Select a different position

Thermal Fluence (n/cm^2)	Fast Fluence (n/cm^2)
3.28e+020	2.72e+020
2.73e+020	2.24e+020
2.94e+020	1.53e+020
1.24e+020	5.69e+019
5.96e+020	4.99e+020
9.42e+018	3.12e+018
3.55e+019	3.87e+018
1.28e+019	2.81e+018
1.07e+019	1.99e+018
5.18e+021	5.70e+021
7.68e+020	4.68e+020
1.75e+020	2.19e+019
9.01e+019	1.69e+019
1.00e+020	1.17e+021
1.80e+020	1.39e+021
3.22e+019	4.64e+018

Feedback

Idaho National Laboratory