Fuel Irradiation Experiment Design – Capsule

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ATR NSUF Experimenter's Course
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Idaho National Laboratory

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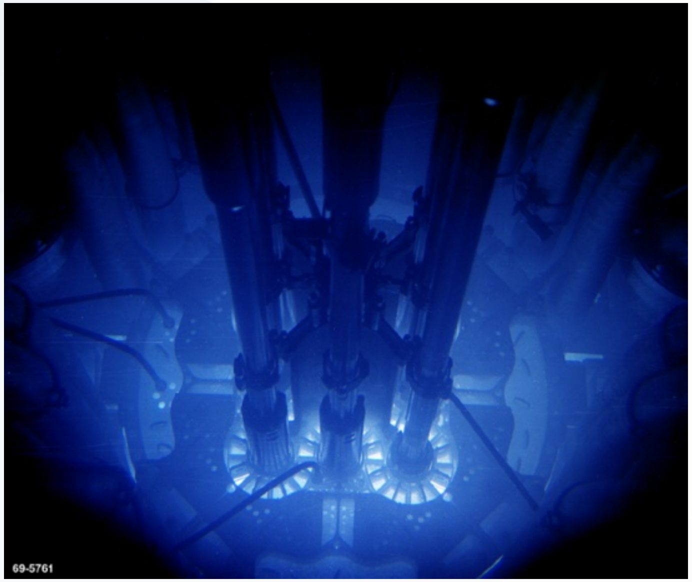
ATR Experiment Configurations

Experiment Configurations in ATR

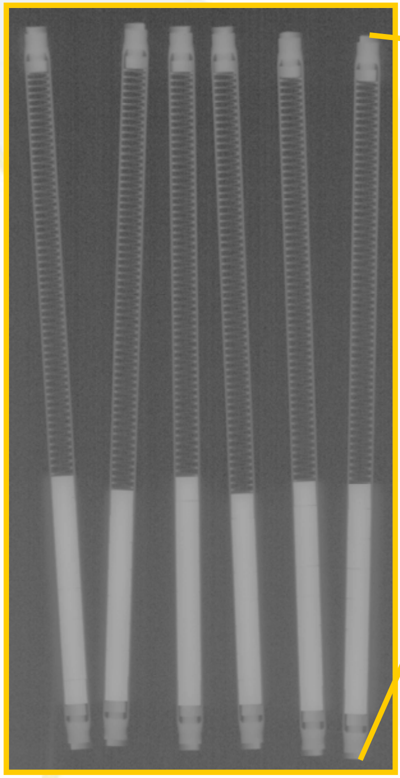
- Drop-in (Static) Capsule (AFCI/FCRD)
  - Design gas gaps and gas fill to tailor temperature
- Open Core Experiment (RERTR)
  - Direct cooling by primary reactor coolant
- Instrumented Lead (NGNP)
  - Online data collection (temperature, fission gas release)
  - Active control (gas mixtures)
- PWR Loop
  - Controlled environment
  - Coolant independent of primary reactor coolant
- Hydraulic Shuttle (Rabbit)
  - New irradiation capability at ATR
  - Short duration irradiations



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 AFCI / FCRD (fuels and materials)

