Irradiation Experiment Design

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ATR NSUF Experimenter Course
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Drop-In Capsule Overview

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Advanced Test Reactor (ATR)

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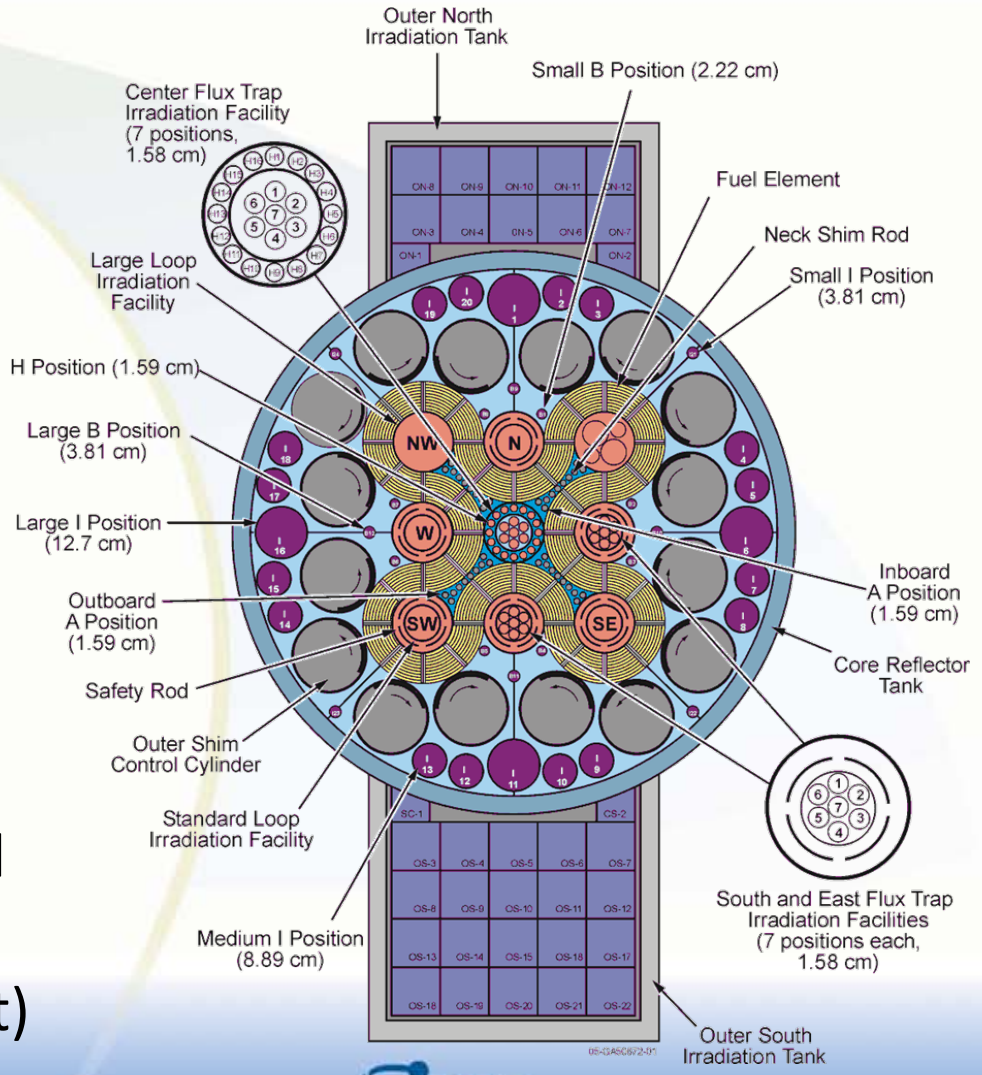
- Test size: up to 5.0 in. OD
- 77 Irradiation Positions
  - 4 Flux Traps
  - 5 In-pile tubes
  - 68 in Reflector
- Approximate Peak Flux
  - 1×10^{15} n/cm^2·sec thermal
  - 5×10^{14} n/cm^2·sec fast
- Rotating Hafnium Control Cylinders – symmetrical axial flux
- Power/Flux Adjustments (Tilt) across the Core



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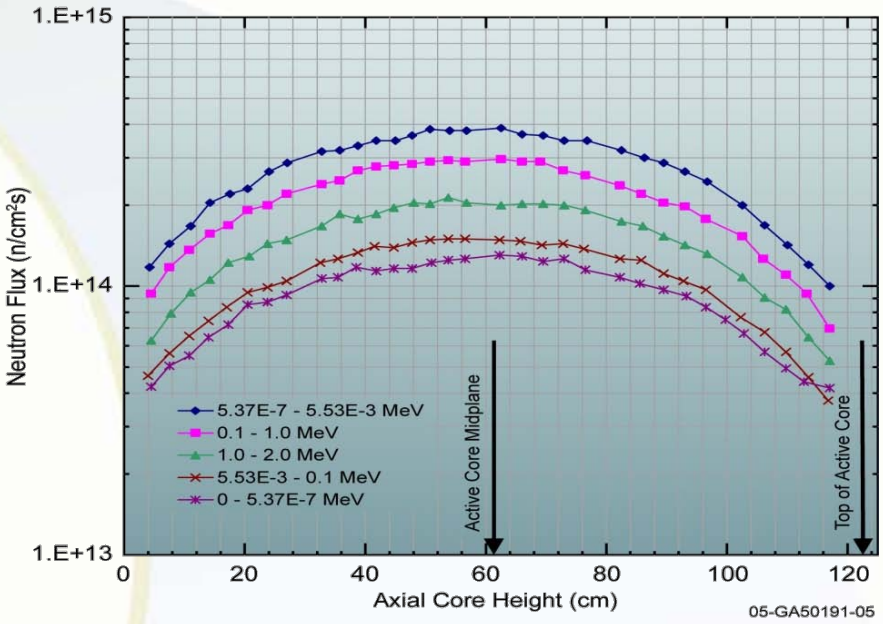
ATR Unique Design Features

- Combination of high flux and large test volumes
- Symmetrical axial power profile
- Power tilt capability between all four corners of core (<3:1 ratio)
- Individual experiment parameter control for multiple tests in a single irradiation position
- Individual experiment control in separate loops
- Accelerated testing for fuels – up to 20× actual operation time for some fuel types
- No design limited lifetime: expected to operate for many more years
  - CIC outages – new reactor internals
  - Large stainless steel reactor vessel – minimal embrittlement

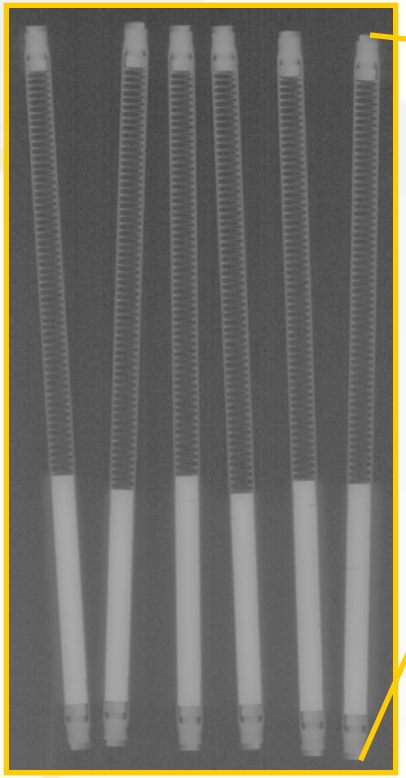


Center Flux Trap Flux Profile (125 MW)

Drop-In (Static) Capsule

- Simplest, quickest, and lowest cost design
- No active control or online data
- Passive instrumentation (flux or melt wires) can be used
- Gas gaps / gas fills used to tailor temperature
- Used by Fuel Cycle Research & Development program (fuels and materials)

Completed Rodlets



Capsule Assembly

Hydraulic Shuttle Irradiation System

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aka Rabbit

- 14 shuttle capsules in train, simultaneously irradiated
- Payload ~ 25 gm/capsule
- ^{235}U mass limit: 0.020 gm/capsule, 0.100 gm/train
- Flux (at 100 MW_t)
  - Thermal = 2.5×10^{14} n/cm^2-s
  - Fast (> 1MeV) = 8.1×10^{13} n/cm^2-s
- Gamma Heating: 4.2 W/gm for SST
- Dimensions (approximate)
  - 0.55 in. (1.4 cm) inner diameter
  - 2.0 in. (5.1 cm) inner height
  - 0.48 in.^{3} (7.8 cm^3) inner volume
- Irradiation Duration
  - 10s sec – few weeks
- Shuttle Wall Temperature
  - ~ 180°F to 240°F (~ 82°C to 115°C)
- Maximum Internal Pressure
  - < 215 psig (1.48 MPa)

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Experiment Design Considerations

