IAEA 60 Years
Atoms for Peace and Development

MTR Test Design

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Presentation Objectives

- Intended to familiarize potential experimenters with the steps involved in planning and executing irradiation experiments
- Addresses materials and fuel experiments
- Focus is on neutron irradiation in reactors, not accelerator, ion, or gamma irradiation
- Design topics
  - Irradiation experiment design
  - Specimen design
  - Capsule design
  - Irradiation vehicle design
  - Ex-reactor experiment design
  - Experiment quality assurance
  - Experiment control and monitoring

Irradiation Experiment Process

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- Interface between experimenter and facility staff starts during proposal development
  - Level of proposal detail influences design activities and timeline
- Experiment Design
  - Define goals/objectives: materials, temperature, dose, energy spectrum
  - Reactor irradiation position: dimensions, flux
  - Experiment hardware: dimension, individual containers,
  - Sample configuration: sample fixtures, standoffs, loading order
- Analyses and Documentation: design and safety, neutronic and thermal
- Paperwork- Requirements, drawings, fabrication and inspection plans
- Fabrication, QA Review
- Insertion of experiment into reactor
- Irradiation and As-run Analyses
- Post Irradiation Activities – Transportation and Post Irradiation Examination (PIE)

ITERATE

ITERATE

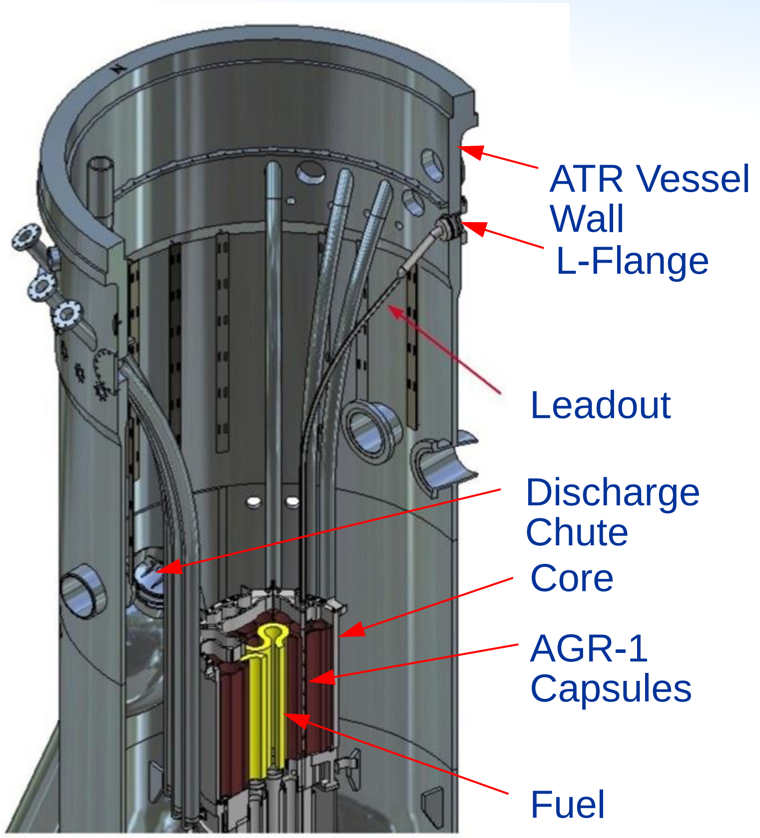
Define Test Objectives

These questions seem obvious, but they must be addressed systematically to ensure useful results through proper experiment design

- Is irradiation absolutely necessary to investigate the phenomena of interest?
  - Irradiation tests are expensive and time-consuming
  - Irradiation volume is limited
- What is the purpose of the experiment?
  - Evaluate materials/fuels performance
  - Generate engineering data
  - Investigate scientific phenomena
- What is the desired outcome of the experiment?
  - Irradiated materials/fuels for PIE
  - Generation of in-situ data during irradiation

Irradiation Vehicle Design

- Test Conditions
- In-Reactor Components
- Ex-Reactor Systems
- Test Specimen Design
- Capsule Design
- Other Design Considerations
- Typical Documentation



Advanced Gas Reactor-1 Test in ATR, USA

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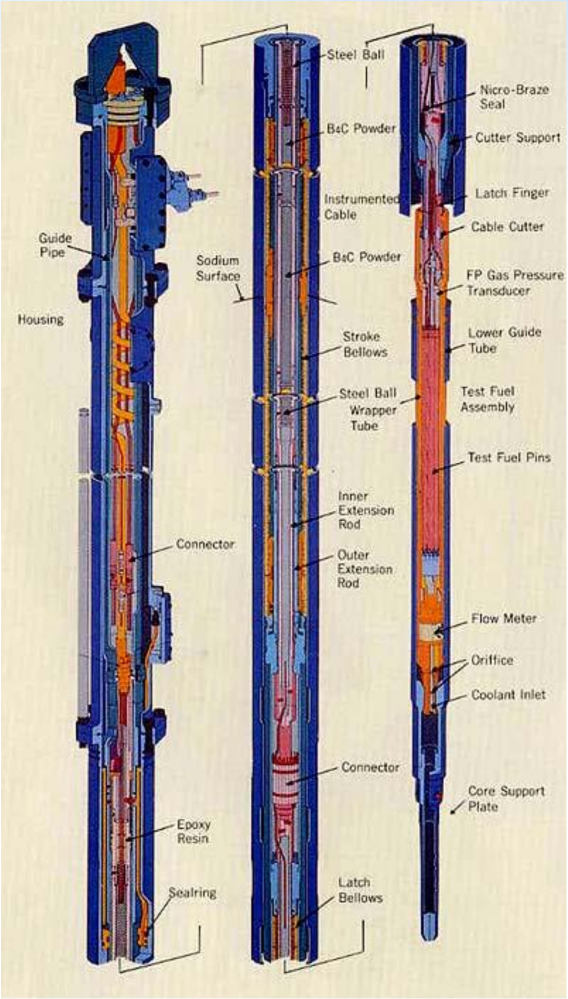
Materials or Fuels?

- Significant differences in experiment design and operation
  - The presence of any fissile (^{233}U, ^{235}U, ^{239}Pu) or fissionable (^{232}Th, ^{238}U, transuranics) isotopes in the test specimens will generally be considered a fueled experiment
  - Safety, analysis, and characterization requirements are different for fuels and materials
  - Choice of irradiation position and irradiation vehicle may differ for fuels and materials
  - In general the lead time will be longer and the cost higher for fuels irradiations
  - Strongly absorbing non-fuel materials (e.g., B, Li, Cd, Hf, Gd) may require extra scrutiny in the safety analyses
- The reactor operator will require a complete accounting for the materials incorporated in the test specimens and irradiation vehicle



Instrumented Test Ass'y (INTA) for Fueled experiments at JOYO, Japan

Irradiation Testing Progression

- Typical fuel and material development programs progress through a series of irradiation test types of increasing complexity
  - Screening
  - Separate-effects (single or multiple)
  - Integral (sometimes with in-situ data collection)
  - Lead test assembly
- Often combined with ex-reactor testing
  - To understand fundamental phenomena during early test phases
  - To establish fully representative fabrication processes during later phases

