NSUF Foundations of Irradiation Testing

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Fundamentals of Irradiation Testing

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Nuclear Science User Facilities

FIT Workshop Guidelines

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

FIT Workshop Guidelines

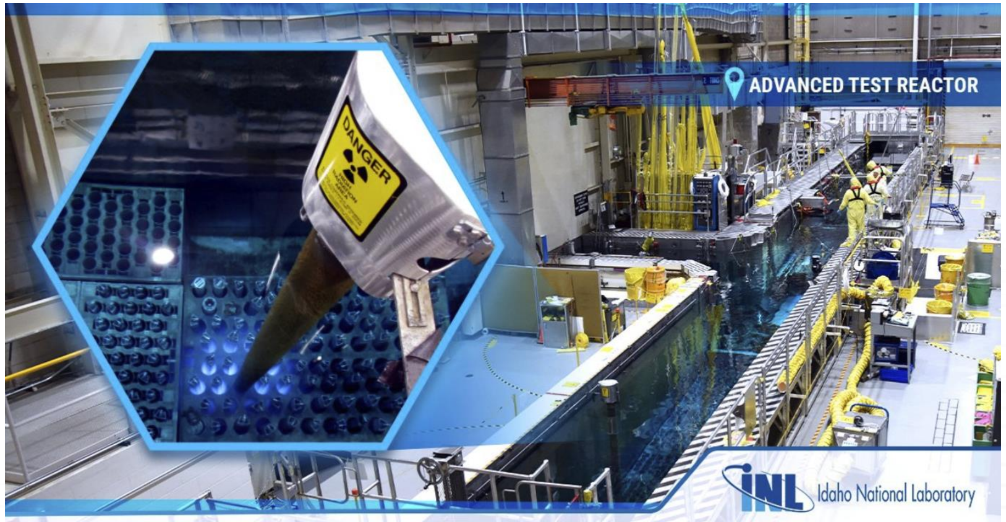
- **Camera Usage:** While it is not mandatory, we encourage you to turn your camera on during interactive portions of the workshop, such as question-and-answer sessions, to foster engagement and collaboration. However, due to the high volume of registrations, we request that cameras remain off during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

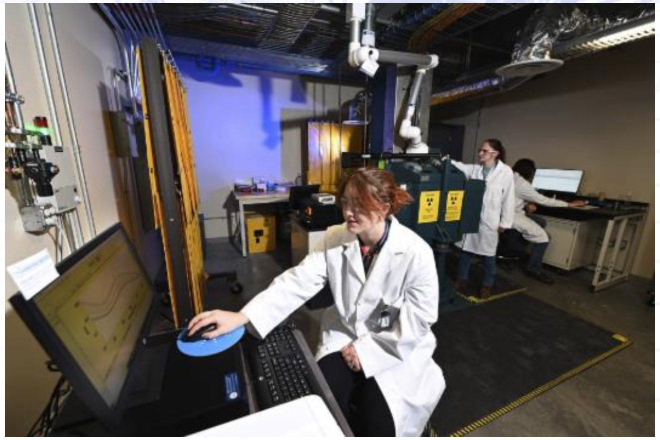
What is Irradiation Testing?

- Irradiation testing assesses how materials behave when exposed to radiation.
  - Goal of understanding how radiation interacts with materials, causing changes and damage in the microstructure that affects thermal and mechanical properties.
- In-core neutron irradiations

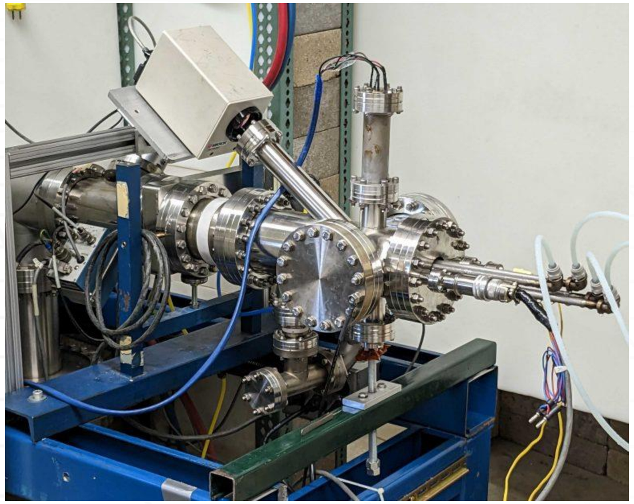
Slight Detour- Other Types of Irradiation Testing