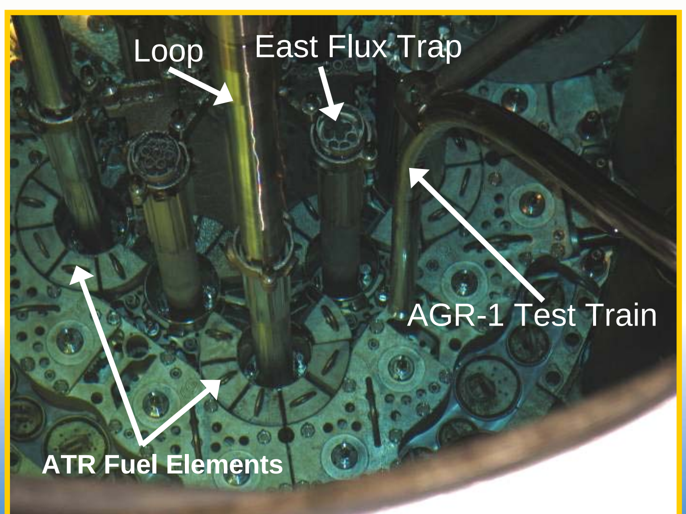
Completed Rodlets

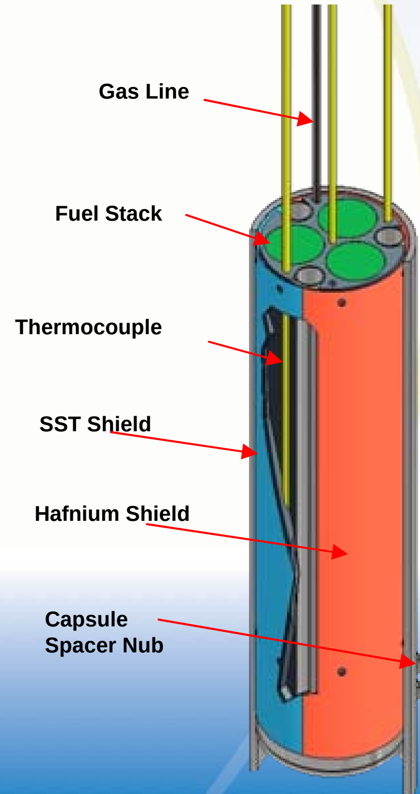


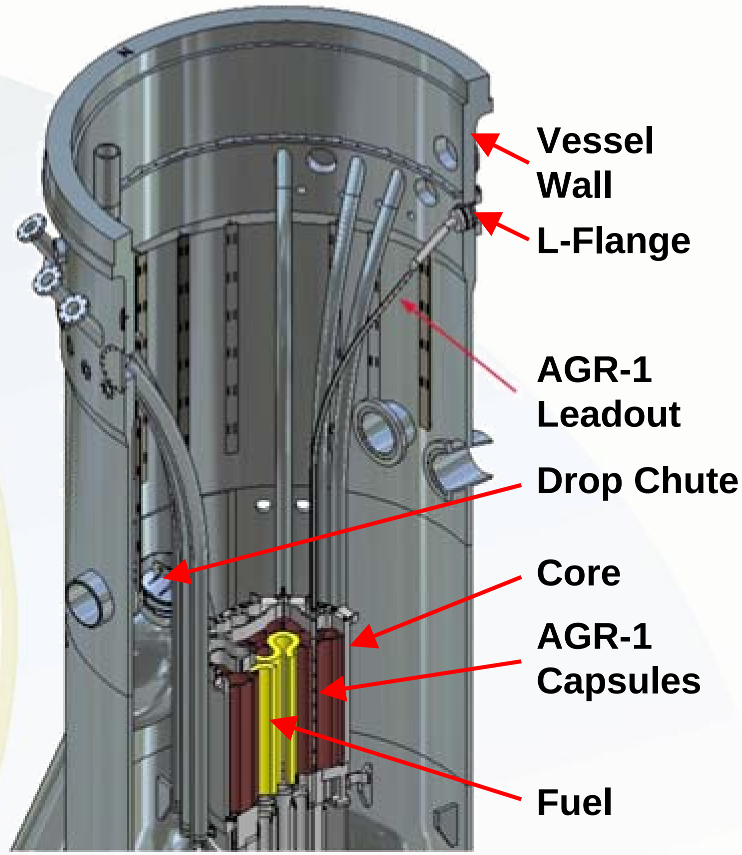
Capsule Assembly

Instrumented Lead

- Online data collection (temperature, fission gas release)
- Active control (gas flow)
- Require detailed design, planning, and mockup
- Used by NGNP for AGR (TRISO fuel particles)



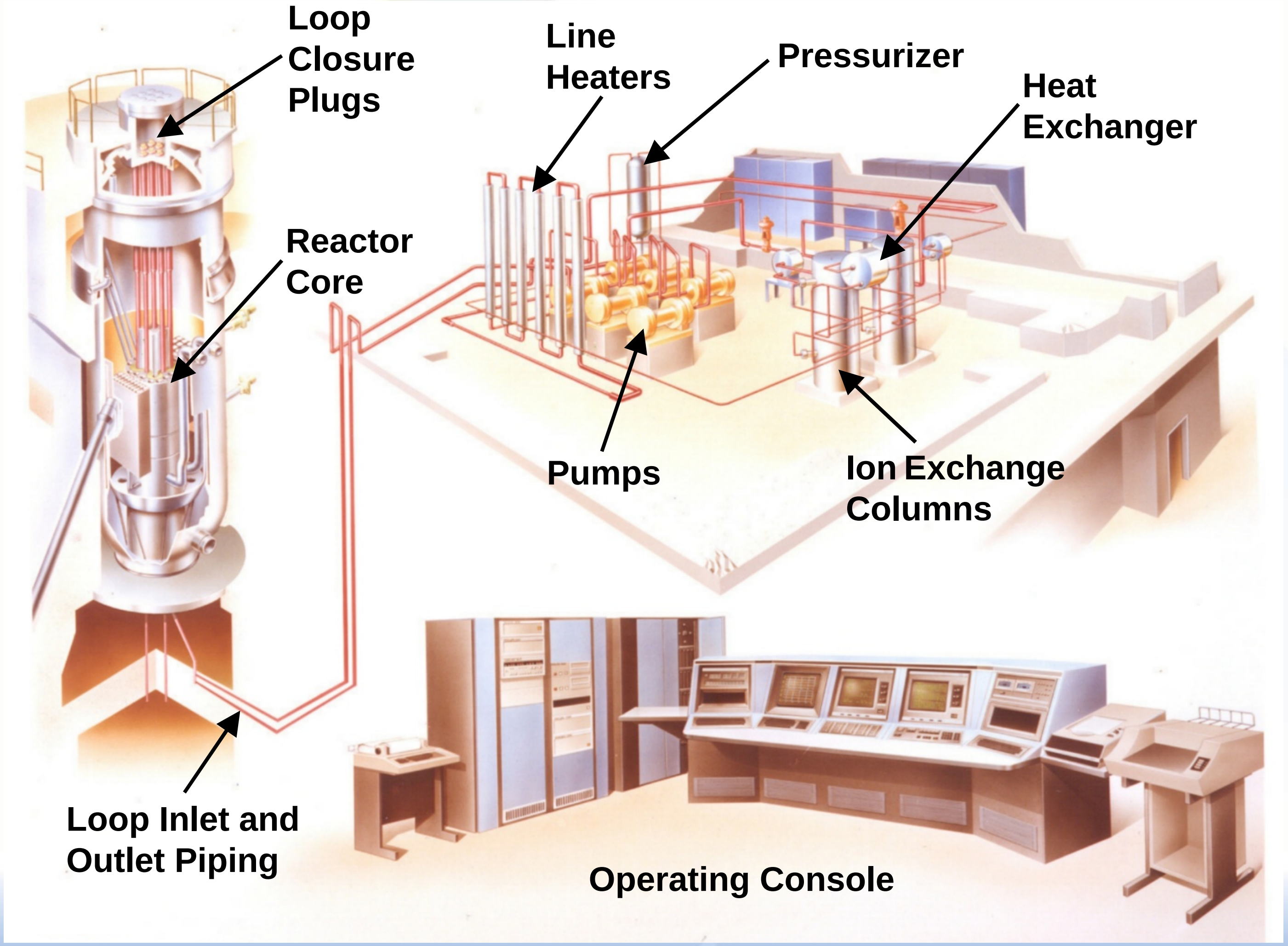




Pressurized Water Loop

- Experiment environment independent of primary reactor coolant
- Controlled environment
  - Pressure, temperature, flow, chemistry
- Require detailed design, planning, and mockup
- 5 loops installed (in use by other customers)
- ATR User Facility installing new loop
- Limited space available for loops

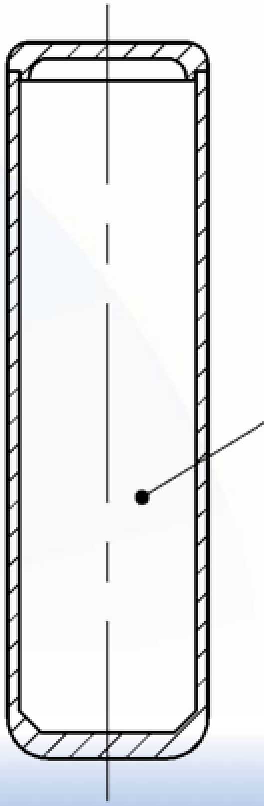
Typical PWR Loop Layout



Hydraulic Shuttle Irradiation System

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
  - Thermal = 2.77×10^{14} n/cm^2-s
  - Fast (> 1MeV) = 1.87×10^{14} n/cm^2-s
  - Total = 7.23×10^{14} 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)