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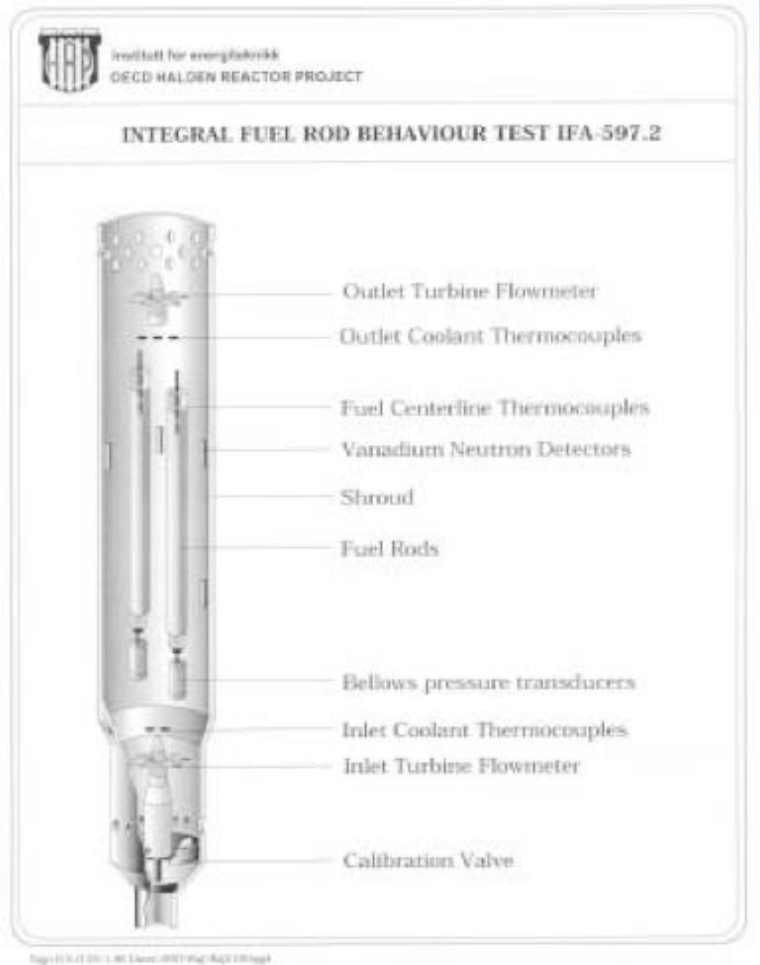
Define Test Conditions

- Screening Tests
  - Comparison of relatively large number of candidate materials or fuels under comparable conditions
  - Shallow but broad
  - Typical test parameters
    - Composition
    - Configuration
    - Fabrication Methods
- Separate Effects Tests
  - Used to generate engineering data for design or understanding of scientific phenomena
    - Single or multiple effects
    - Interactions with other components/other phenomena limited to evaluate effects of parameters on performance
  - Often combined with screening tests in the early stages of a qualification campaign
  - Typical test parameters
    - Temperature
    - Flux, Fluence (Burnup), Time
    - Damage (dpa) rate
    - Environment (e.g., water chemistry)

Define Test Conditions (2)

- Integral Tests
  - Performance evaluation of prototypic materials in near-prototypic configuration and conditions
  - Typically used in the latter stages of a qualification campaign after earlier tests have established the science and engineering
    - Steady-state - normal operation
    - Transient - accident conditions
  - Scaling from integral test results at short lengths (rodlets) to predict full-length performance is not always straightforward
    - Requires fundamental understanding of performance phenomena to apply correct scaling factors



T Tverberg and W Wiesenack. 2002. IAEA-TECDOC-1299, pp. 7-16.

Define Test Conditions (3)

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- In-situ experiments
  - Measure phenomena of interest during irradiation
    - Material properties
      - Electrical (e.g., resistivity)
      - Thermal (e.g., thermal diffusivity)
      - Mechanical (e.g., creep strain)
    - Performance parameters
      - Fission gas release
      - Swelling
  - Very challenging, particularly for in-core instrumentation

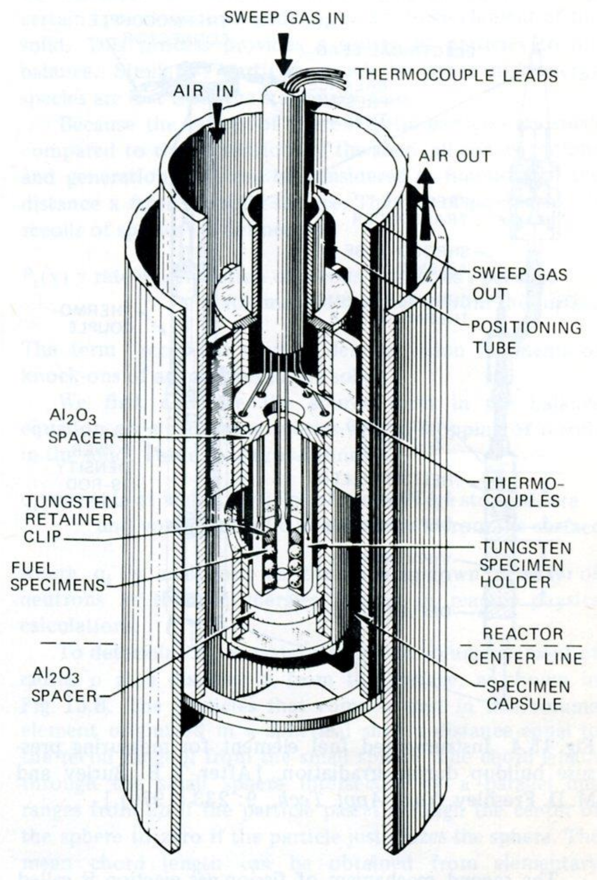

Fig. 15.3 Detail of capsule for in-pile fission-gas release investigation of fused crystal spheres of UO_2. [From R. M. Carroll et al., *Nucl. Sci. Eng.*, 38: 143 (1969).]

DR Olander.1976. *Fundamental Aspects of Nuclear Reactor Fuel Elements.*

Define Test Conditions (4)

- Lead Test Assemblies
  - Typically the final step of a qualification campaign
    - Serves as a performance verification
  - Fully prototypic materials, configuration, and conditions
  - Typically conducted in prototypic plant rather than test reactor

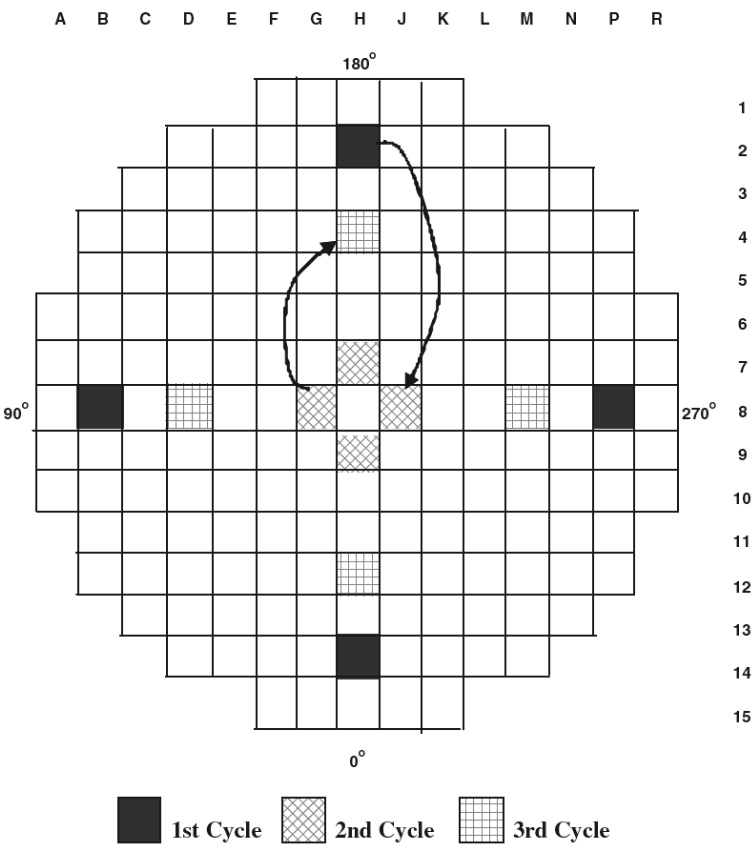

Fig. 7 PLUS7 LTA locations in the core

Kim, KT, et al. 2008.
J. Nucl. Sci. Tech., pp. 836-849.