Experiment Design Considerations

- Sample Material, Size, and Geometry
  - finite test volume
  - potential materials interaction
  - sample preparation for PIE (handling, labeling/identification)
  - sample positioning and experiment handling
    (your experiment will be turned upside down!)
- Capsule Size and Geometry
  - gap size & gas composition for tailored temperatures
  - independent capsules require increased volume (hardware, plenum)
- Irradiation Position – geometry, experiment size, flux
- Flux Modifications – filters (Cd basket), booster fuel
- Long-lead vs. Off-the-shelf Components
  - small irradiation positions may require small/custom parts
- Passive Measurements – flux wires, melt wires, temperature monitors

Sample Materials

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U Illinois

Model Alloys			Commercial Alloys
Fe Fe-14Cr Fe-19C	Fe-9Cr Fe-9Cr-0.1C Fe-9Cr-0.5C	Fe-12Cr Fe-12Cr-0.1C Fe-12Cr-0.5C	T91 HT-9
			Developmental Alloy MA-957

TEM, Tensile

U Wisconsin

Ferritic-Martensitic Steels HT-9 T91 HCM12A, HCM12A TMP NF616 9Cr ODS 800H, 800H-TMP 9Cr Model Alloy 12Cr Model Alloy	Austenitic Steels HT-UPS-AX-6 D9 NF709 Super 304H
	Refractory Alloys and Silver Mo-ODS W Ag
Ceramics MgO-ZrO_2 SiC	Amorphous Metals Fe-B compounds (5)

TEM, Tensile (528 total samples + 8 SiC monitors)

UCSB

Tempered-Martensitic Steels T91 HT-9 NF616 F82H-IEA F82H-mod3 F82H-1.4Ni Eurofer 97	Nano-Structured Ferritic Alloys MA-956 MA-957 PM2000 9Cr2WYT 14CrYWT 15Cr2WYT
Stainless Steels Cast SS 316 SS	Model Alloys Pure Fe Fe-3Cr, Fe-6Cr, Fe-9Cr Fe-12Cr, Fe-15Cr, Fe-18Cr MAR

Disc Multi-Purpose Coupons, Diffusion Multiples, Tensile, Disc Compact Tension, Fracture, Deformation and Fracture Minibeams, Chevron Notch Wedge, SiC monitors

U Florida

MgO $MgO{\cdot}1.5Al_2O_3$ $MgAl_2O_4$	$Nd_2Zr_2O_7$ $0.7MgO$-$0.3Nd_2Zr_2O_7$ Mg_2SnO_4

Diffusivity, TEM

NCSU

Plain Carbon Steel regular ultrafine-grained	Pure Cu Pure Ni MA-956 MA-957

TEM, Tensile, Hardness

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Example Samples

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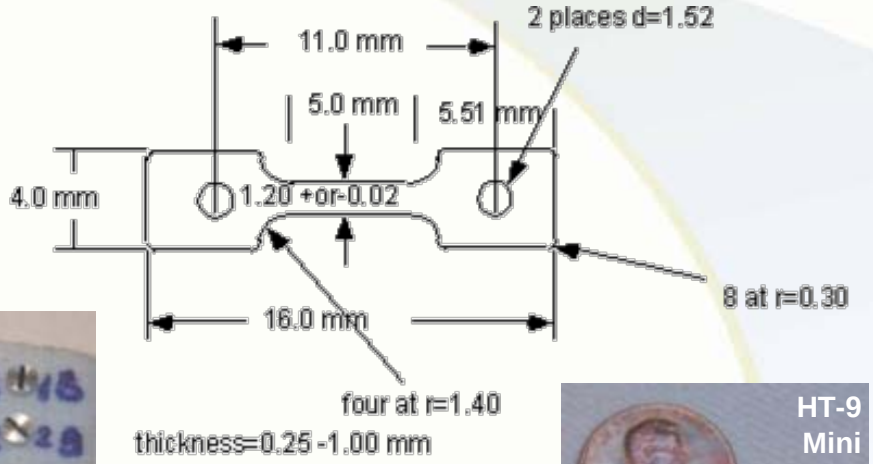
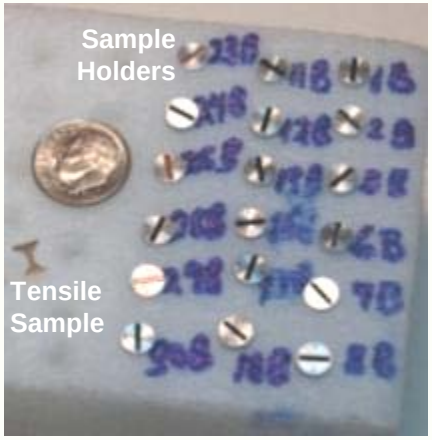
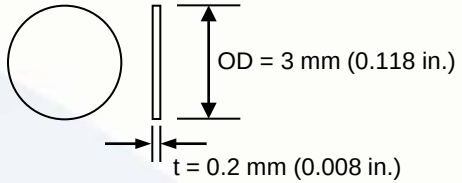
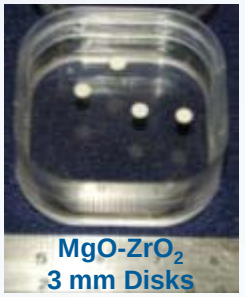
Mini-tensile



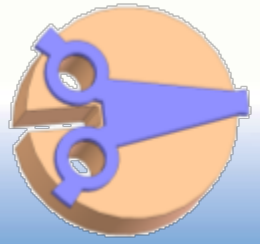


TEM Disk





Compact Tension



Larger disks (6 mm) used for diffusivity measurements

Thicker disks used for shear punch and hardness testing

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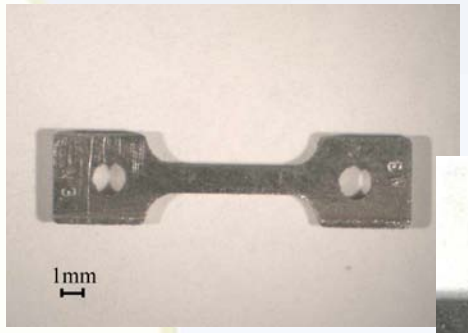
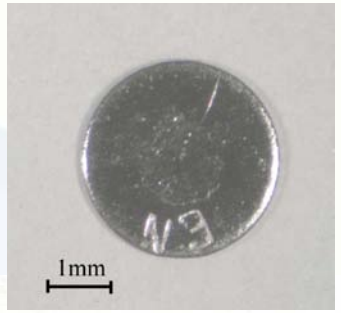
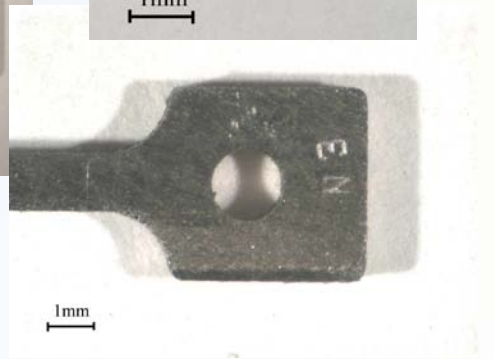
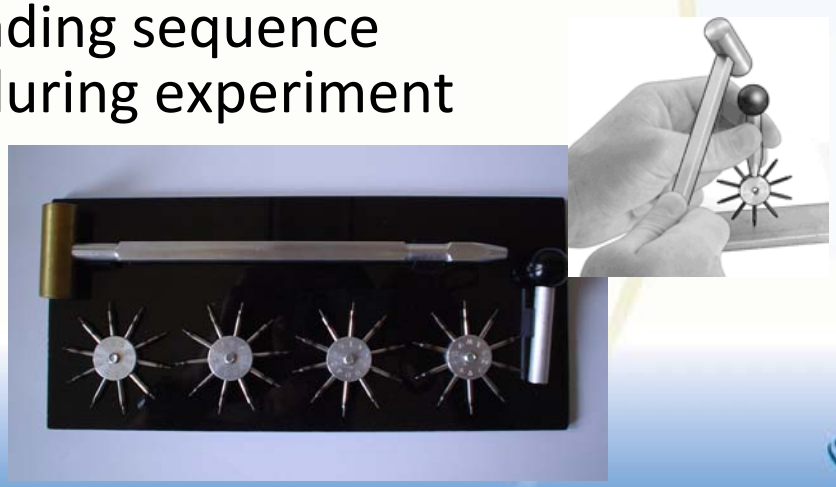
Sample Preparation and Marking

- Consider PIE preparation during experiment design
- Evaluate potential material interaction
- Label samples with unique ID
  - Mini-punch set to mark samples
- Sample loading sequence recorded during experiment assembly