Fueled Capsule Experiments for AFCI

Drop-In (Static) Capsule

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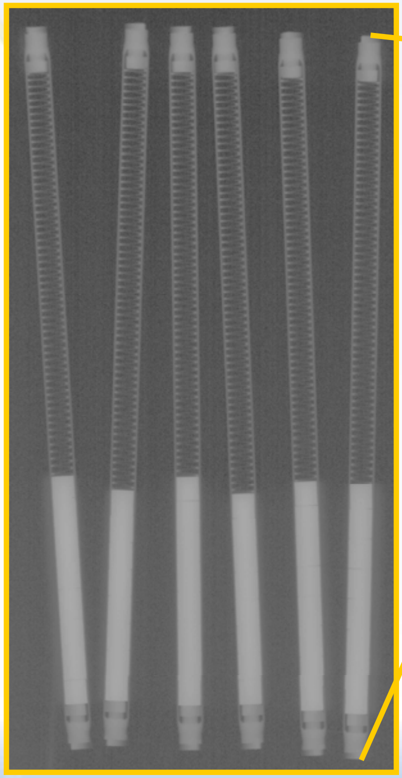
Completed Rodlets



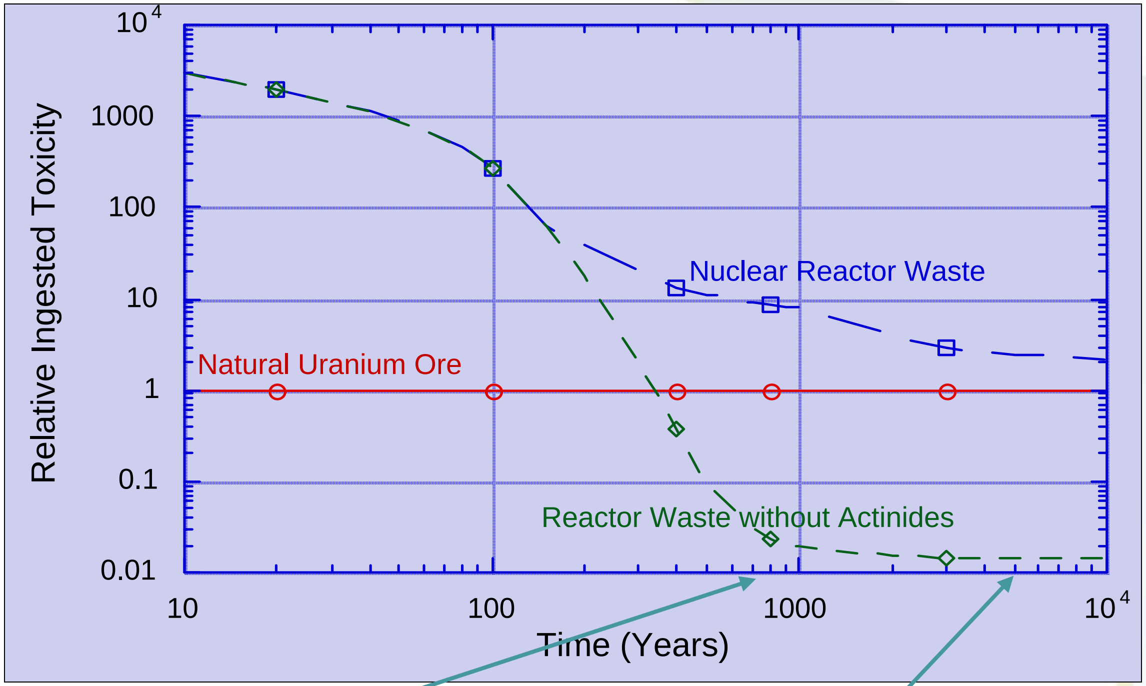
Capsule Assembly

Advanced Fuel Cycle Initiative (AFCI)

- Mission
  - *Enable the safe, secure, economic, and sustainable expansion of nuclear energy by conducting research, development, and demonstration focused on nuclear fuel recycling and waste management to meet U.S. needs*

- Programs to develop and demonstrate mature technologies
  - Separations
  - Transmutation Fuels (and Core Materials)
  - Reactor
  - Systems Analysis
  - Safeguards
  - Modeling and Simulation

Motivation for Partitioning and Transmutation



Yucca Mountain

Notre Dame

Pyramids at Giza

- Plutonium and minor actinides are responsible for most of repository hazard beyond ~400 years
- Many examples of man-made structures > 400 years old

Transmutation Fuel Types

Fast Reactors

- Metallic
- Oxide

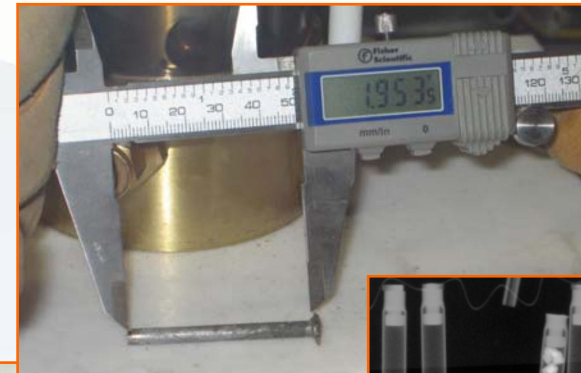
Mature technologies
Extensive experience