Define Test Conditions (5)

- When test specimens and test conditions are fully defined, the result is the test matrix for the experiment
- Because a complete test matrix is rarely practical (due to cost and volume limitations), experiment design is used to bound the results and provide some statistical analysis opportunities

Specimen ID	Capsule	Material	Temperature (°F)	D_2O Pressure (torr)
TMIST-1D-1	TMIST-1D	Zircaloy-4	626	7.5
TMIST-1D-2	TMIST-1D	Zircaloy-4 LTA	626	7.5
TMIST-1D-3	TMIST-1D	SM-0.0002	626	7.5
TMIST-1D-4	TMIST-1D	SM-0.0003	626	7.5
TMIST-1C-1	TMIST-1C	Zircaloy-4	698	7.5
TMIST-1C-2	TMIST-1C	Zircaloy-2	698	7.5
TMIST-1C-3	TMIST-1C	SM-0.0002	698	7.5
TMIST-1C-4	TMIST-1C	SM-0.0003	698	7.5
TMIST-1B-4	TMIST-1B	Zircaloy-4	698	2.25
TMIST-1B-3	TMIST-1B	SM-0.0001	698	2.25
TMIST-1B-2	TMIST-1B	SM-0.0002	698	2.25
TMIST-1B-1	TMIST-1B	SM-0.0004	698	2.25
TMIST-1A-4	TMIST-1A	Zircaloy-4	626	2.25
TMIST-1A-3	TMIST-1A	SM-0.0001	626	2.25
TMIST-1A-2	TMIST-1A	SM-0.0002	626	2.25
TMIST-1A-1	TMIST-1A	SM-0.0004	626	2.25

Reactor Selection - Spectrum

- Typically try to match prototypic environment as closely as possible
- Materials damage is primarily caused by fast neutrons so matching prototypic fast flux is desirable
- Matching prototypic thermal flux is typically more important for fuels or absorbing materials
- Matching prototypic conditions is not always possible
  - Accelerated damage (e.g., irradiating thermal reactor materials in a fast reactor spectrum)
  - Fusion reactor materials
  - Must consider effects of non-prototypic spectrum on interpretation of results
- In some cases, spectrum can be tailored for experiment requirements:
  - Addition of thermal filters
  - Addition of reflectors to increase thermal flux
  - Addition booster fuel to increase fast flux

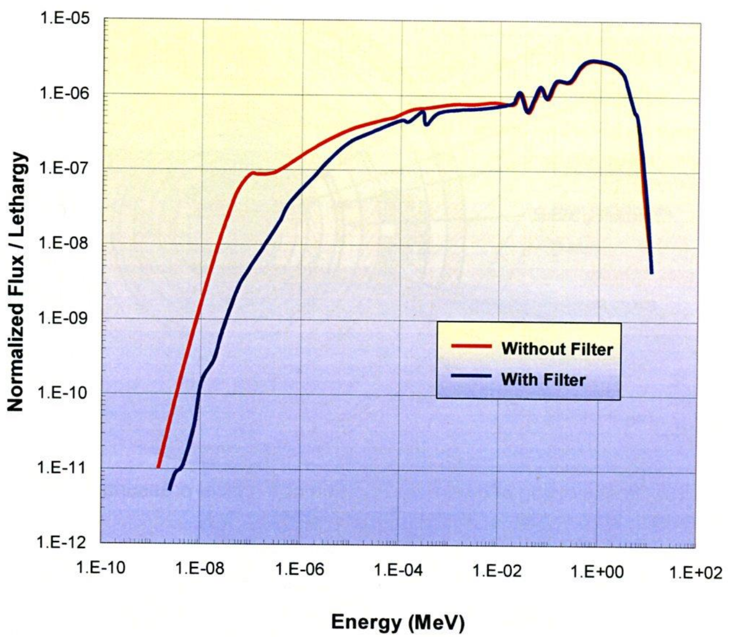

Figure 18. A filter may be used with the ITV to substantially reduce the thermal neutron flux density.

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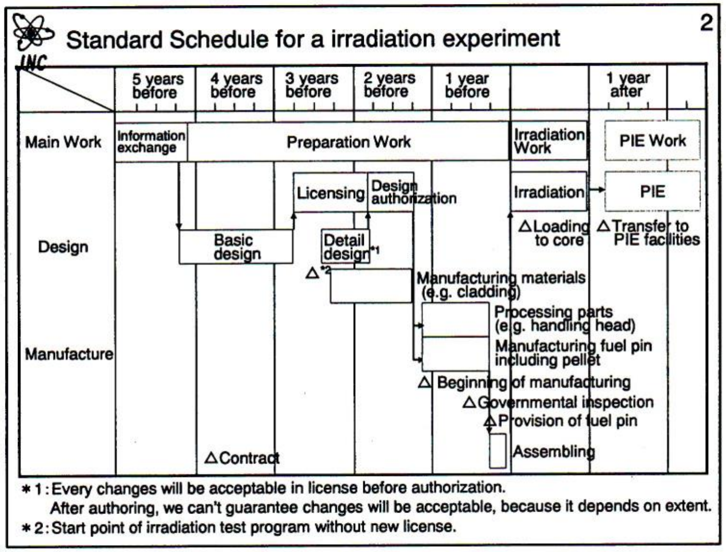
Reactor Selection (2)

- Coolant -Spectrum choice will dictate coolant options
  - Separate consideration of coolant is important if specimens are to be exposed to fluid during irradiation (e.g., corrosion experiment)
  - Incompatible fluids will present reactor safety issues (e.g., alkali metals and water)
- Operating Characteristics
  - Availability (EFPD per year)
  - Cycle length
  - Experiment planning lead time
  - Reactor mission will impact operati
    - Irradiation testing (ATR, JOYO)
    - Isotope production (NRX, HFIR)
    - Demonstration plant (Monju)
    - Power reactor



Reactor Selection (3)

- Special Considerations
  - Projected reactor lifetime
  - Security requirements on test specimens or data
  - Unique irradiation capabilities
    - Materials or gas handling (e.g., tritium)
    - Rabbit or loop operations
    - Reactor instrumentation (e.g., gas tagging)
  - Special post-irradiation examination (PIE) capabilities
    - Experiment reconstitution
    - In-cell examination or test capabilities