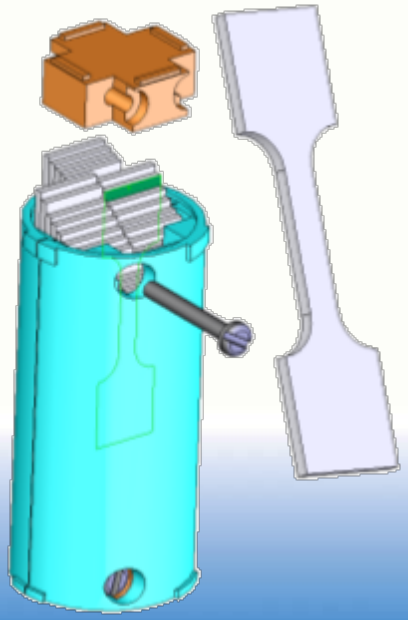


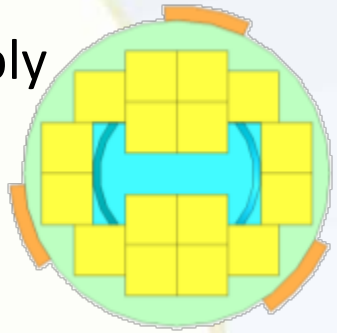


Sample Configurations / Holders

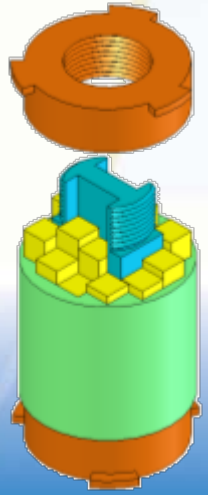
- Considerations
  - Thermal – maximize or minimize heat transfer
  - Positioning / centering
  - Ease of assembly / disassembly
  - Irradiation / thermal effects

UCSB Tensile

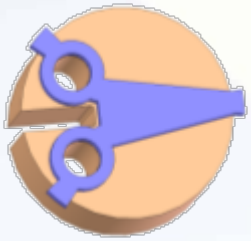


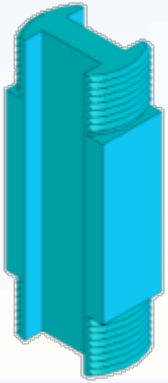


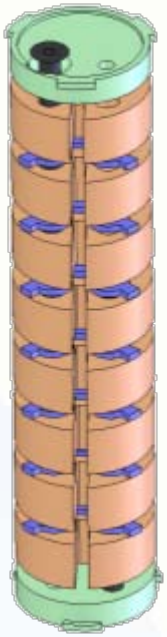
UCSB Sample Holder



UCSB Compact Tension







Sample Holders

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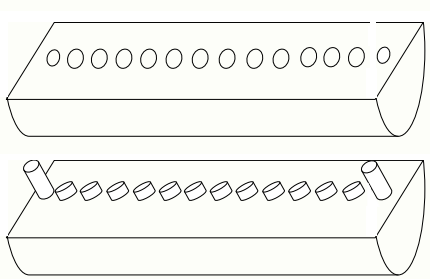
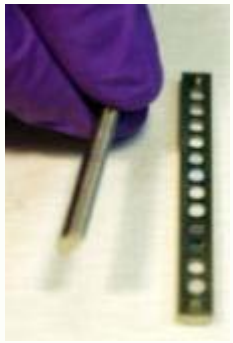
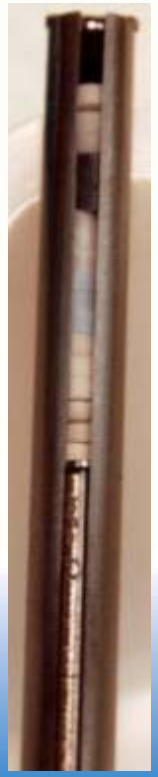
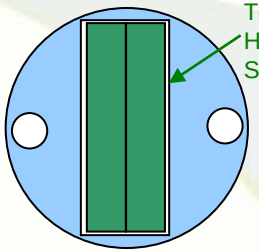
U Florida TEM & Small Disk Holder

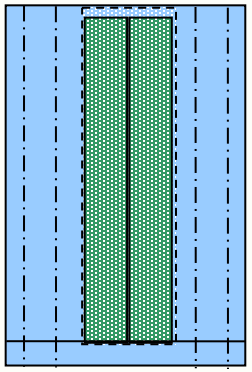




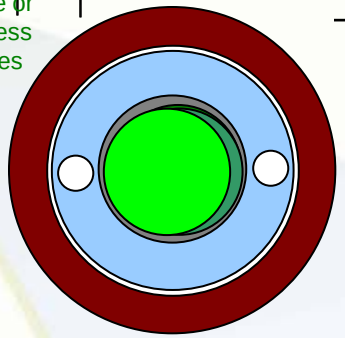


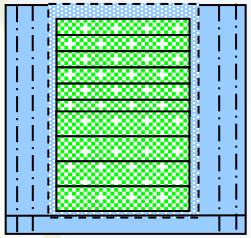
NCSU Tensile Holder





NCSU TEM Holder and Outer Tube

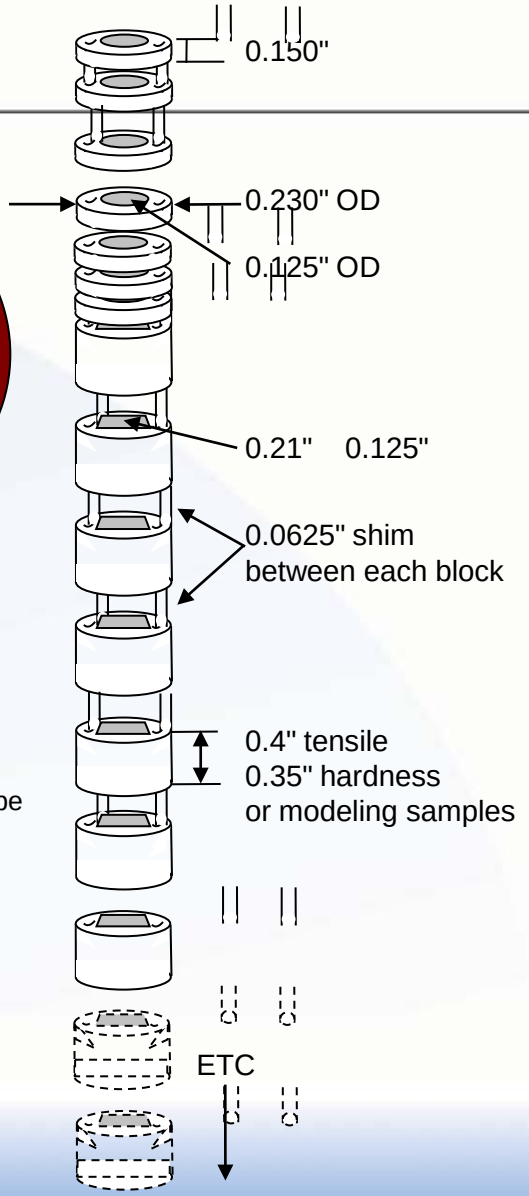




Stainless Steel Outer Tube
OD = 0.354 in. (9 mm)
ID = 0.234 in. (5.9 mm)

NCSU Sample Stack

NCSU Sample Stack



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Sample Configurations / Holders

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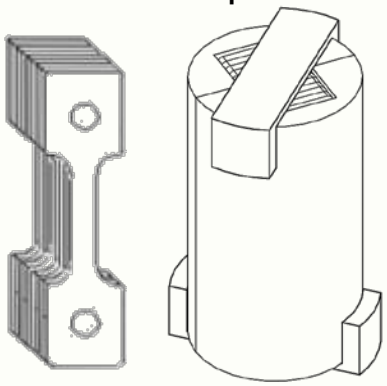
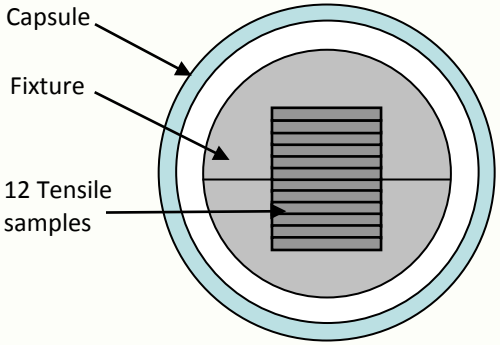
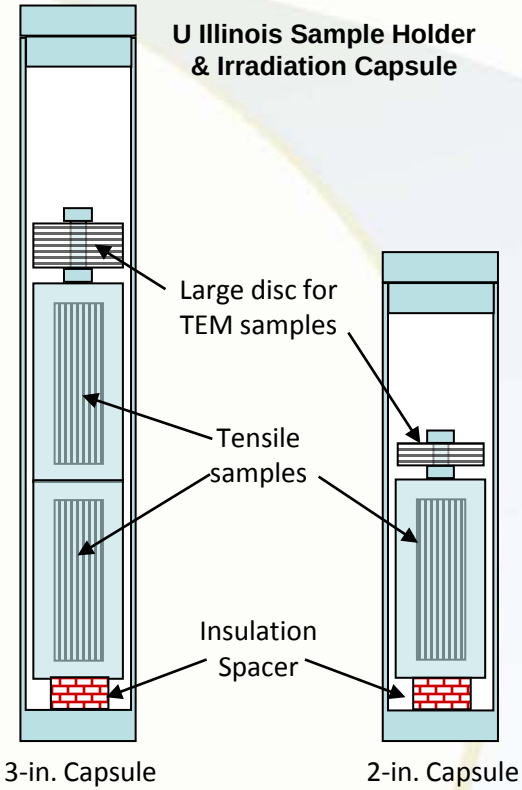
U Illinois Tensile Holder & Irradiation Capsule