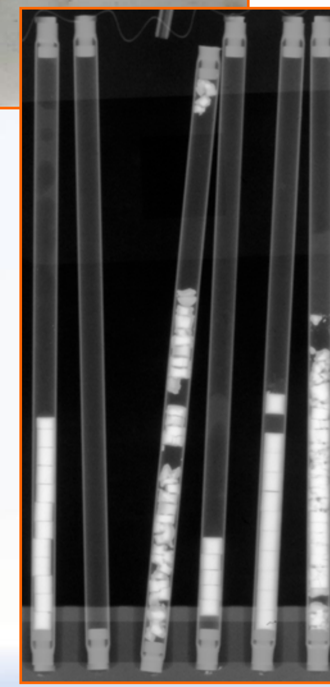
- Nitride
- Ceramics
- Dispersion

Innovative technologies
Potential improved performance

Light Water Reactors

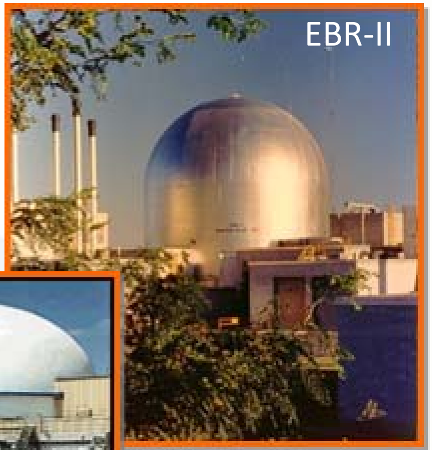
- MOX
- Particle Fuel
- Dispersion

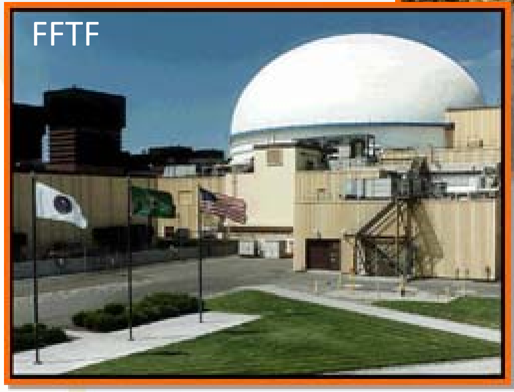


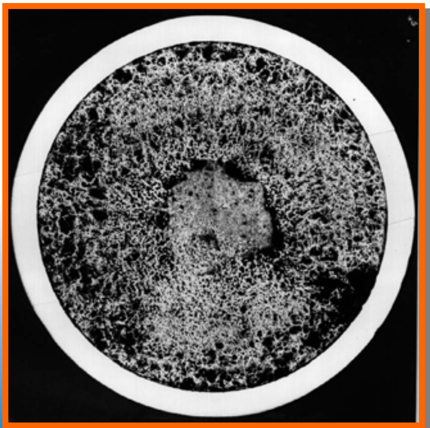


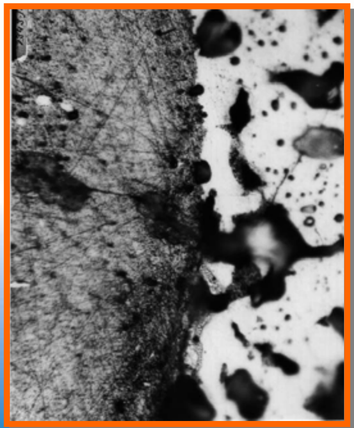
Important Fuel Performance Phenomena

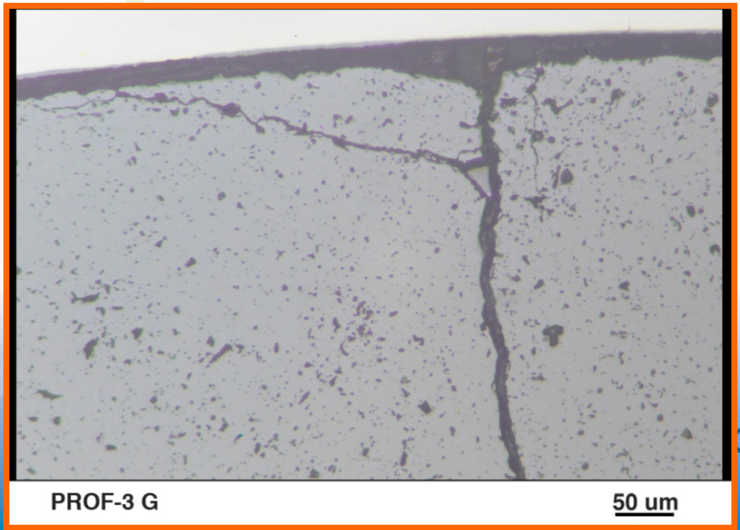
- Irradiation growth
- Fuel swelling and fuel-cladding mechanical interaction (FCMI)
- Gas release
- Fuel constituent redistribution
- Fuel-cladding chemical interaction (FCCI)
- Fuel restructuring
- Fuel-coolant compatibility











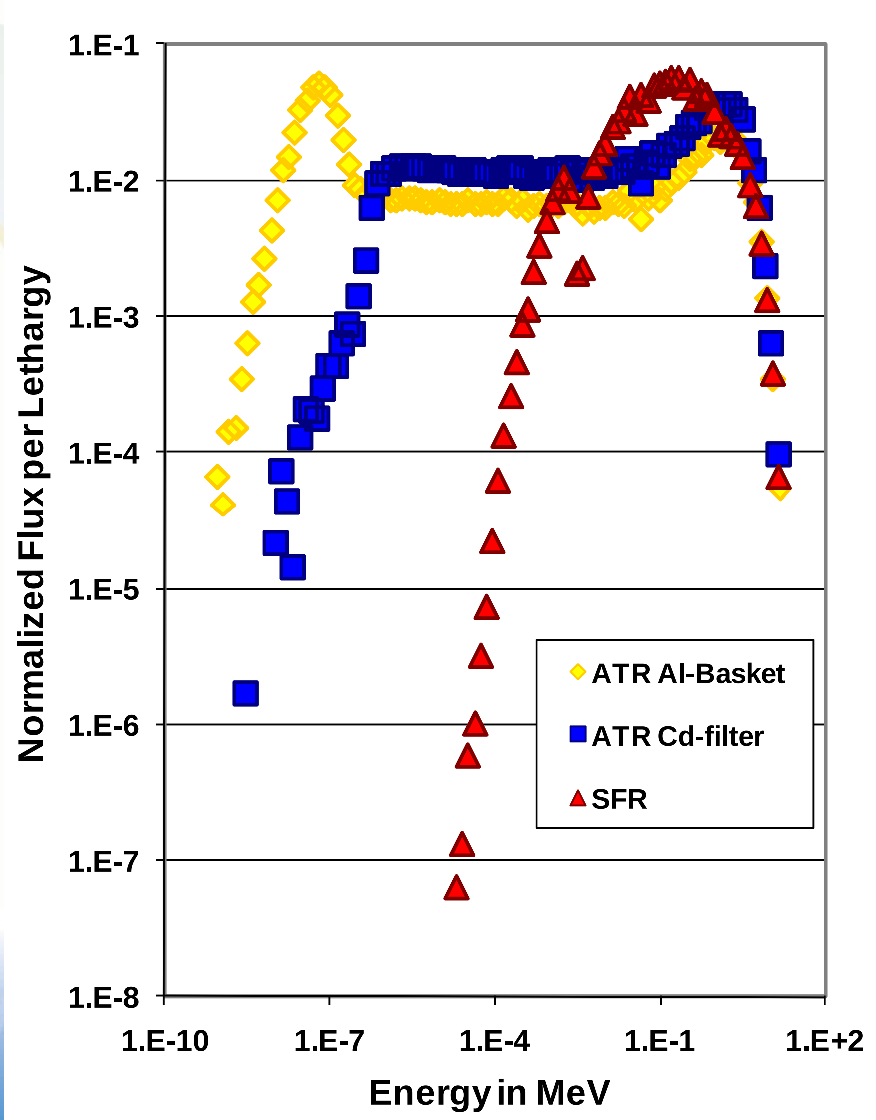
AFCI Fuel Testing in ATR

Advanced Fuel Cycle Initiative (now Fuel Cycle Research & Development)

- Objective of AFCI experiments is to test irradiation performance of minor-actinide bearing metallic and oxide fuels (U, Pu, Am, Np) for fast reactor applications
- Identify differences in fuels with/without minor actinides
- Challenge:
  - No fast reactor in US for fuel testing
  - How to conduct a prototypic (or relevant) experiment for a fast reactor fuel in a thermal reactor
- Solution:
  - Drop-in capsule with gas gap to elevate cladding temperature
  - Cadmium shroud to filter thermal neutrons and minimize flux depression in test fuels