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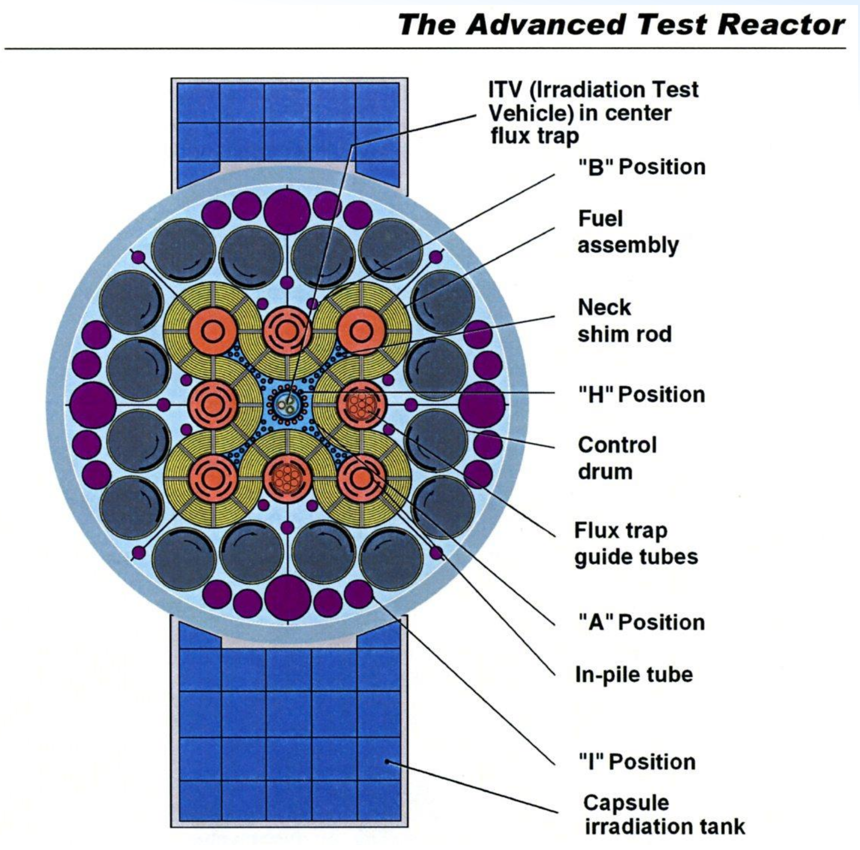
Reactor Selection (4)

- Reactor location
  - Impacts cost and (potentially) schedule
  - Language barriers impact cost/schedule and increase importance of deliberate planning
  - Inter-governmental agreements typically required for work outside your country before specific scope can be agreed
- Quality Assurance Requirements
  - It is important to understand the quality expectations of the reactor
    - Material certification required?
    - Who owns design responsibility?
  - The reactor QA organization will evaluate your QA program - particularly if test articles will be provided by you
    - ASME NQA-1 (basic, supplemental, different versions)
    - ISO programs common overseas
    - ASME Boiler and Pressure Vessel Code

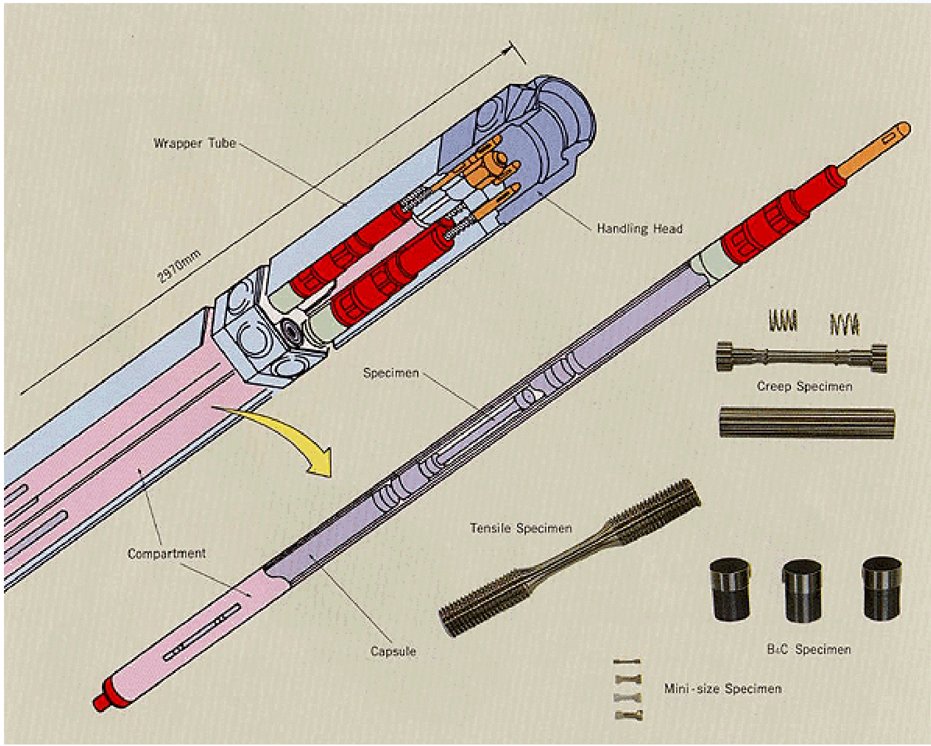
Select Irradiation Position

- Match desired test conditions
  - Spectrum
  - Flux
  - Environment
- Irradiation volume
  - Most reactors offer a variety of irradiation positions that vary in size
  - In general, higher volume locations tend to be in regions of lower flux
- Special experiment needs
  - Active gas handling
  - Closed coolant loop



Select Test Design Type

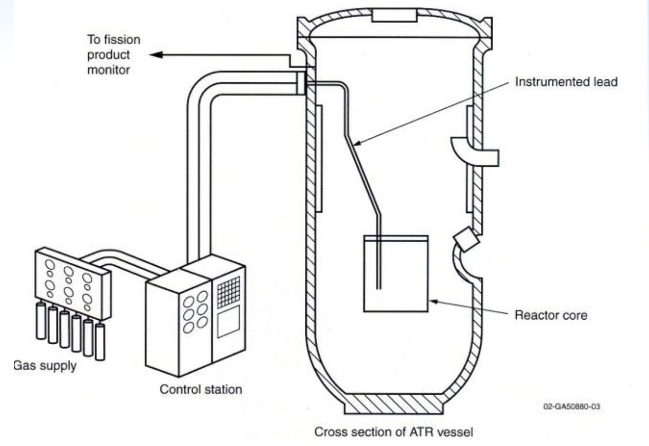
- Static Capsule
  - Relatively simple to design and fabricate
  - Usually located in specific reactor positions with well-defined spectrum/flux
  - No active temperature measurement or control
  - Passive temperature monitoring possible
- Hydraulic Tube ("rabbit")
  - Good for short exposure
  - Least expensive option
  - Little to no temperature control
  - Passive temperature and fluence monitoring possible



Materials Irradiation Test Assembly (MITA) at JOYO, Japan

Select Test Design Type (2)

- Instrumented (lead) experiments
  - More complex and costly to design and fabricate
  - Can be tailored for very specialized experiments
  - Active temperature measurement and control possible
  - Introduction of sweep gases possible
  - Leads for in-situ testing
  - Available reactor positions may be limited due to possible interference of leads with fuel handling
- Loops
  - Some test reactors operate closed coolant loops that can provide an isolated environment
    - ATR, SM-2 - Pressurized water loops
    - BOR-60 - Sodium loop channel within core
  - Specific coolant conditions possible
  - Separate experiment releases from reactor primary coolant
  - Typically most expensive option



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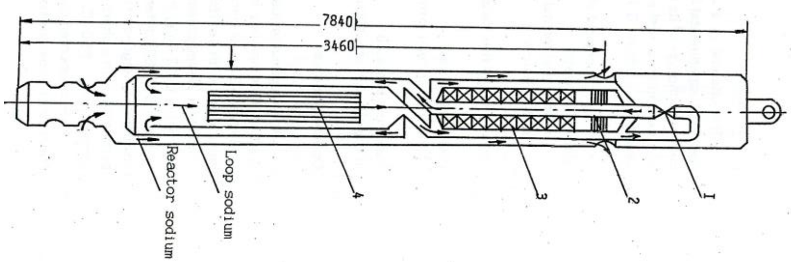