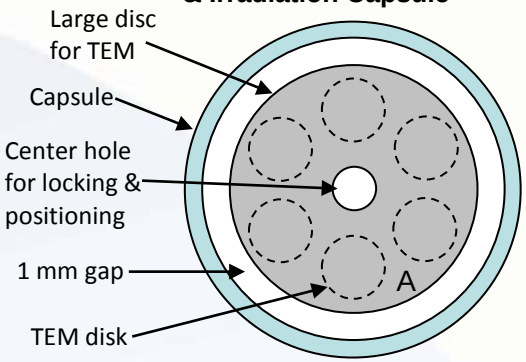




U Illinois Sample Holder & Irradiation Capsule



U Illinois TEM Holder & Irradiation Capsule



UW TEM Disk Fixtures

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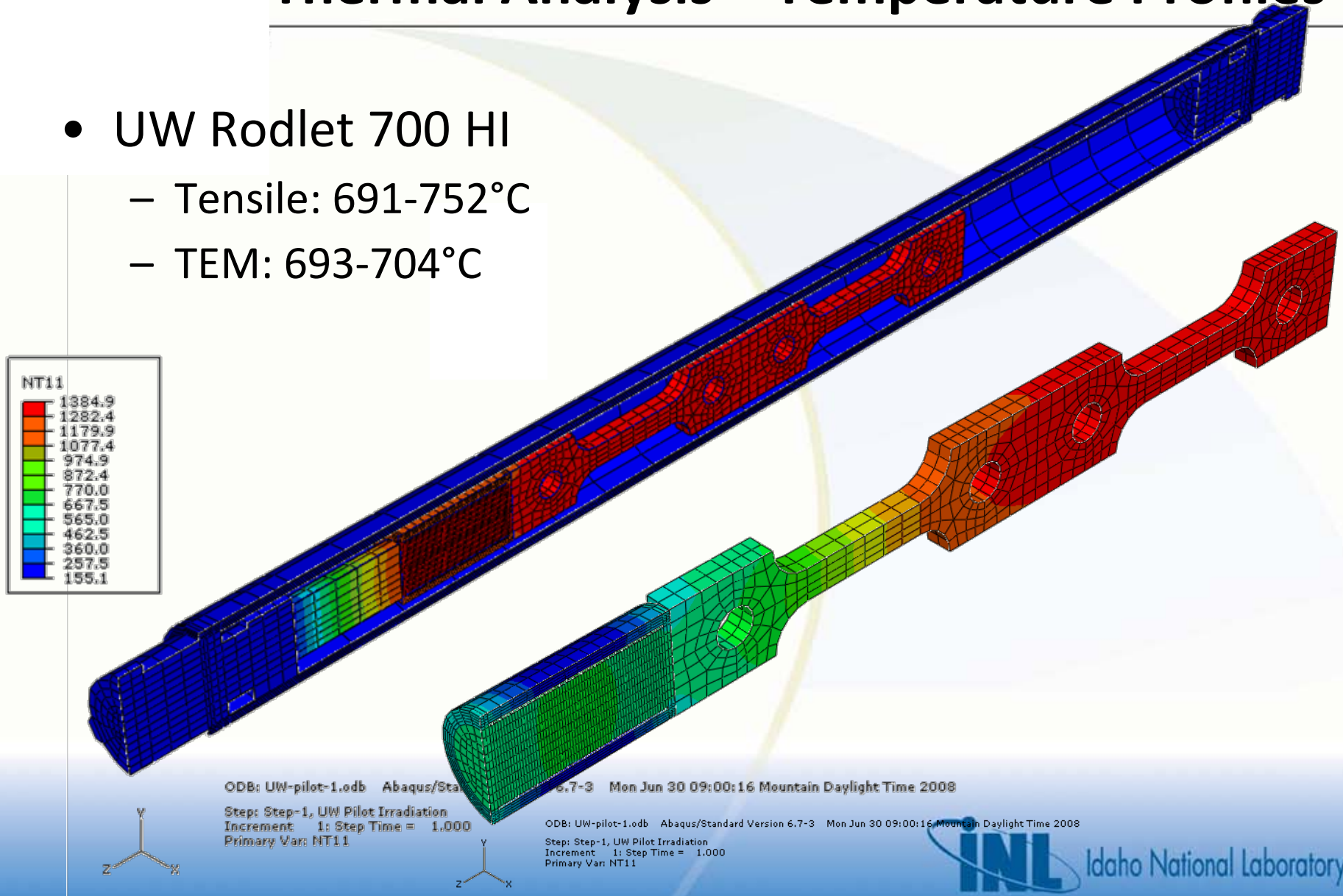
Thermal Analysis – Temperature Profiles

- UW Rodlet 700 HI
  - Tensile: 691-752°C
  - TEM: 693-704°C



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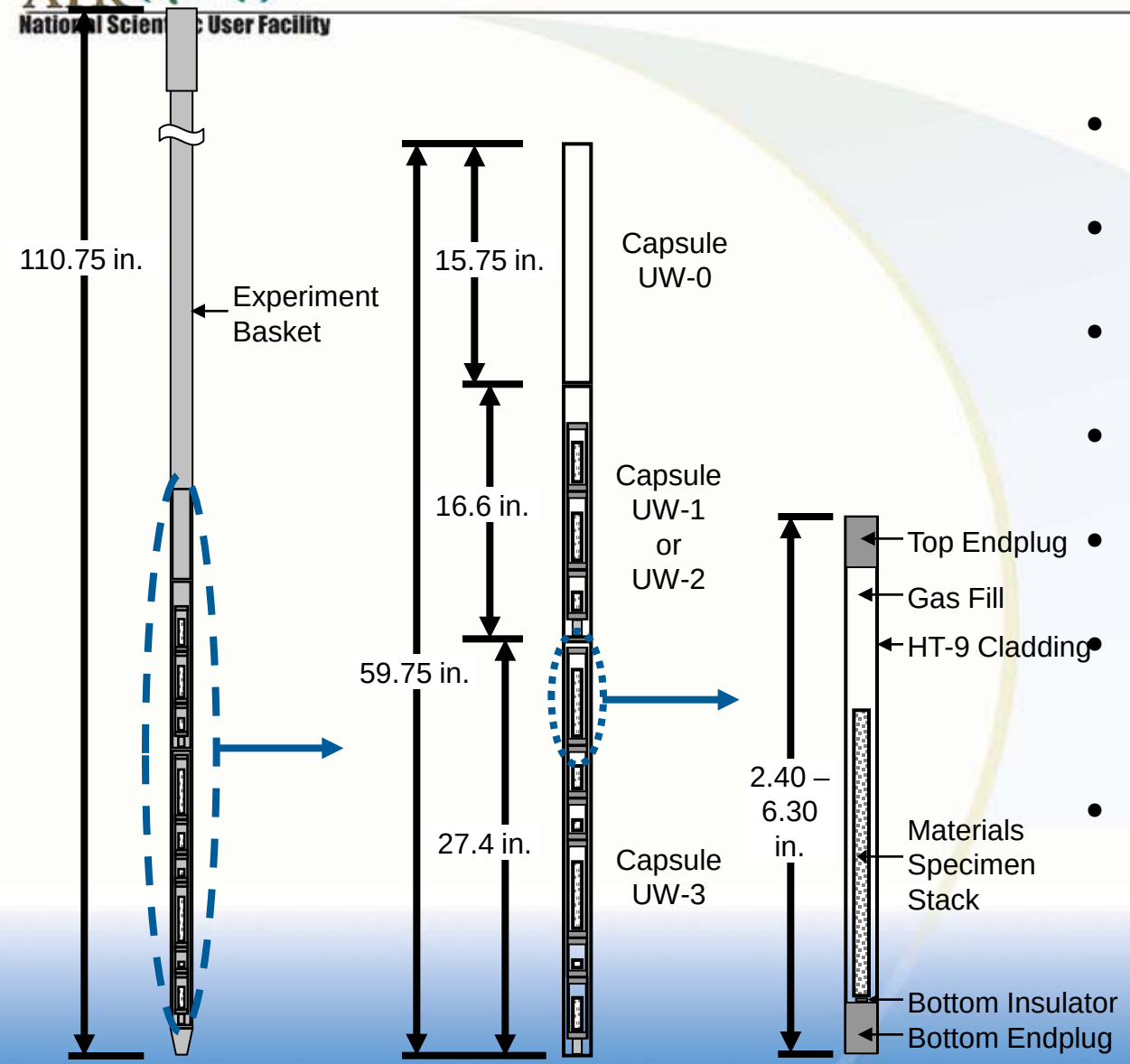
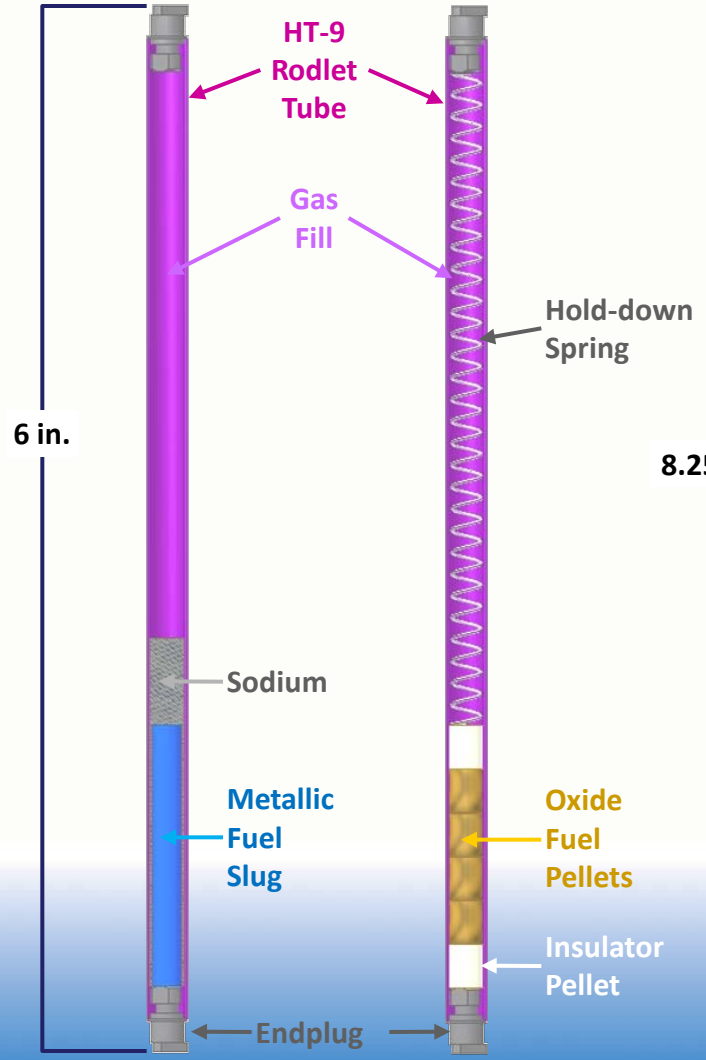
UW Experiment Assembly