- Gamma irradiations



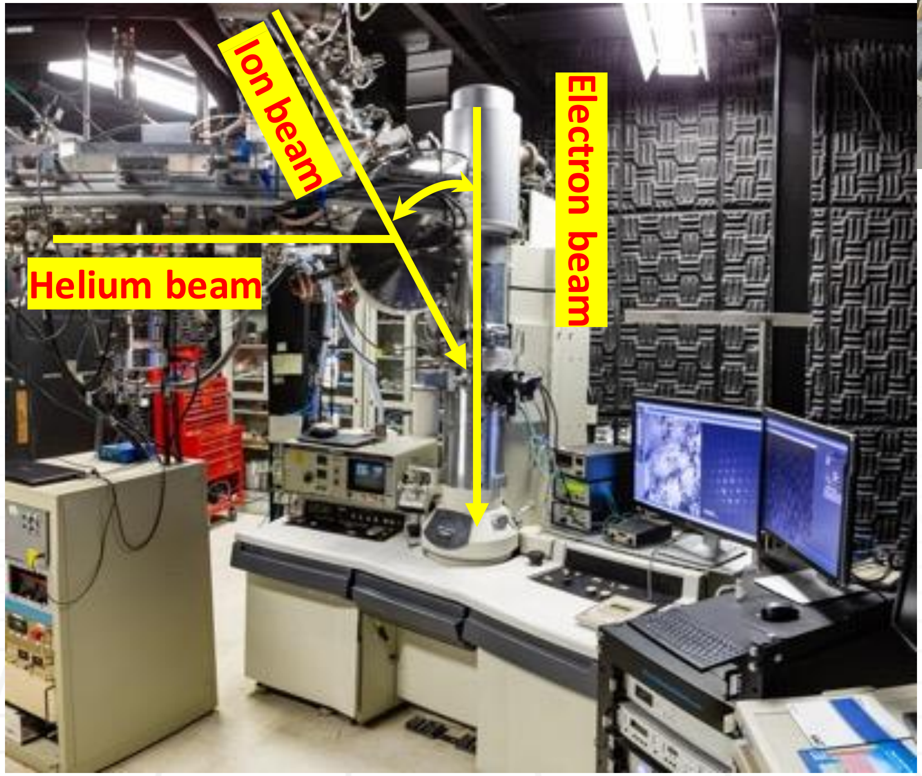


- Ion beam irradiations

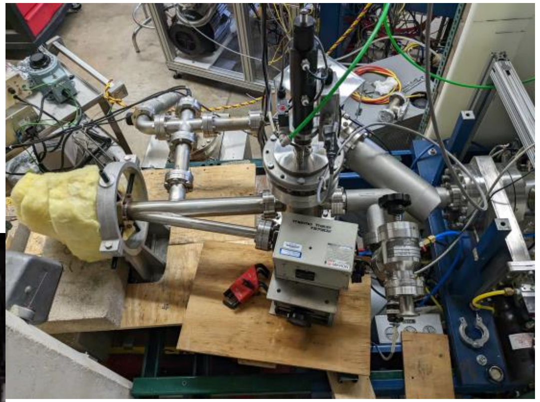


Complex Ion Beam Irradiations

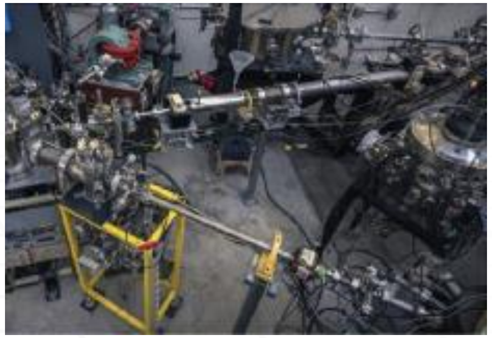
- Both heavy and light ions (electrons, protons, actinides, short-lived species)
- Multiple beams
- Controlled environments (heating and cooling, corrosion cells)
- In situ instrumentation for PIE



IVEM at ANL-In situ TEM



Triple beam (10 kV +400 kV +1.7 MV) at Texas A&M

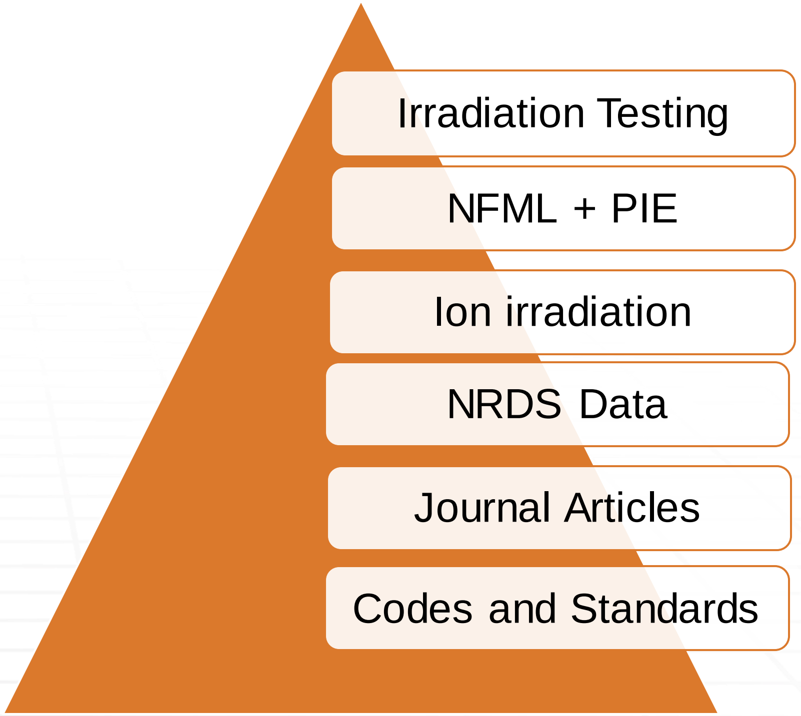


In-situ molten salt corrosion at U. Wisconsin

Right tool for the right job.

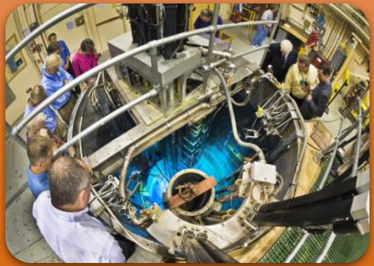
Fundamentals of Irradiation Testing (In-Core Neutrons)

- Why do we do it?
  - Difficult and expensive
  - Prototypic conditions
    - Neutron and gamma flux
    - Neutron spectrum
    - Temperature



- What do we want to know?
  - Multiple presentations-all of these damage defects determine material performance, strength, ductility, etc., and all are specific to irradiation damage.

Start from the Ending

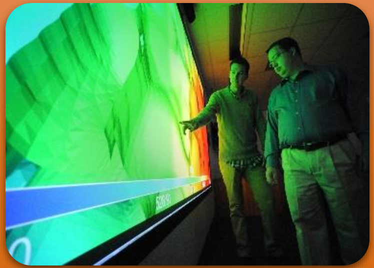


Scientific Objective

- What question am I trying to answer?
  - Testing hypothesis
  - Expand knowledge and data base
  - Inform, test, or validate microstructure model

Post Irradiation Examination (PIE)

- What measurements are needed?
- Under what conditions?
  - Determines specimen size, form, and preparation
- Determines PIE facility
- Activity at experiment completion-can the facility handle the material?



Data Needs

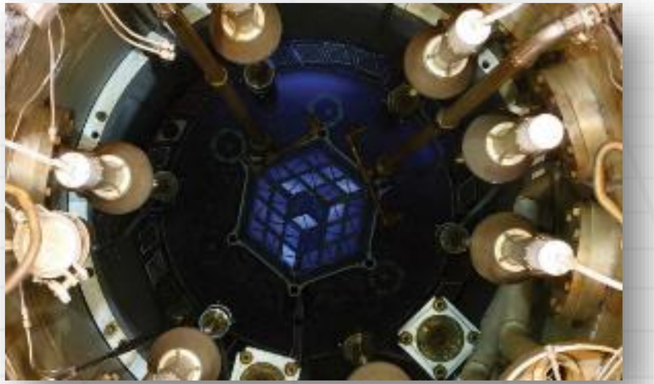
- NQA-1
- Regulatory requirements or code case
  - Determines specimen quantity
- Determine how many measurements are needed for a statistically significant result