Neutron Spectra Comparison (ATR vs. SFR)

- 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; <u>much more penetrating</u> 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



AFCI/FCRD Experiments

- Many fuel compositions have been irradiated
  - metallic, oxide, including minor actinides
- Simulate fast reactor conditions in ATR
  - Cd-shrouded experiment baskets
  - U enrichment used to achieve linear heat generation rates (LHGR)
- Safety bounds developed for fuel experiments used to bound materials experiments (GFR, UW)

Irradiation capsule contains 6 fueled rodlets

AFC-2 Metallic Fuel Compositions

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Example Metallic Fuel Compositions		
Historic	AFCI	
U-10Zr	U-20Pu-15Zr	U-30Pu-20Zr
U-20Pu-10Zr	U-20Pu-MA-15Zr	U-30Pu-MA-20Zr
	U-20Pu-MA-RE-15Zr	U-30Pu-MA-RE-20Zr

Metallic alloy composition expressed in weight percent

MA = Am + Np
U-20Pu-3Am-3Np-15Zr or U-30Pu-5Am-3Np-20Zr

RE = 6%La + 16%Pr + 25%Ce + 53%Nd

- TRU Ratio
  - Representative of LWR fuel cooled for 30 years
  - Batch recycling:
    45.5% Pu, 5.7% Am
    3.8% Np, 0.2% Cm
  - 20Pu-3Am-2Np
    30Pu-5Am-3Np
- Rare Earth Additions
  - RE = 6% La, 16% Pr
    25% Ce, 53% Nd
  - Simulates carry-over from pyro-processing of fast reactor fuel
- ^{235}U Enrichment
  - Varies to allows rodlets to operate at 350 W/cm
- Burnup
  - Low ≥ 10 at.%, High ≥ 25 at.%

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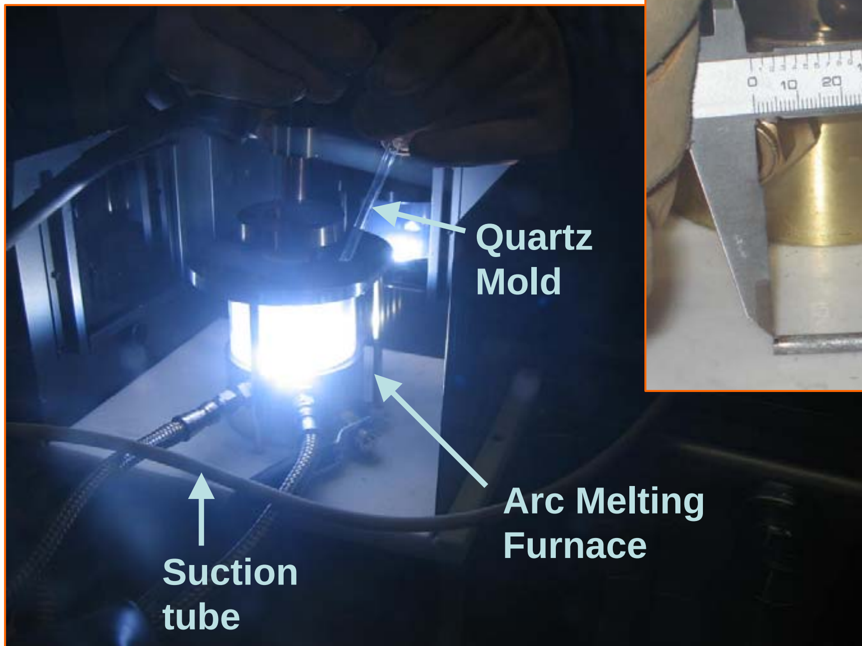
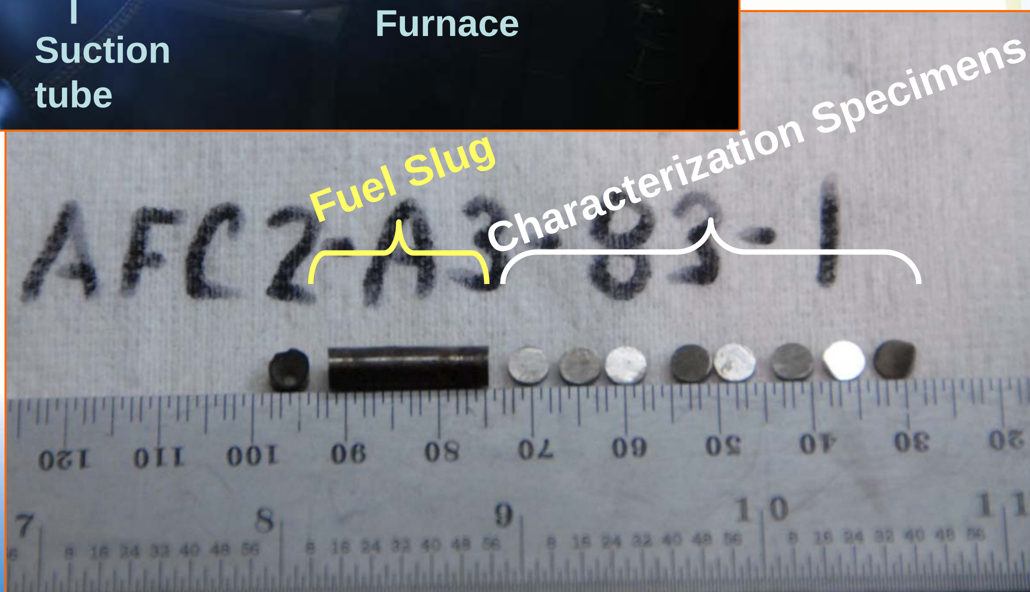
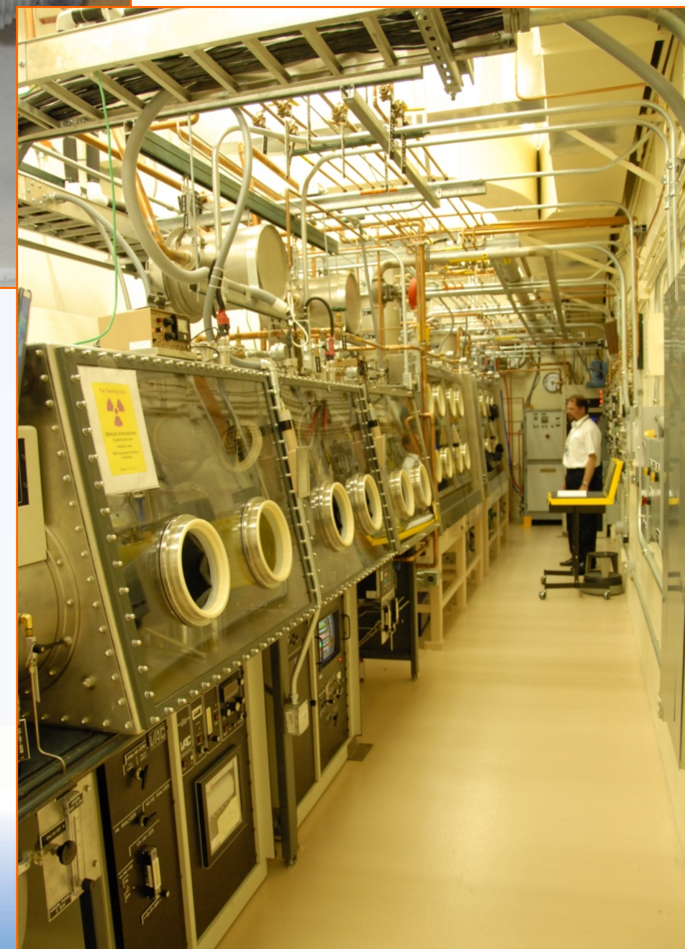
Fabrication – Metallic Fuels