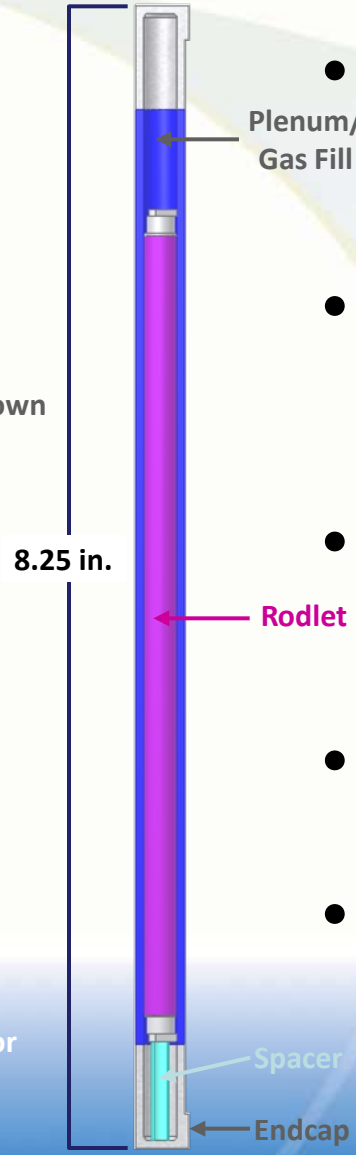


- Drop-in capsule; no active measurements
- Based on approved test assembly design
- Cd-shroud basket filters thermal neutrons
- Independent capsules for target doses
- Independent rodlets for tailored temperatures
- SS-316 Capsule
  - 0.234 in. ID
  - 0.354 in. OD
- HT-9 Rodlet
  - 0.194 in. ID
  - 0.230 in. OD