Reactor Selection

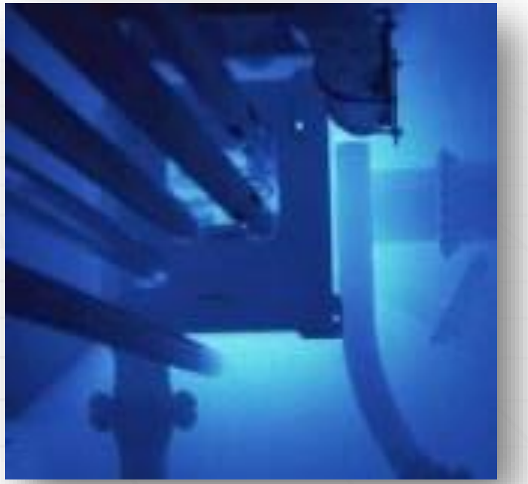
- General considerations
  - Transient or steady state
  - Neutron spectrum
  - Damage level vs. time
  - Physical size of samples
    - Micro vs. macro
  - Instrumentation
    - Passive or active
  - Temperature, average, maximum, variance
  - Environmental conditions, inert gas, Na bonding,
  - PIE, Location, Shipping
- Fuels, structural materials, instrumentation

HFIR

ATR

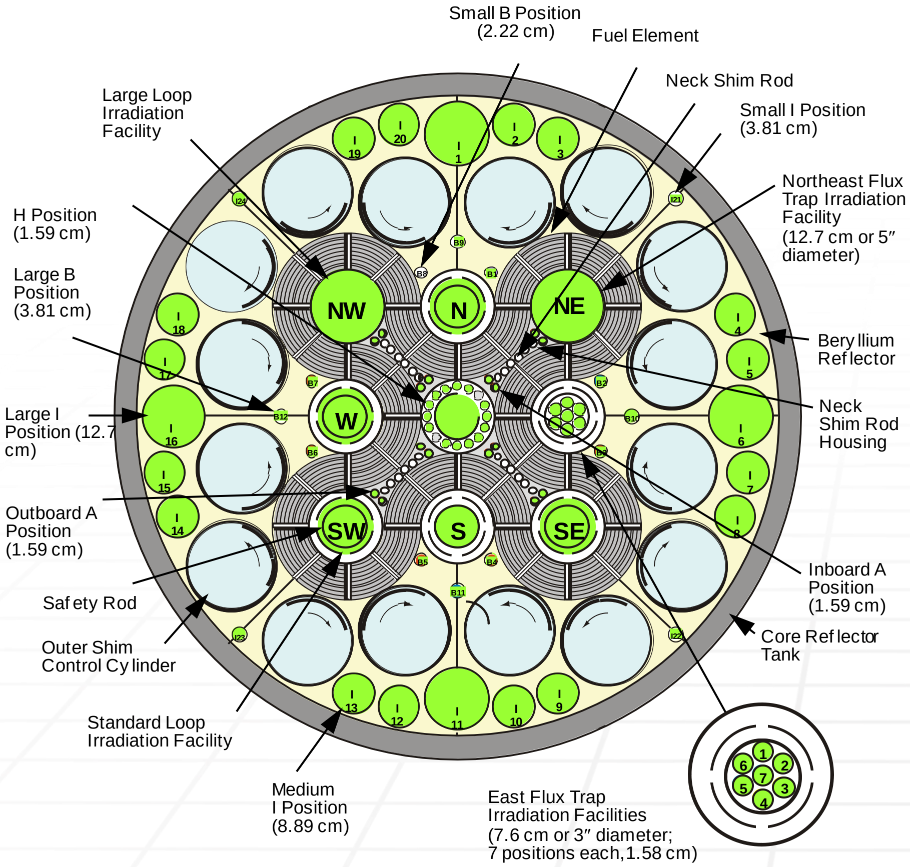


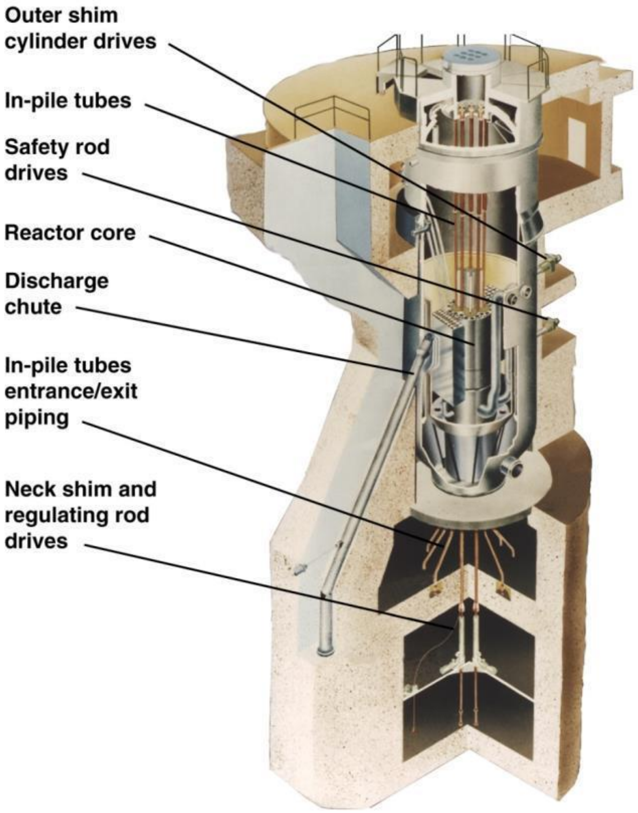
MITR



OSURR

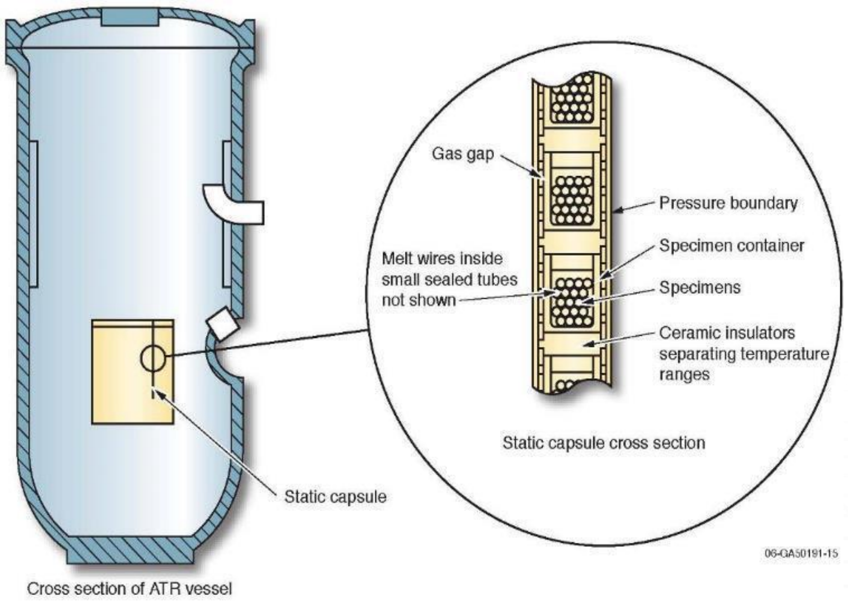
Advanced Test Reactor

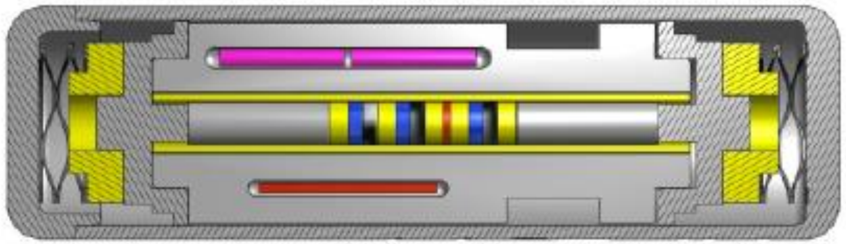




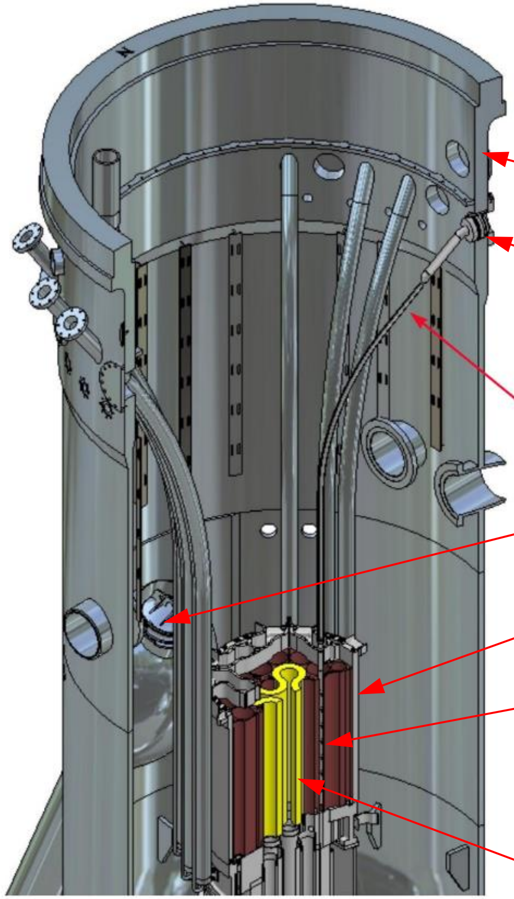
Simple Static Drop In Capsule

- Passive instrumentation (flux wires, melt wires)
- Enclosed in sealed pressure boundary
- 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 fuel and material testing