Shielded Glovebox in FMF

AFC-2 Oxide Fuel Compositions

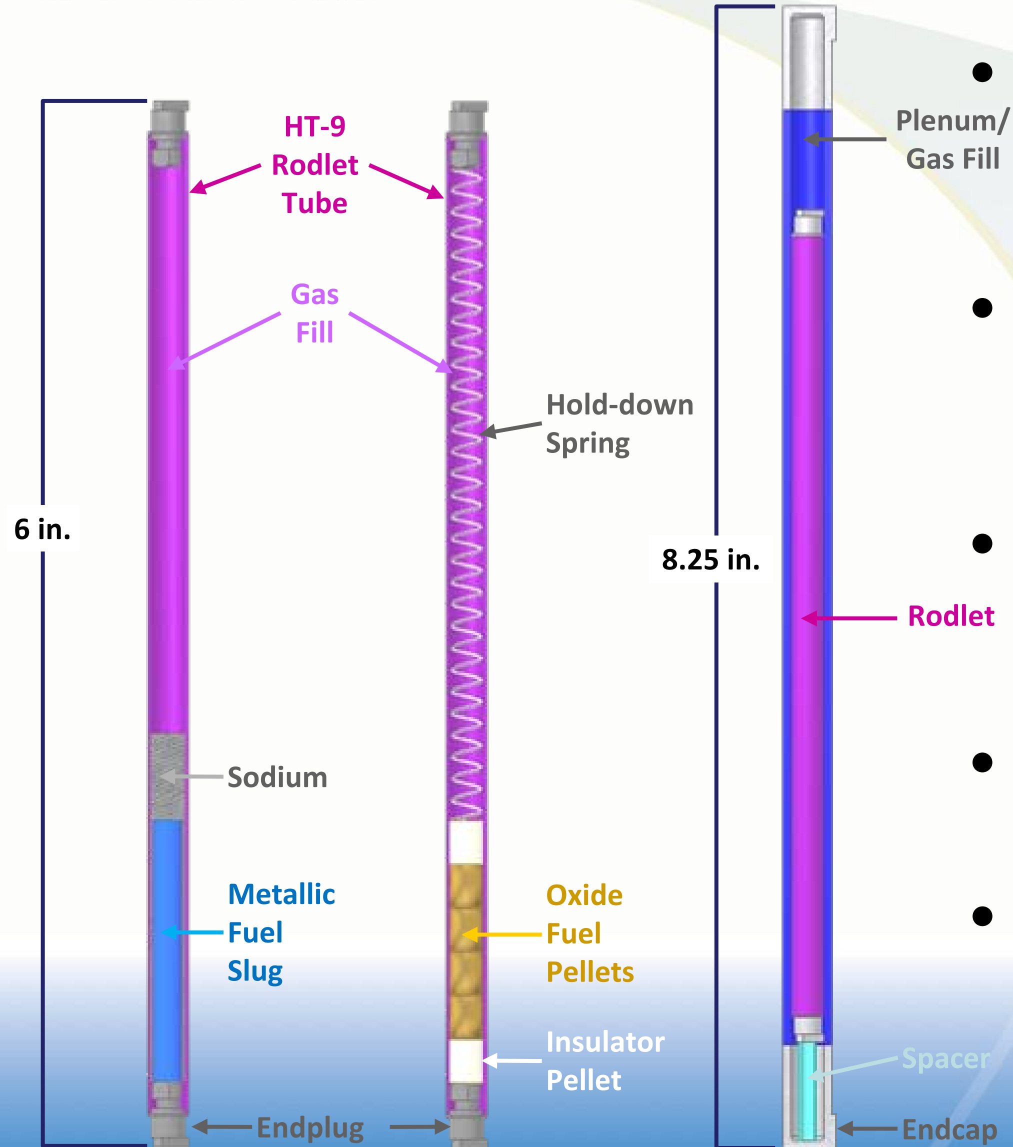
Example Oxide Fuel Compositions	
Historic	AFCI
$(U_{0.8},Pu_{0.2})O_2$	$(U_{0.8},Pu_{0.2})O_{1.98}$
$(U_{0.7},Pu_{0.3})O_2$	$(U_{0.75},Pu_{0.2},MA_{0.05})O_{1.98}$
	$(U_{0.75},Pu_{0.2},MA_{0.05})O_{1.95}$

Oxide fuel composition expressed in mole percent

MA = $(Am_{0.03},Np_{0.02})$

- Compositions
  - Baseline MOX
  - + MA (TRU ratio)
  - Vary O/M (1.98 vs 1.95)
- TRU Ratio
  - Representative of LWR fuel cooled for 30 years
  - Batch recycling:
    45.5% Pu, 5.7% Am
    3.8% Np, 0.2% Cm
- Burnup
  - Low ≥ 10 at.%, High ≥ 25 at.%