Irradiation Test Assembly | Capsule Assembly | Rodlet Assembly

FCRD Fuel Experiment

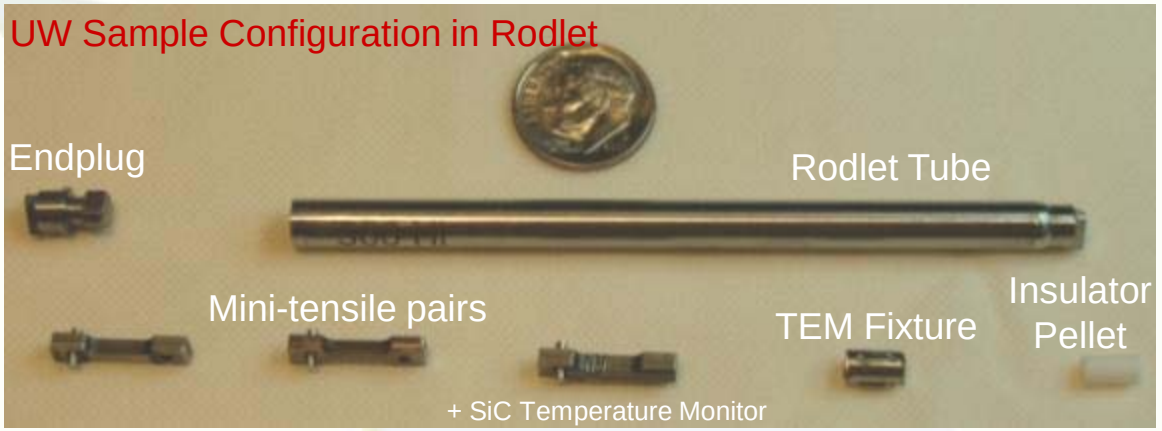


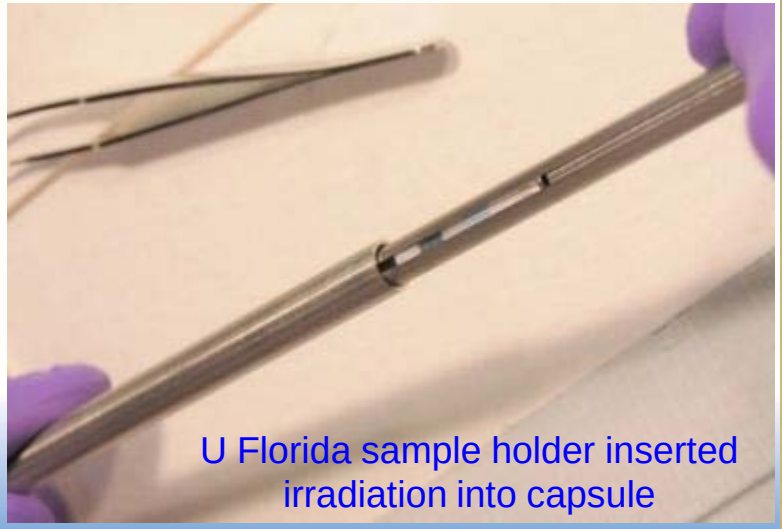


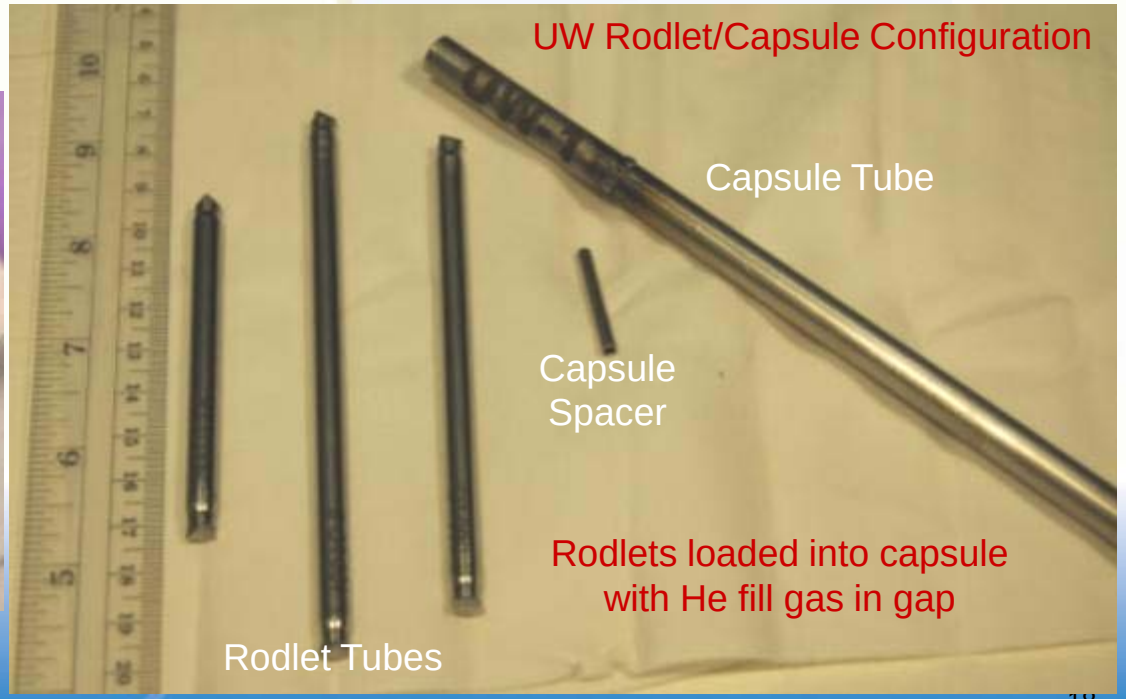
- HT-9 Rodlet
  - 0.230 in. OD (5.82 mm)
  - 0.194 in. ID (4.93 mm)
- SS-316 Capsule
  - 0.354 in. OD (8.99 mm)
  - 0.234 in. ID (5.94 mm)
- Gas gap (0.002 in.) between capsule and rodlet increases rodlet / cladding temperature
- Centering standoffs built into endplugs and endcaps
- Drop-in / Static Experiment
  - No active measurements

Sample / Experiment Configuration

- Example capsule OD / ID
  - 0.354 / 0.234 in. (9 / 6 mm)
  - 0.375 / 0.303 in. (9.5 / 7.7 mm)
  - 0.480 / 0.430 in. (12.2 / 10.9 mm)
  - 0.476 / 0.433 in. (12.1 / 11 mm)
- Gas mixtures in sample holders and capsules tailor temperatures: 200-700°C
  - Ar/He







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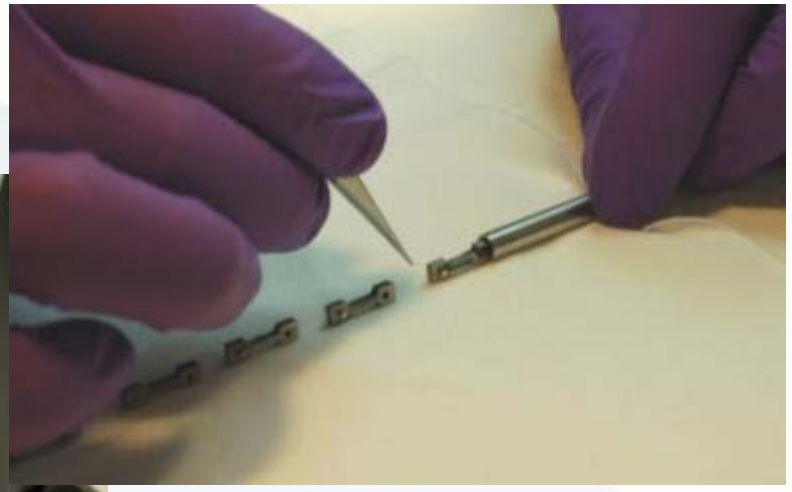
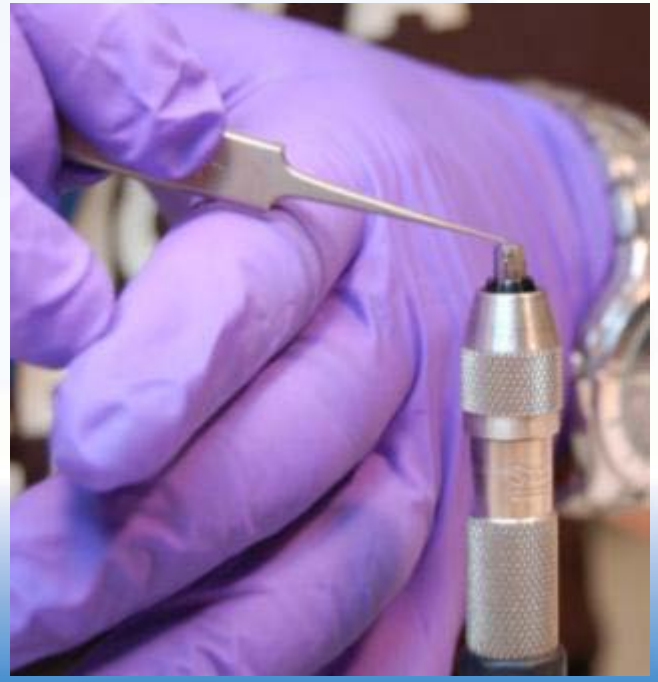
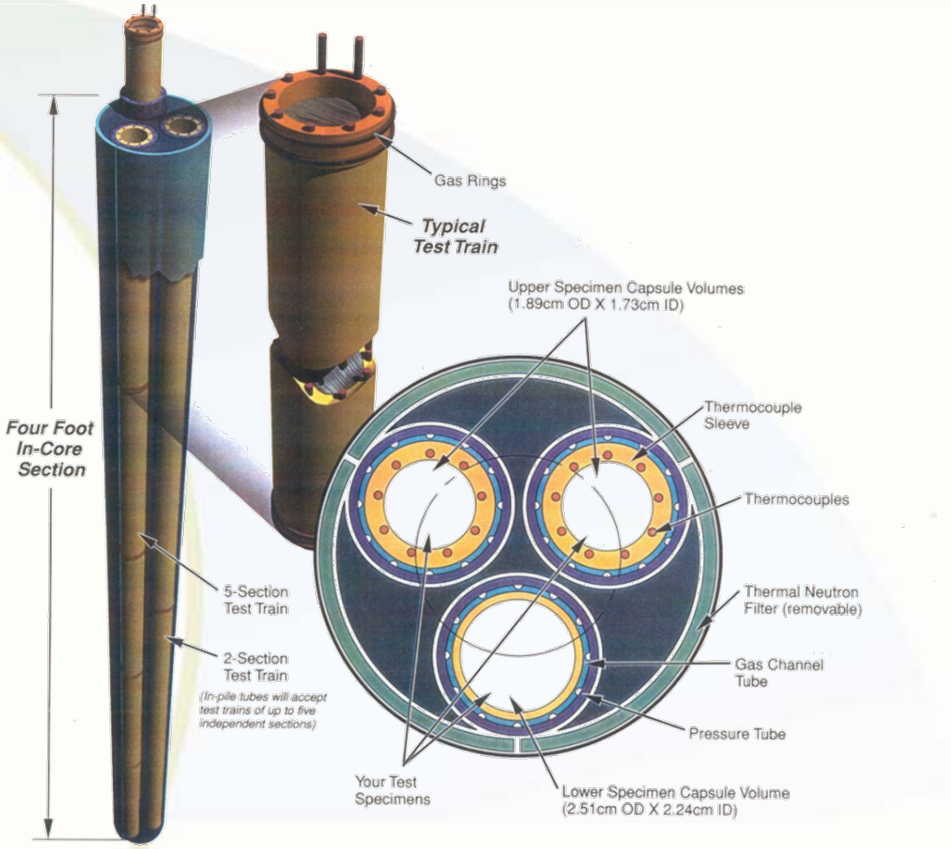
Sample Loading