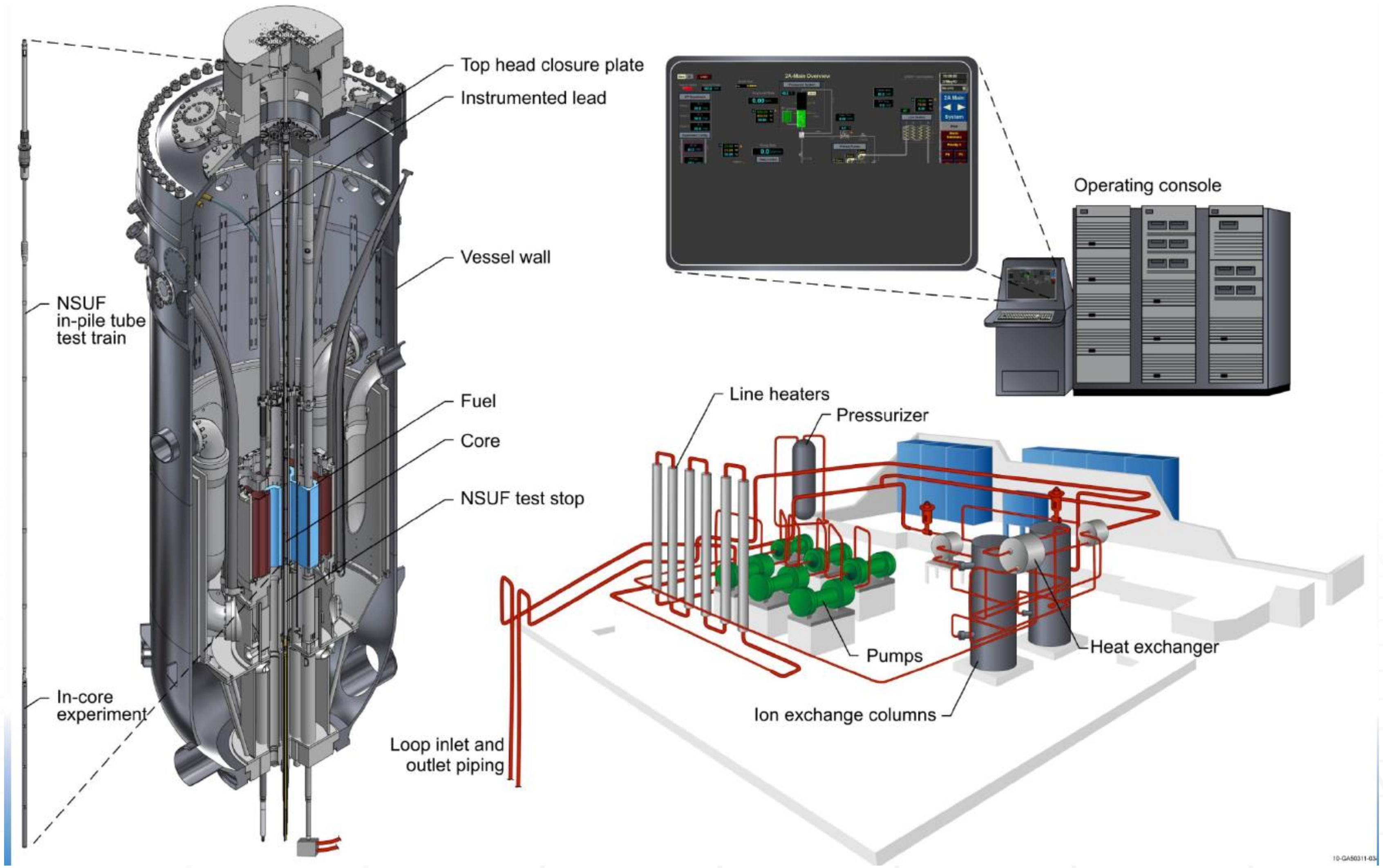


Instrumented Lead Experiments



- On-line experiment measurements
- Temperature control range 250-1200°C, within +/- 5°C
- Monitoring of temperature control exhaust gases for experiment performance (e.g., fission products, leaking materials, etc.)
- Specialized gas environments (oxidizing, inert, etc.)

PWR Loop Layout



Experiment Design and Analysis-Conceptual

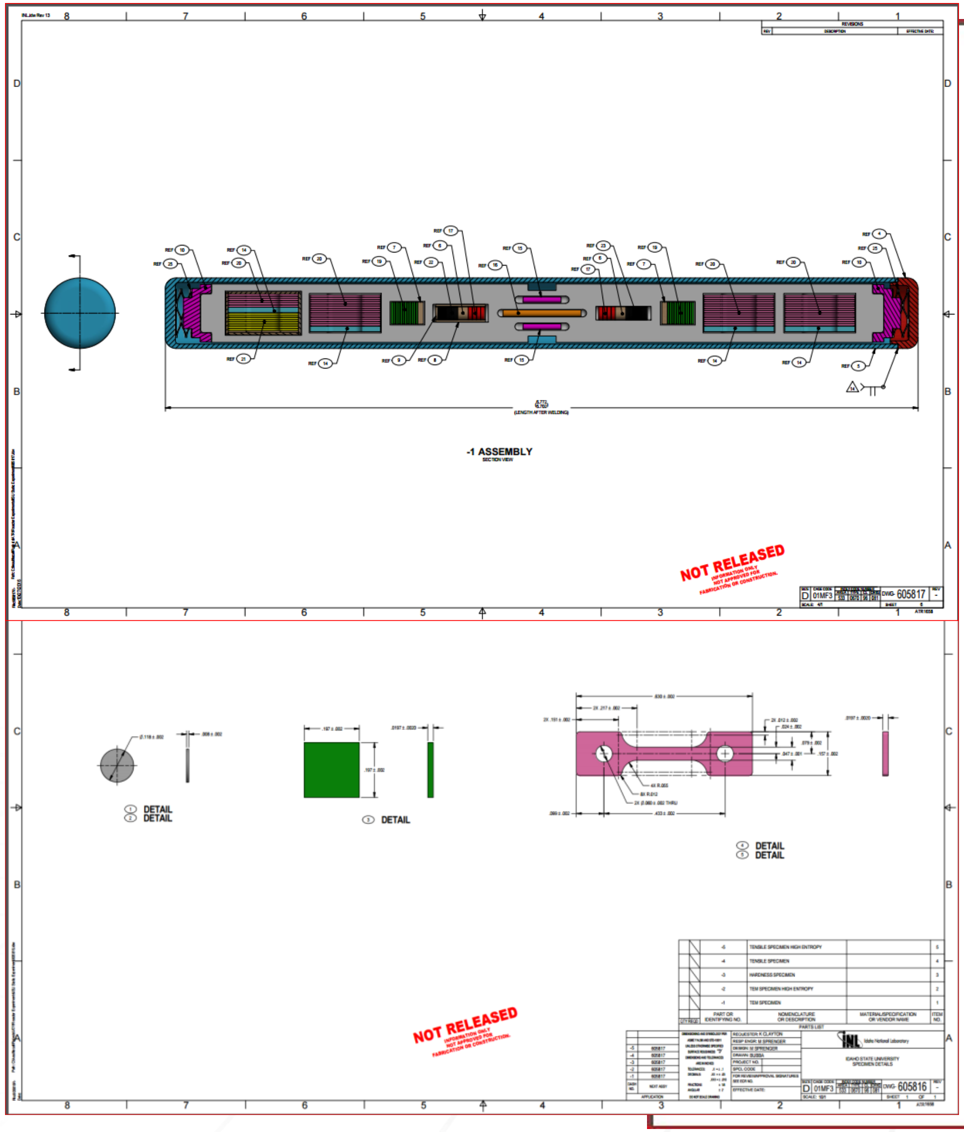
- Overall Experiment Scoping-One year prior to insertion date
  - Drop-In capsule design