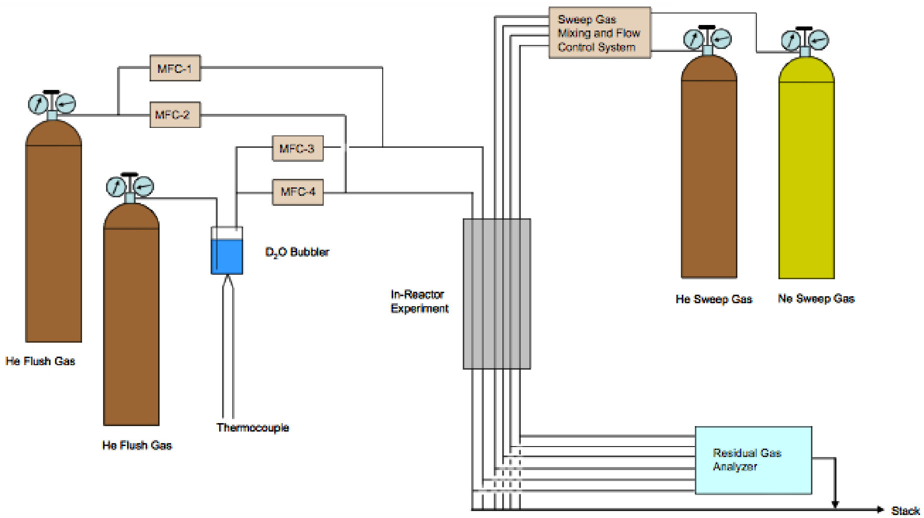
RIAR. 1995.

Experiment Design Considerations

- Sample material, size, and geometry
  - Finite test volume
  - Potential materials interactions
  - Sample preparation for PIE
  - Sample positioning (experiment will be turned upside down!)
- Rodlet/capsule size and geometry
  - Existing designs may save analysis time and cost
  - Independent volumes (for tailored temperatures) require increased volume (plenum, hardware)
  - Gas gap size and gas composition (for tailored temperature)

Ex-Reactor Systems (Lead Experiments Only)

- Ex-reactor support systems must be designed to interface safely with reactor systems
- Number of leads dictated by
  - Experimental needs
  - Available cross-section area within irradiation position
  - Available ex-reactor space for necessary equipment
  - Cost



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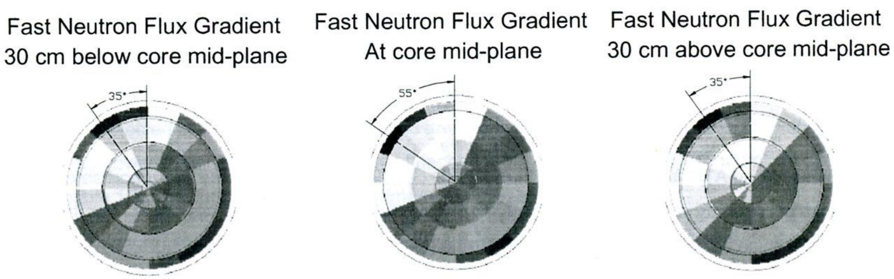
Test Specimen Design

- Geometry influences irradiation characteristics
  - Temperature
    - Radial temperature profile
    - Gamma or neutron heating
    - Internal heat generation for fuels or strong absorbers
    - Self-shielding
  - Fluence
- Adjacent test specimens (within same holder or capsule) must be chemically compatible



Fast flux gradients across small B position in ATR (Parry 2007)

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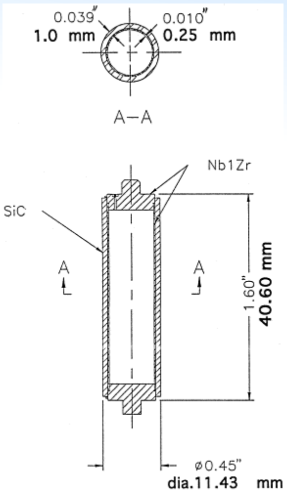
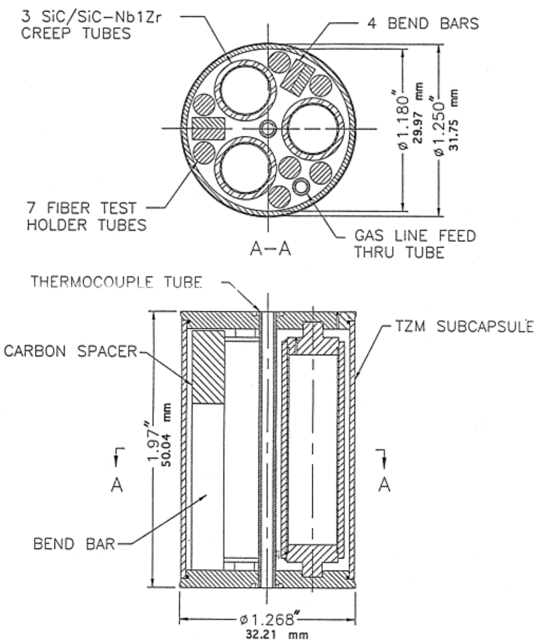
Test Specimen Design (2)

- Capsule Fixturing
  - Holds specimens in place to achieve desired test conditions
  - Must be inert at operating conditions in capsule environment
  - Must survive desired fluence (with margin)
  - Must allow for thermal expansion and irradiation growth of specimens
  - Must allow disassembly and removal of specimens for PIE
- Specimen environment
  - Gas (e.g., He)
  - Liquid (e.g., water or liquid metal)