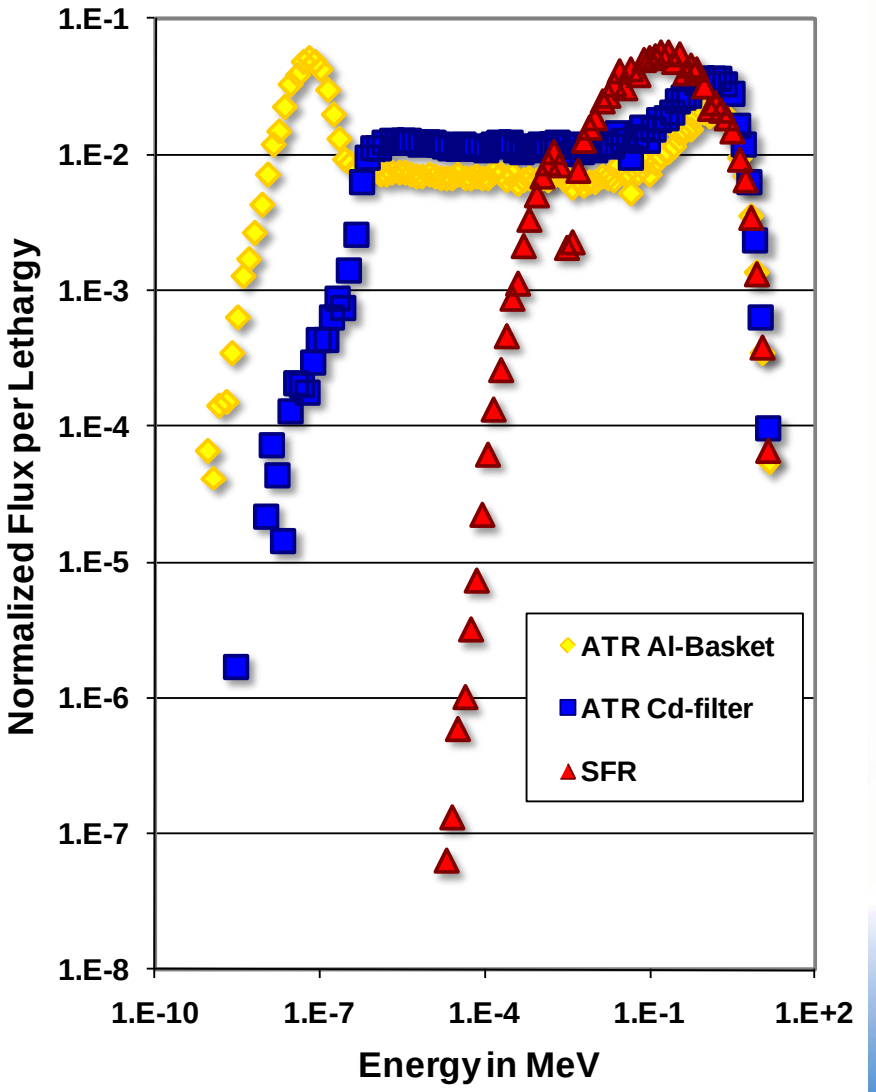
Flux Tailoring

- Irradiation position
  - Close to driver fuel to increase fast fluence
  - Flux trap or reflector to increase thermal
- Fixed neutron absorption shroud
  - Integral with encapsulation design
  - More choices of absorption material if isolated from coolant
  - Consumable (e.g., boron)
- Removable/replaceable neutron absorption shroud
  - Solid – chemistry compatibility with reactor coolant
  - Gas shroud – He^3
- Booster fuel



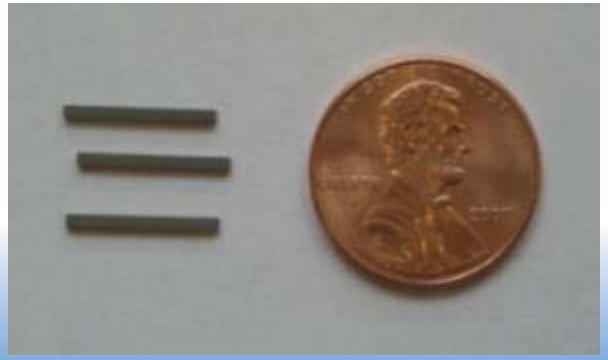
Flux Tailoring

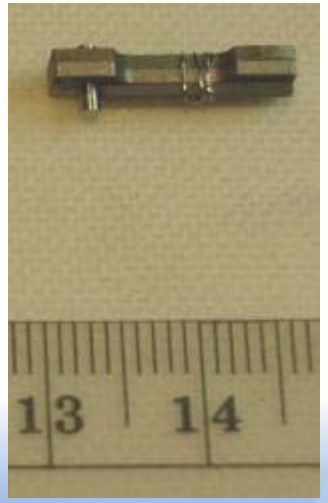
- ATR Neutron Energy Spectrum
  - Highly thermal spectrum in with no neutron filter
  - Unaltered spectrum will result in significant self-shielding in dense fuels
- Cd-shroud Integral with Experiment Basket
  - Efficient removal of neutrons with energies below cadmium cut-off
- Resulting Spectrum
  - Filtered spectrum in experiment does not have prototypic fast neutron component
  - However, epi-thermal component responsible for most fissions; much more penetrating than thermal neutrons
  - Test fuels should be free of gross self-shielding
  - Applicable for fuel performance results, but not for cladding performance
- Identical experiments in fast reactors will provide direct comparison



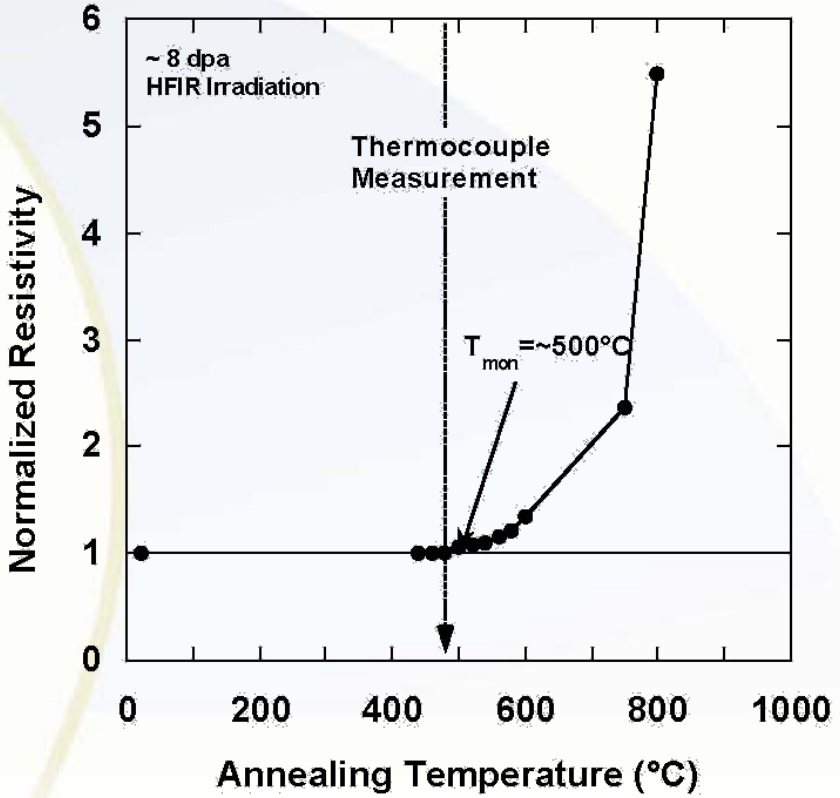
Instrumentation

- Limited to passive measurements in a drop-in/static capsule
  - Flux wires
  - Melt wires
  - Temperature monitors
- Instrumented Lead
  - Thermocouples are most common
  - Consider temperature and irradiation effects





Monolithic SiC obtained from Rohm and Haas, Philadelphia, PA ($130/each)



Other Considerations

- Material Selection
  - Compatibility with specimens or irradiation environment
  - Thermal issues (expansion stresses & clearances, service & design temperatures, brazes)
  - Neutronic or activation effects (flux variations, heating, waste disposal, etc.)
  - Design code requirements
- Marking or Features
  - Specimens or specimen holders for identification in hot cell
  - On capsules to provide orientation for installation in core & PIE
  - Cut lines for disassembly of test trains/capsules in hot cell
- Assembly & Disassembly
  - Walk through assembly of capsule & test train
  - Consider disassembly in a hot cell – with manipulators

Postirradiation Examination (PIE)

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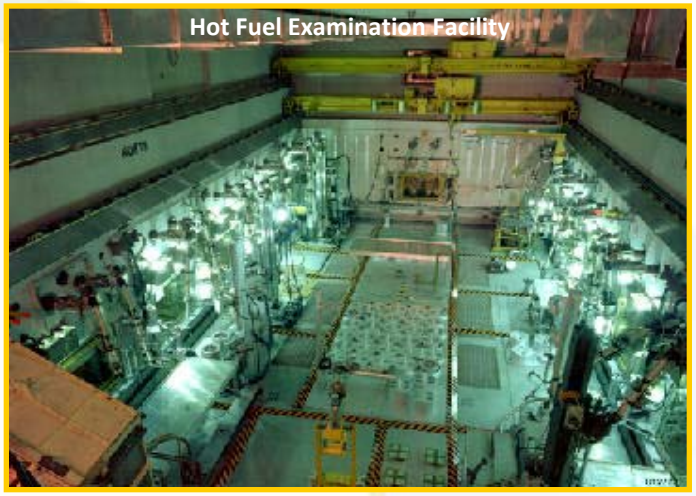
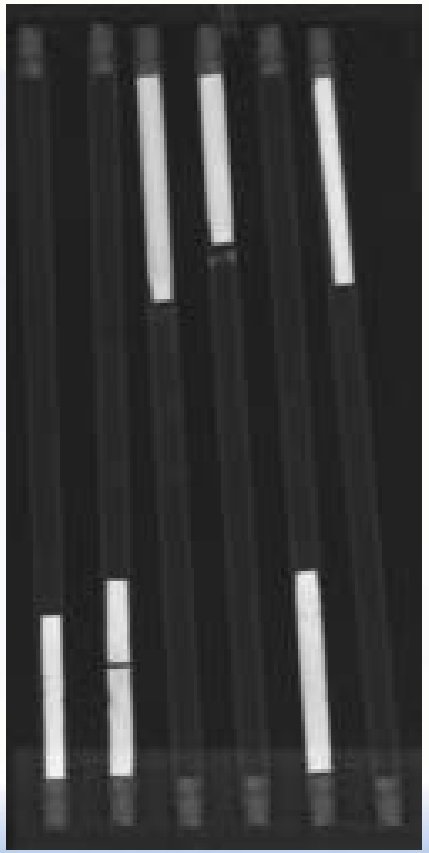
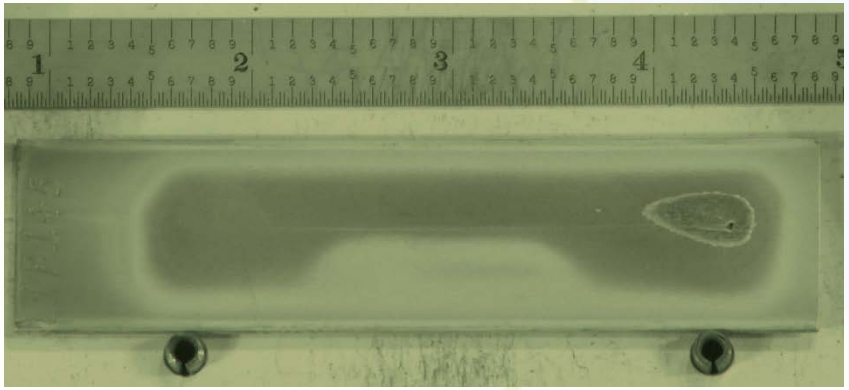
Non-Destructive Exams