  - Four capsules irradiated to a targeted range of fluence and temperature
  - Two 2-dpa capsules and two 6-dpa
  - Cycle 164A insertion
    - 2 dpa capsules removed after Cycle 166A
    - 6 dpa capsules removed at CIC
  - 504 specimens will be irradiated
    - Tensile Specimens
    - Hardness Specimens
    - TEM Specimens

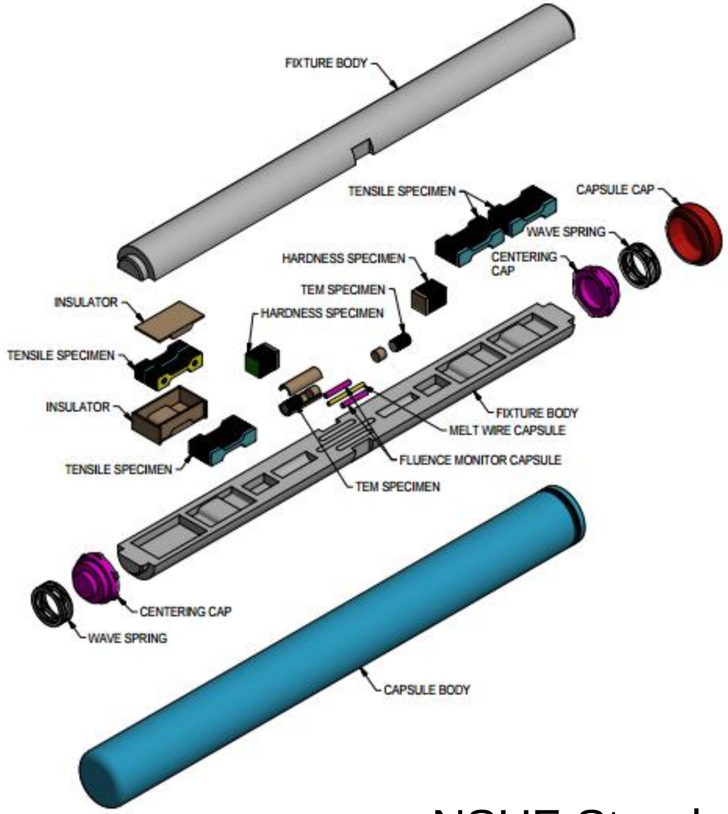
	Capsule 1	Capsule 2	Capsule 3	Capsule 4
Temperature	300°C	300°C	500°C	500°C
Dose	2 DPA	6 DPA	2 DPA	6 DPA
Tensile Specimens	56	56	56	56
Hardnes Specimens	24	24	24	24
TEM Specimens	46	46	46	46