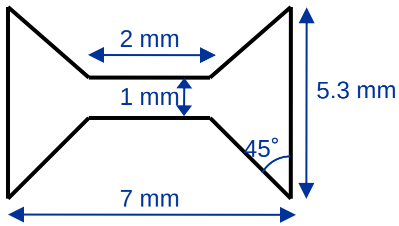


Lewinsohn et al. 1998. *JNM*, 253:36 -46

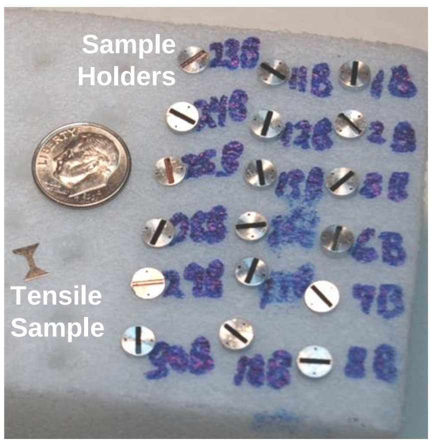


Specimen Examples, Materials

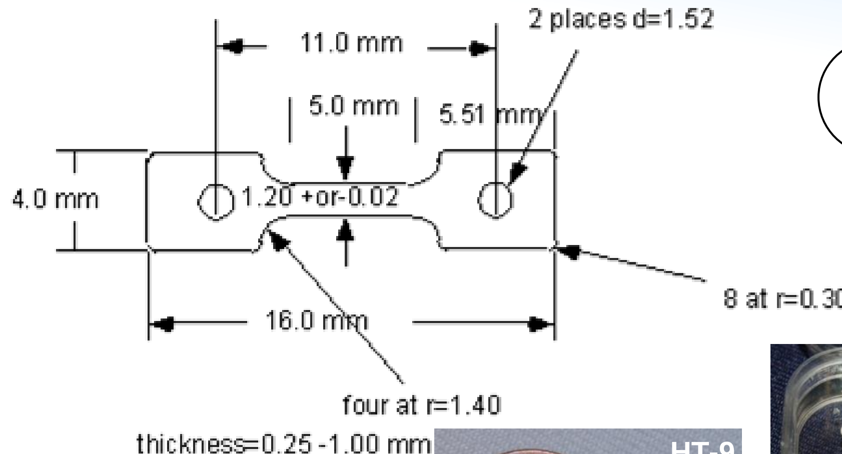
Mini-tensile



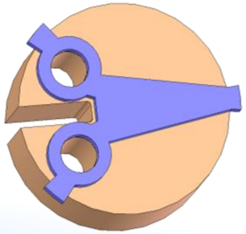
thickness = 0.2-1.0 mm



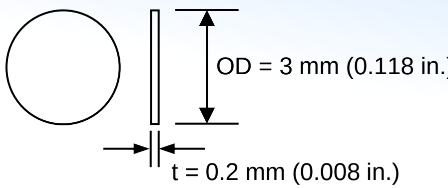
Mini-tensile

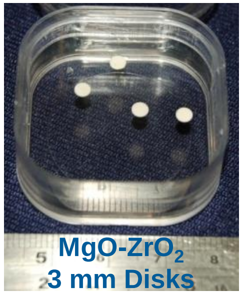


Compact Tension



TEM Disk



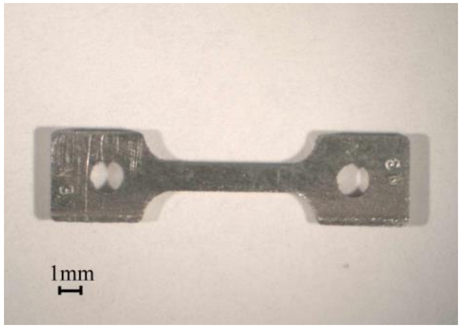


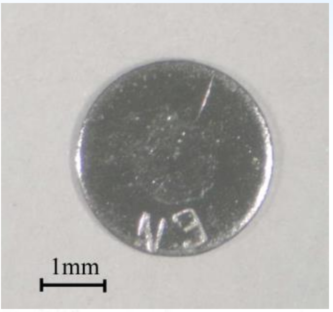
Larger disks (6 mm) used for diffusivity measurements

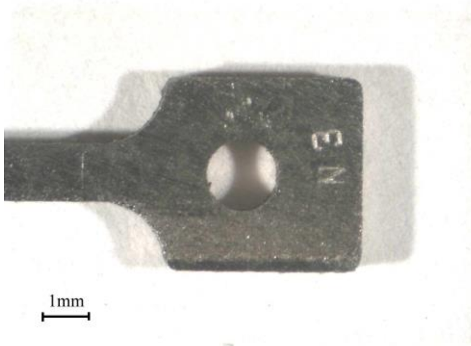
Thicker disks used for shear punch and hardness testing

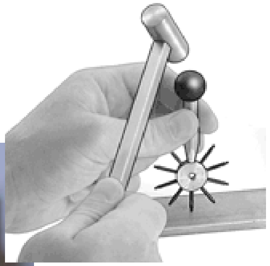
Sample Preparation and Marking

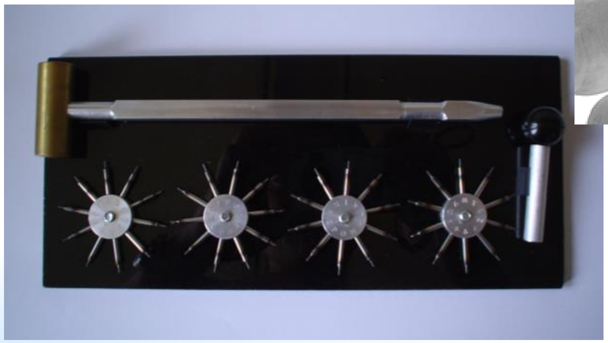
- Consider PIE preparation during experiment design
- Evaluate potential material interaction
- Label samples with unique ID
  - Mini-punch set to mark samples
- Sample loading sequence recorded during experiment assembly





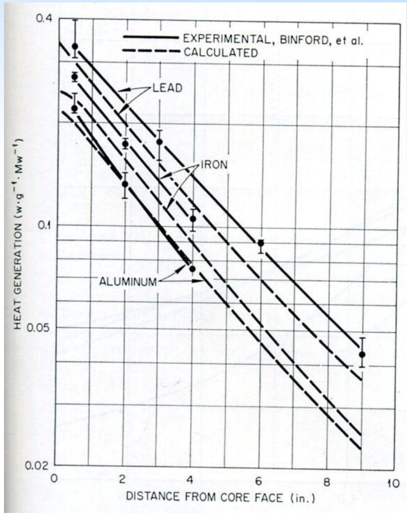






Capsule Design - Temperature

- Gamma/Neutron Heating
  - Caused by interaction of gammas or neutrons with nuclei
  - Heating is proportional to the flux
  - Gamma heating most important for structural materials
  - Neutron heating can be important for low-Z materials or reactor positions with very soft spectrum
- Ballast
  - Used when specimen temperatures need to be increased beyond the ability of gas gaps and gamma heating in specimens/fixturing
  - Takes advantage of fact that gamma heating is proportional to atomic number
- Gas Gap Temperature Control
  - Introduces a low conductivity radial gap to increase temperature of capsule interior
  - Can be passive (fixed mixture) or active (variable mixture)
  - One or more gas gaps using He-Ne or He-Ar mixtures



Blizard and Abbott (Eds), Reactor Handbook, Vol. IIIB - Shielding, 1962

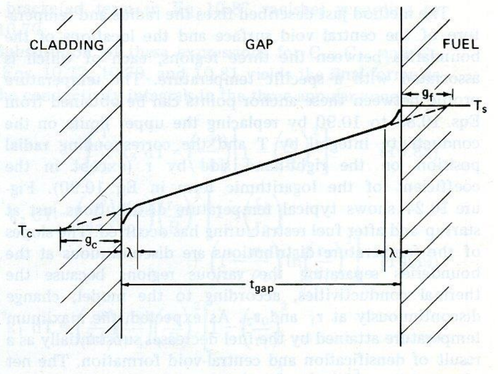


Fig. 10.25 Temperature profile in a gas between two plane surfaces.