- Visual
- Neutron Radiography
- Gamma Scanning
- Dimensional Analysis
- Eddy Current







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Postirradiation Examination (PIE)

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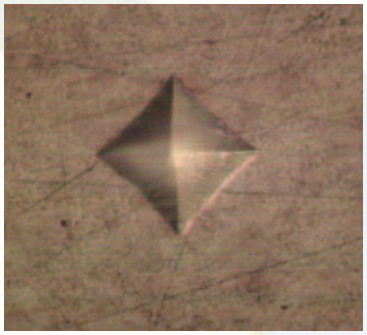
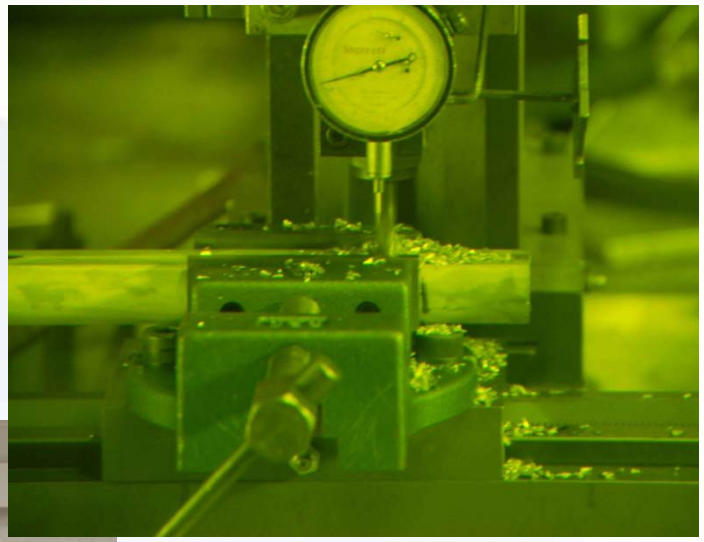
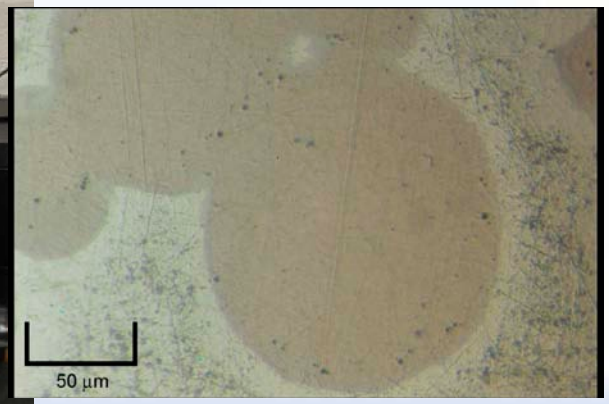
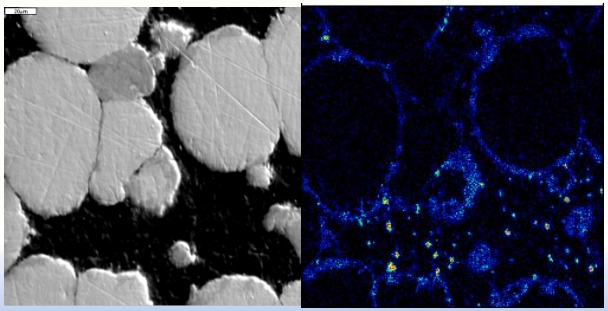
Destructive Exams

- Disassembly
- Gas Puncture & Analysis
- Optical Microscopy
- Burnup Analysis
- Mechanical Testing
- SEM, TEM, FIB









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PIE Considerations

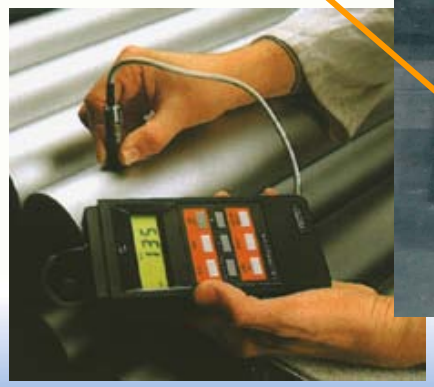
- Experiment disassembly
  - remote handling
  - small parts, magnetism, static
- Capsule and sample labeling and tracking
  - sample identification – binoculars, scope, periscope, camera
  - increased handling time
- PIE Equipment
  - Custom design for hot cells with full mock-up and testing
  - Radiation resistant electronics and lenses required
  - Minimize equipment/controls required in cell

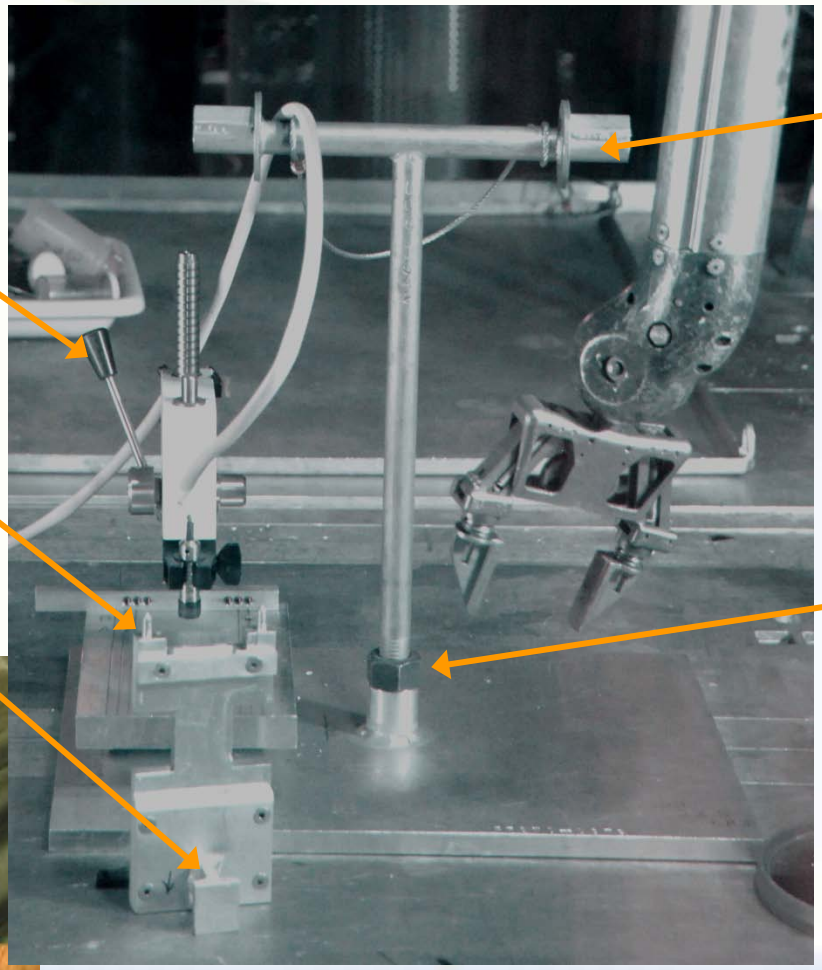
PIE Handling

Exaggerated handles

Location guides

Manipulator handles





EM “T” Handle

Oversized Bolts

Irradiation Experiment Design

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