Specimen Dimensions & Quantities

224	Tensile Specimens	16mm x 4mm x 0.5mm	.629 x .157 x .0197 in.
96	Hardness Specimens	5mm x 5mm x 0.5 mm	.197 x .197 x .020 in.
184	TEM Specimens	3mm diameter x 0.2 mm	.118 x .008 in.

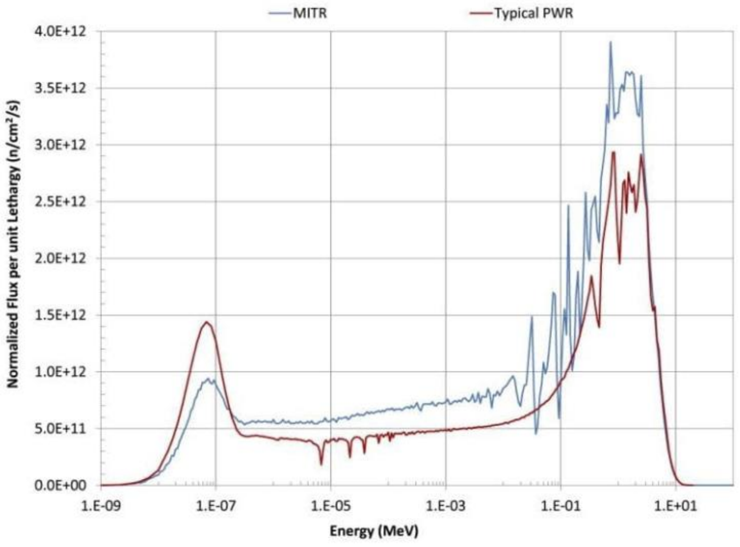
Experiment Design and Analysis-Mechanical





NSUF Standard Capsule
for drop-in, static experiments

Experiment Design and Analysis-Neutronics



Material specific Atomic Displacement Energy E_d calculated for each material given atomic composition

Every material has an E_d of ~ 40 +/- 1

Average DPA/EFPD projection

Capsule 1 -- 0.011

Capsule 2 -- 0.013

Capsule 4 -- 0.013

Capsule 3 -- 0.012

- Starting from known neutron spectrum, model the mechanical design in MCNP to produce expected fluence and damage for every specimen

170 EFPD to 166A – 414 EFPD to CIC

ATR Cycles 170A and 171 projected to run 35 EFPD.

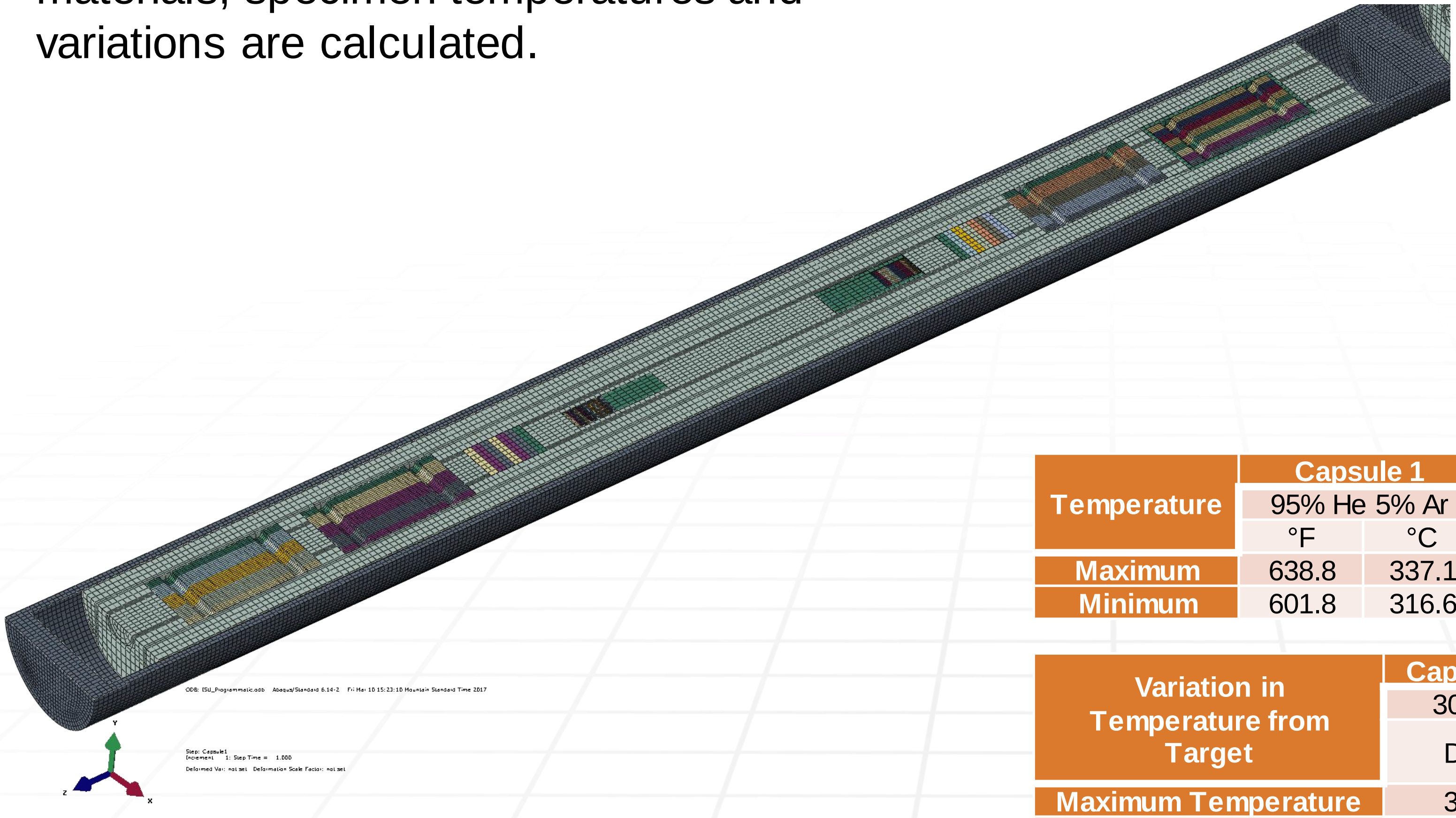
Capsules 2 and 4 projected to be within 1 cycle of reaching 6 DPA by CIC