DR Olander.1976. *Fundamental Aspects of Nuclear Reactor Fuel Elements*

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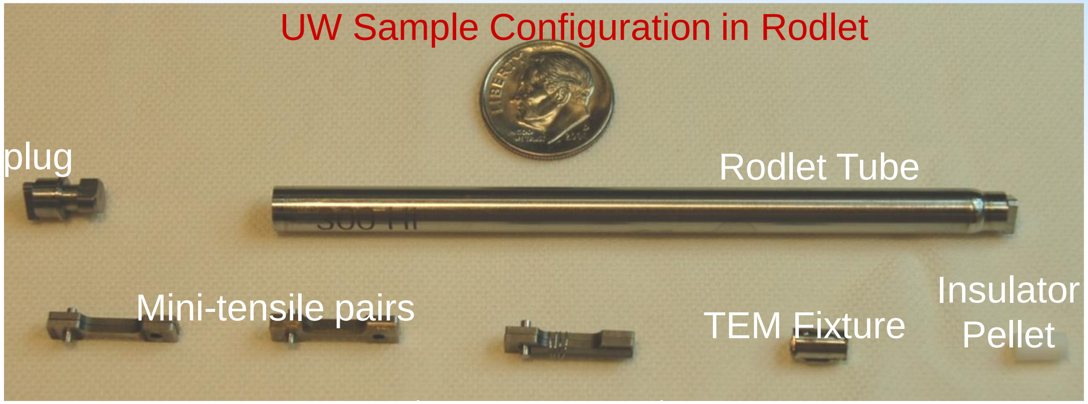
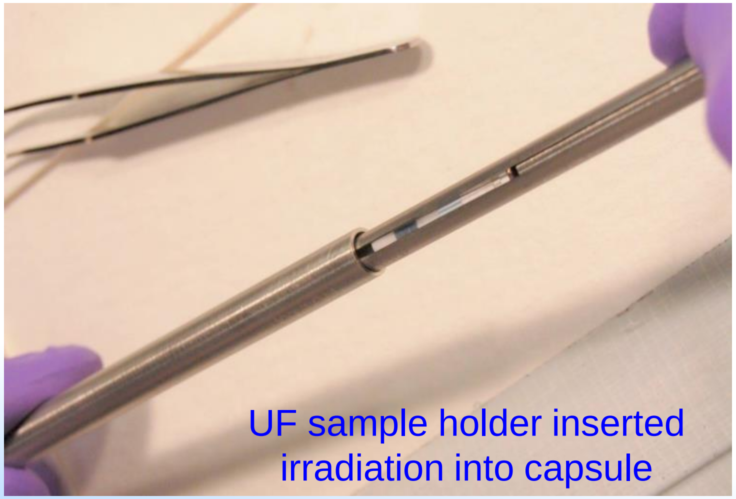
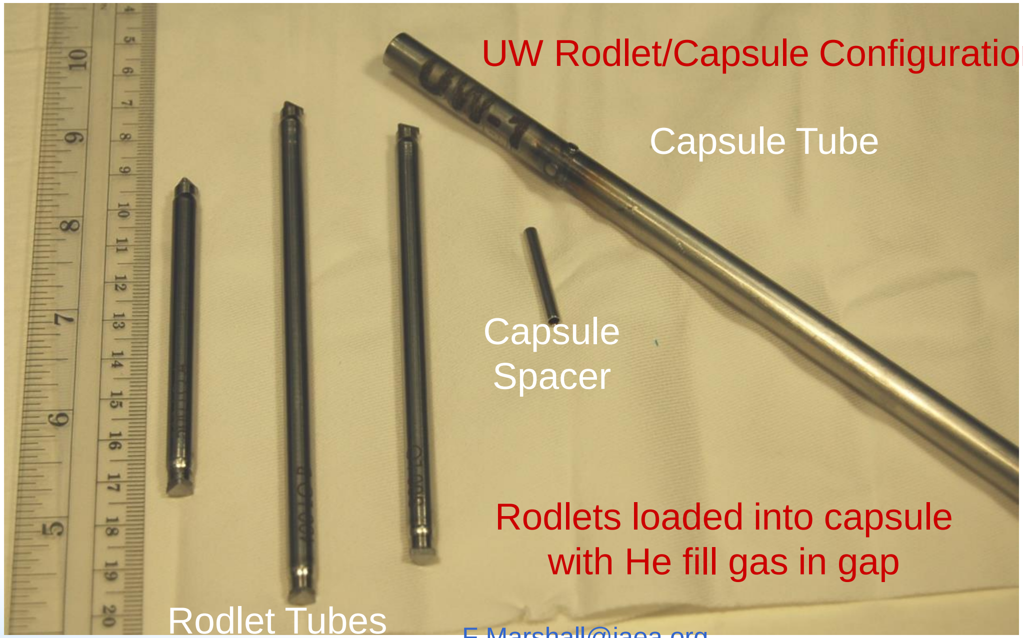
Sample / Experiment Configuration

- Example capsule OD / ID
  - 9 / 6 mm
  - 9.5 / 7.7 mm
  - 12.2 / 10.9 mm
  - 12.1 / 11 mm
- Gas mixtures in sample holders and capsules tailor temperatures: 200-700°C
  - Ar/He







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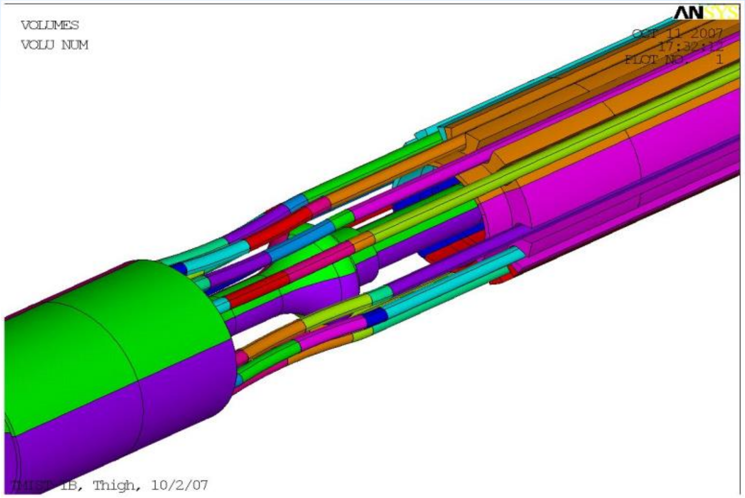
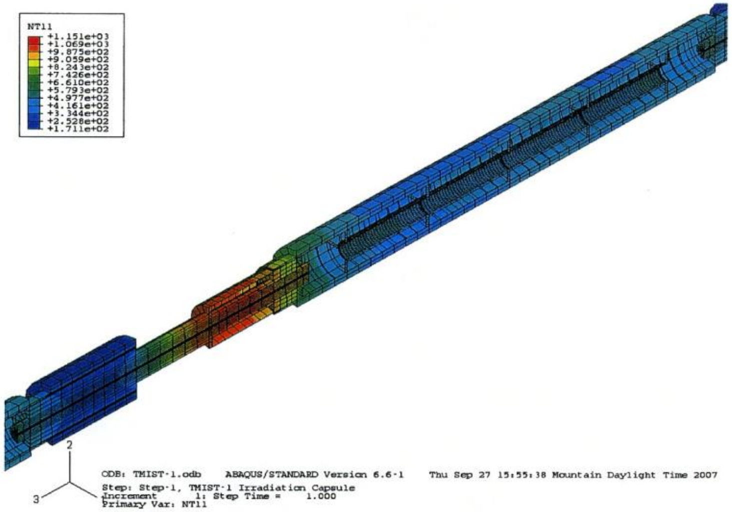
Capsule Design

- Thermal Modeling
  - Scoping calculations may be performed using 2D codes (e.g., Heating)
  - Final calculations, particularly for complex arrangements, should be performed using 3D codes (e.g., ANSYS, ABAQUS)
    - Consider axial and circumferential variability
  - Radiation effects
- Routing leads
  - Number of leads
    - Active temperature control will require pair of inlet/outlet gas lines for each temperature control region
    - Sweep gases also will require pairs of lines
  - Materials/Sizes
    - Typically 304 or 316 SS (1.57 mm OD x 0.381mm wall thickness)
    - Smaller gas lines can be used, but present significant fabrication challenges
  - Generally routed from the top of the experiment down - must be accommodated by capsule design features