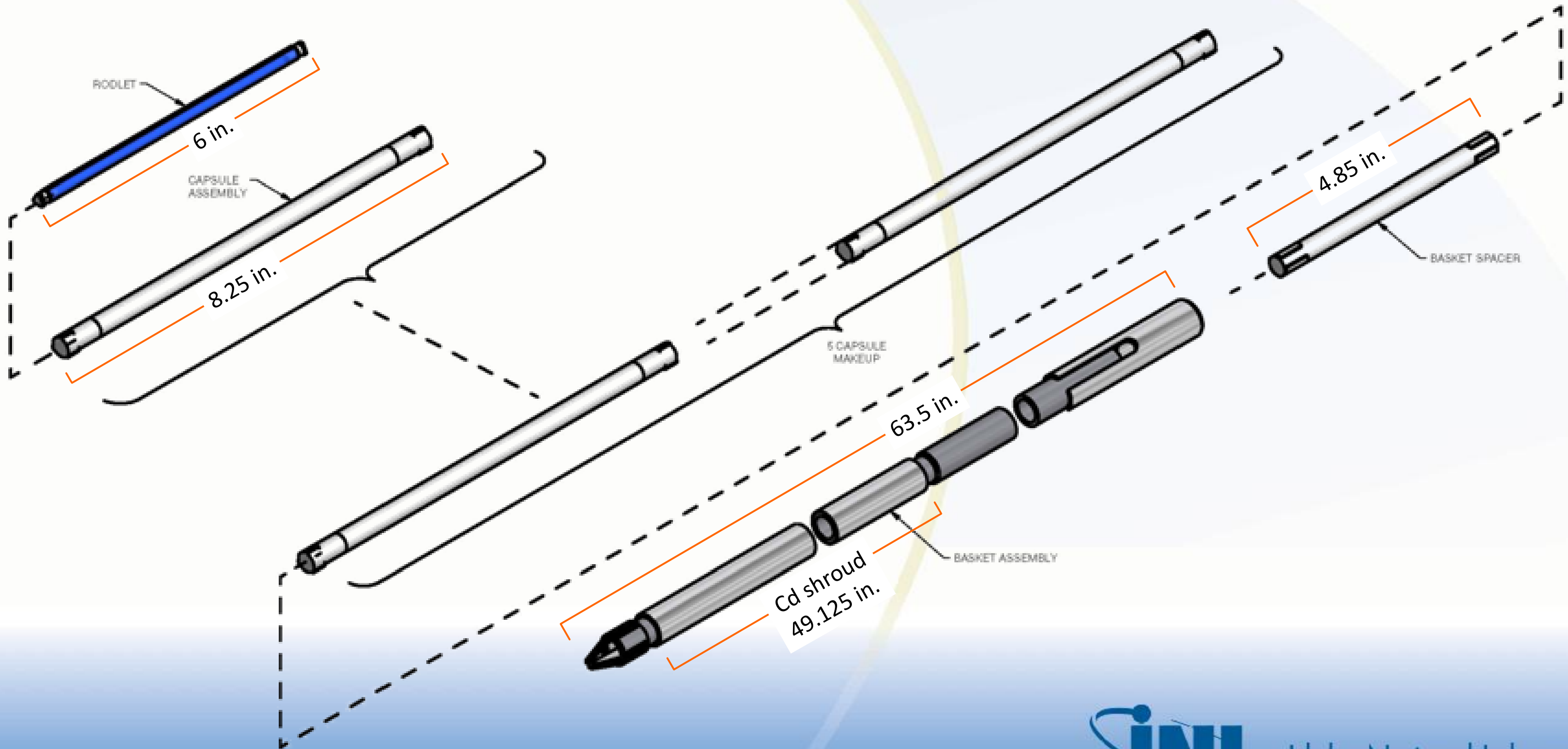
FCRD Fuel Experiment



- 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

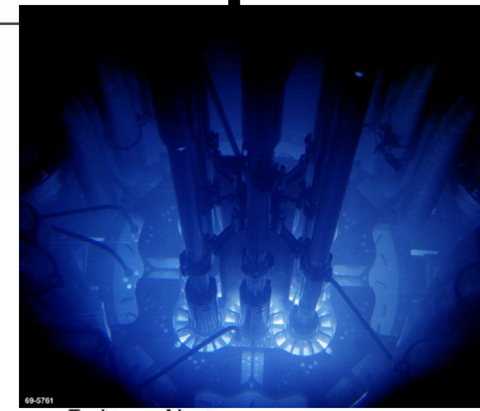
Typical Experiment Assembly

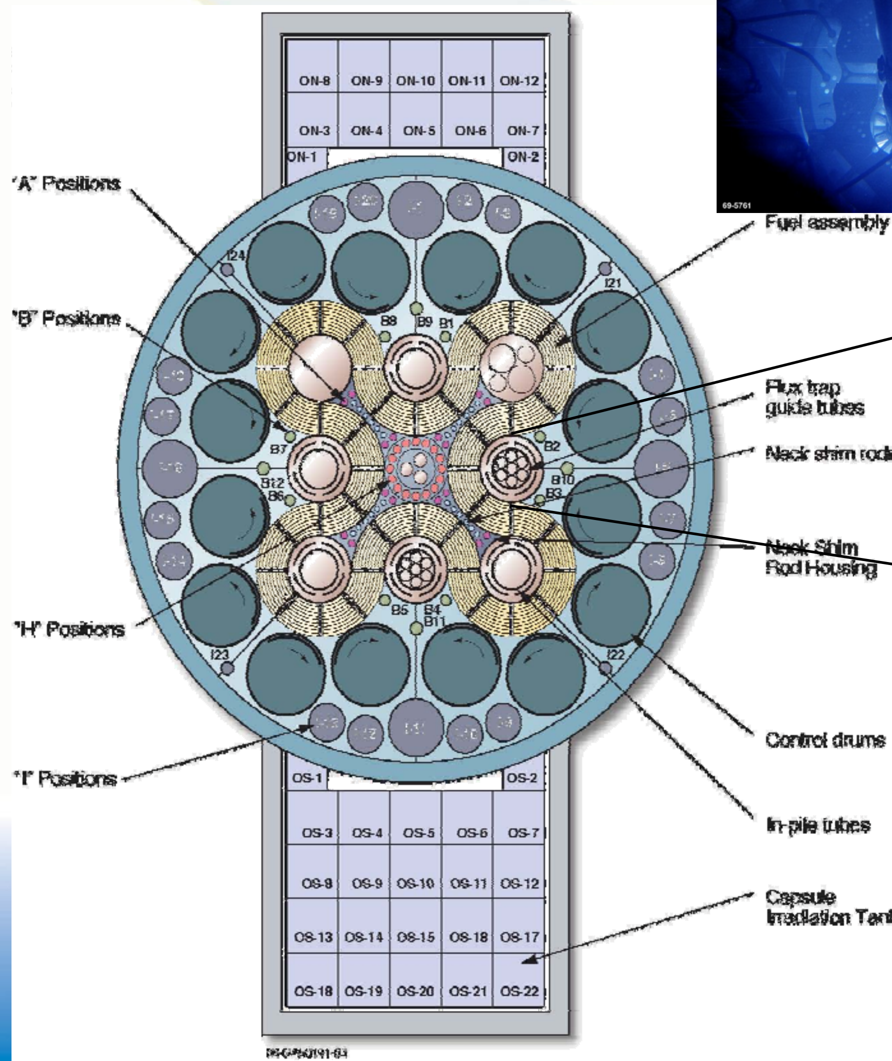
- 1 rodlet per capsule (new FCRD design)
- 5 capsules per basket
- Cd shroud in basket filters thermal neutrons