Heat Generation Rate (HGR)

		Capsule 4	
Location	#	Materials	HGR (W/cc)
Tensile (1)	2	HE Material 5	95.9
	2	HE Material 6	
	2	HE Material 7	
	2	HE Material 9	
	6	SS 316	46.6
Tensile (2)	12	F/M Grade 91	43.4
	2	SS316	42.2
Tensile (3)	12	SS304	44.0
	2	SS316	41.2
Tensile (4)	12	Kanthal D FeCrAl	41.1
	2	SS316	42.9
Hardness (1)	6	F/M Grade 91	43.0
	6	Kanthal D FeCrAl	39.5
Hardness (2)	6	SS304	42.6
	6	SS316	44.2
TEM (1)	4	HE Material 5	74.8
	4	HE Material 6	
	4	HE Material 7	
	2	HE Material 8	
	2	HE Material 9	
	2	HE Material 10	
	2	HE Material 11	
	2	HE Material 12	
TEM (2)	6	F/M Grade91	40.3
	6	Kanthal D FeCrAl	38.1
	6	SS304	43.2
	6	SS316	42.9
Tensile Shroud		SiC	21.9
TEM Shroud		SiC	20.2
Zirc Shroud		Zirc-4	48.1
Capsule		SS316	54.9

Experiment Design and Analysis-Thermal

- Using results for HGR for the materials, specimen temperatures and variations are calculated.



Sensitivity Analysis

Specimen Tolerance
- Minimum Tolerance and not contacting holder
- +4°C

Coolant Temperature
- Increase from 125°F to a maximum (from safety analysis) of 138°F
- +4.9°C

High Entropy Conductivity
- Values relatively unknown
- Negligible impact on results

Gap Between the holder and capsule
- Increased by 0.001 inches
- +9.3°C

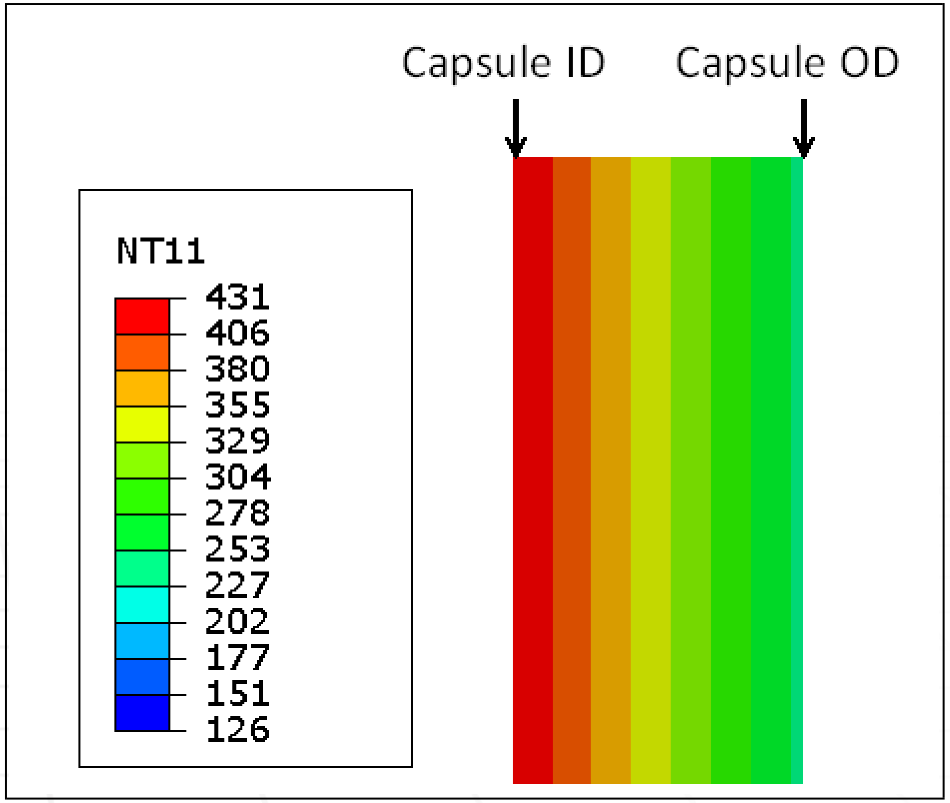
Temperature	Capsule 1		Capsule 2		Capsule 3		Capsule 4	
	95% He 5% Ar		100% He		75% He 25% Ar		65% He 35% Ar	
	°F	°C	°F	°C	°F	°C	°F	°C
Maximum	638.8	337.1	654.7	345.9	944.7	507.1	970.8	521.6
Minimum	601.8	316.6	613.6	323.1	899.1	481.7	913.3	489.6

Variation in Temperature from Target	Capsule 1	Capsule 2	Capsule 3	Capsule 4
	300°C	300°C	500°C	500°C
	D°C	D°C	D°C	D°C
Maximum Temperature	37.1	45.9	7.1	21.6
Minimum Temperature	16.6	23.1	-18.3	-10.4
Range	20.5	22.8	25.4	32.0

Experiment Design and Analysis-Structural and Safety

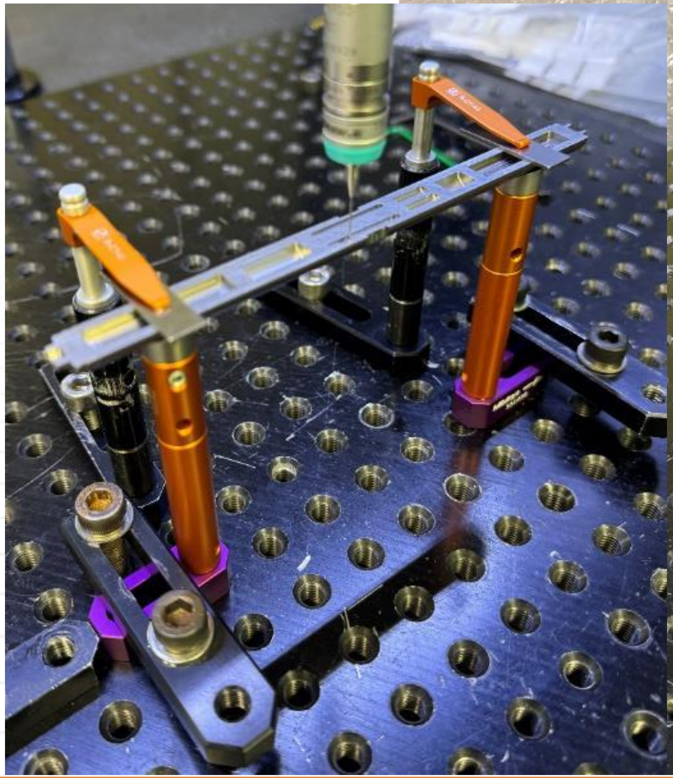
- External Design Pressure Calculations
  - Maximum Capsule Length – 48 in.
  - Min Wall Calculation – 0.027 in.
    - 485 psig > 468 psig (Service Level C)
- Internal Design Pressure Calculations
  - 235 psig Internal – 0 psig External
    - Min. Wall – 0.006 in.
- Axial Compression due to External Pressure
  - Design Factor = $\frac{Allowable\ Stress}{Calculated\ Stress}$ = 3.8
- Thermal Stress
  - ASME Section III Class 1 Methods
    - Evaluated at Flow Coast Down Conditions
    - Wall Thickness – 0.040 in. (Max)
    - Design Factor – 1.35

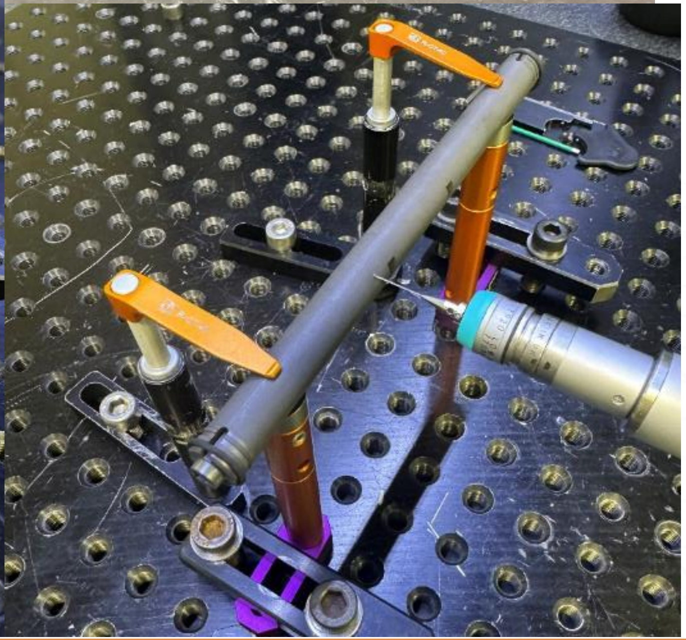
Thermal Stress Evaluation



Fabrication and Assembly

- Capsule hardware fabrication
- Specimen fabrication and marking
- Instrumentation
- Weld development
- Weld qualification
- Assembly
- Capsule ready for reactor insertion

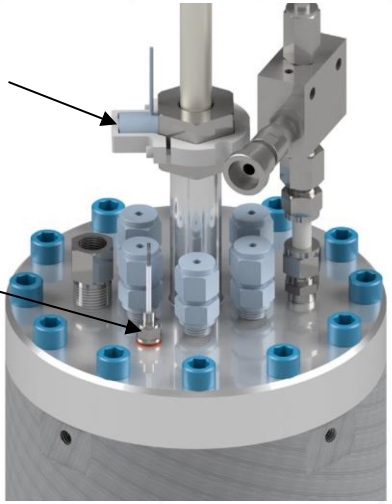


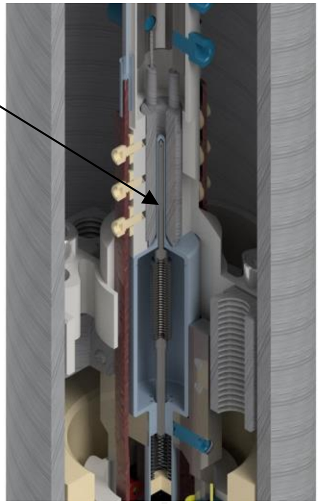


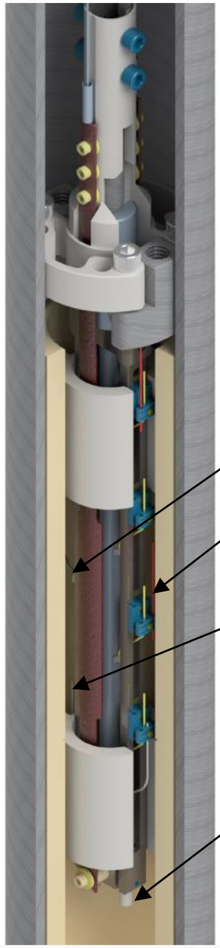
Complex Designs-Transient Water Irradiation System for TREAT (TWIST)

- Simulates Loss of Coolant Accident (LOCA) for LWR conditions

- Instrumentation
  - 6-10 thermocouples measure cladding, water, fuel centerline temperature
  - Pressure transducer for capsule pressure
  - Optical Pyrometer for cladding temperature
  - Fiber optic pressure sensors
  - Boiling detector plates for phase change
  - Acoustic emission for rupture detection







Irradiation and PIE

- At least a year of design and fabrication
- Multi-year irradiations possible
- Cooling, shipping, hot cell disassembly
- PIE campaign can take multiple years

HFEF Hot Cell at INL

BRR cask for shipping

Best practices and lessons learned

- Plan and design from the desired end result
  - Define the final data needed to test hypothesis
- Standard designs
  - Time and cost savings
  - Example used (NSUF Standard Capsule) has been re-used 6 times
- Test everything
  - The specimen material is not what you think it is
  - The specimen material will not remain what it was
- Patience, patience, patience