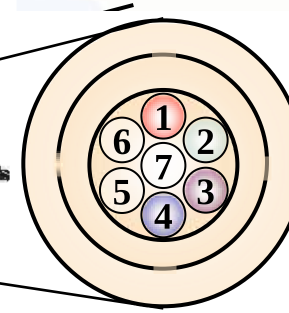


Irradiation in ATR East Flux Trap

- 4 Capsule Positions in EFT
  - Cd shrouds in 1,2,3,4
  - 6 rodlets per capsule
  - 24 rodlets irradiated simultaneously
- Capsule Limits
  - LHGR ≤ 500 W/cm
  - PICT ≤ 650°C
  - Capsule pressure ≤ 975 psi
- Drop-in capsule is water-cooled
- Duration
  - Low burnup ~ 1 year
  - High burnup ~ 2-3 years







East Flux Trap

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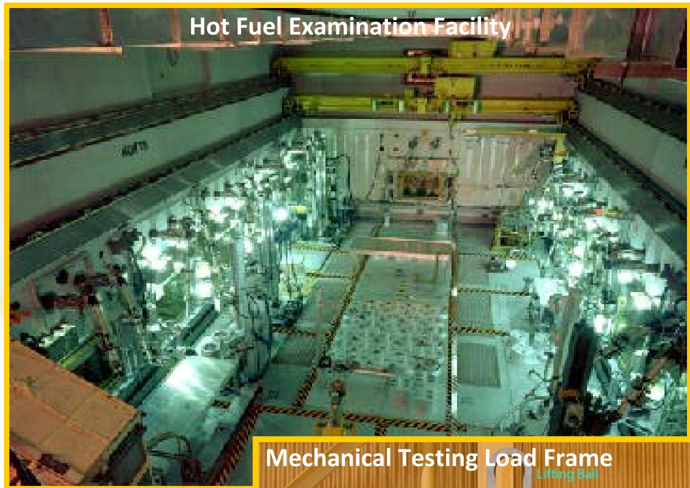
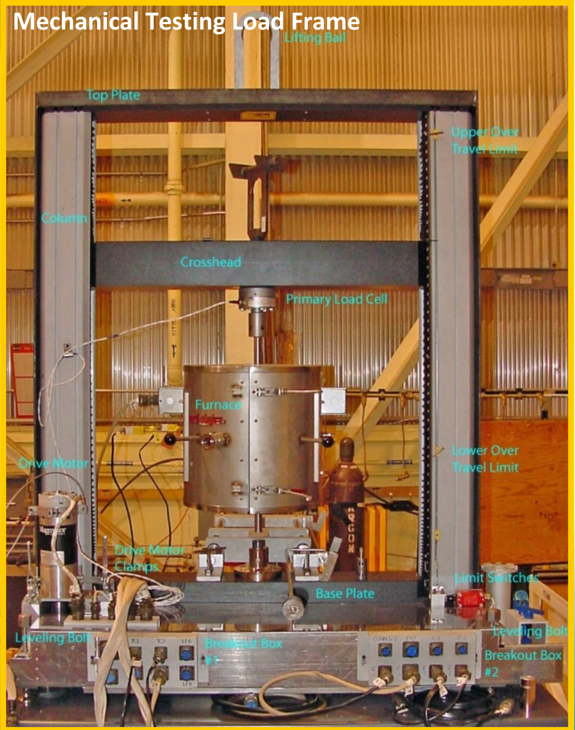
Postirradiation Examination (PIE) Capabilities

- Experiments shipped from ATR to Hot Fuel Examination Facility (HFEF) after irradiation
- HFEF Main Cell
  - 70-ft long, 30-ft wide, 25-ft high
  - Inert argon atmosphere
  - 15 workstations with M/S manipulators
  - Complete fuels PIE capability



Hot Fuel Examination Facility



Mechanical Testing Load Frame

Shipping Cask

Hot Fuel Examination Facility

Postirradiation Examination (PIE) Capabilities

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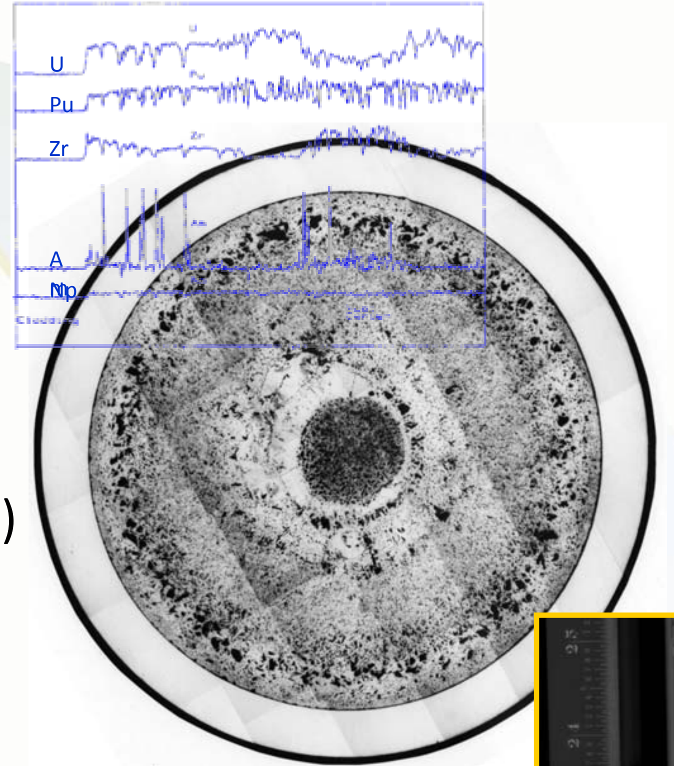
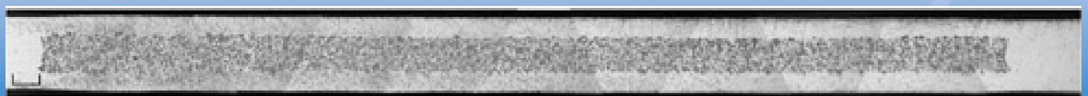


- Neutron radiography
- Capsule/Element non-destructive examination (NDE)
  - Visual examination
  - Dimensional measurement
  - Fission/activation product distribution (gamma spectroscopy)
- Gas sample
- Sample cutting and preparation
- Metallography and ceramography
- Microhardness measurement
- Electron microscopy
- Burnup determination
- Physical and thermo-physical properties



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