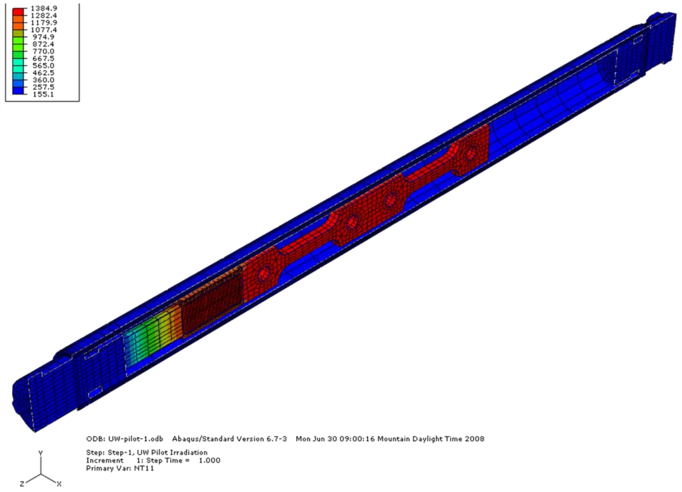
Capsule Design (2)

- Bulkheads
  - Used to isolate independent temperature control gas volumes
  - Penetrations through bulkheads for gas lines/thermocouples must be gas tight (e.g. via brazing)
  - Capsule design must consider effects of welding/brazing bulkheads on test specimens
  - Braze material must survive irradiation
- Differential Strain Relief
  - Differential axial strain will occur in lead experiments
    - Temperatures inside the gas gap are hotter than pressure boundary, causing capsule internals to expand more than pressure boundary
  - Various approaches have been used
    - Bellows or pigtails attached to bulkheads to accommodate strain of capsule internals
    - Pre-bends in gas lines/thermocouples to accommodate differential strain without uncontrolled bowing

Mini-Flex Hydroformed Bellows

Capsule Design Analysis

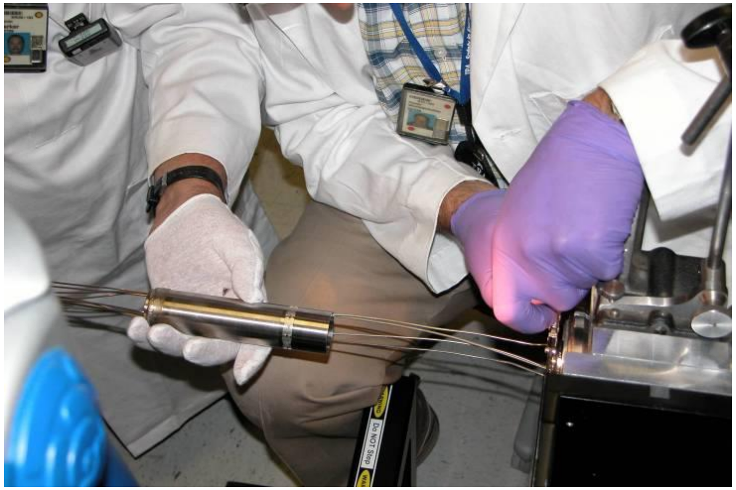
- Neutronics
  - Reactivity worth
  - Activation analysis
- Thermal-Hydraulics
  - Departure from Nucleate Boiling (DNB)
  - Flow Instability Ratio
  - Various steady-state and transient conditions
- Structural
- Radiological
- Overpressure protection
- Seismic



→ Experiment and Reactor Safety Analyses – Required by the experiment facility to ensure no risk to facility or personnel due to experiment

Other Design Considerations

- Fabricability
  - Clearances/straightness
  - Weld/braze joint design, approved process?
  - Handling/cleanliness
  - Glovebox assembly required for fuel?
- Post-Irradiation Examination
  - Ease of disassembly
  - Activation/dose effects
  - Specimen identification
- Shipping/handling
  - Existing shipping container?
  - Closed road
  - International
- Waste Disposal
  - Existing disposition path for all activated materials?



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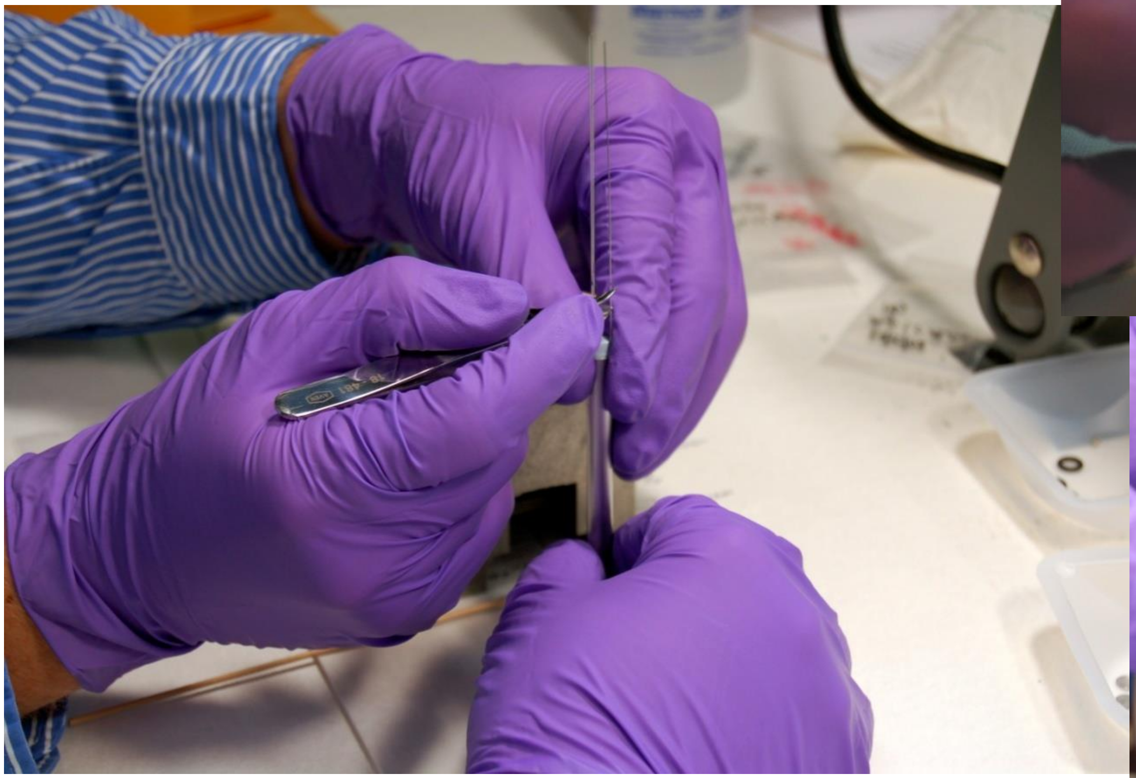
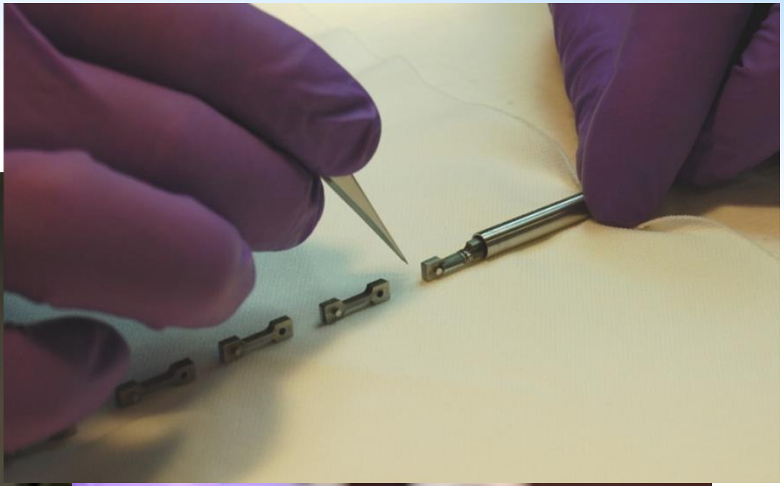
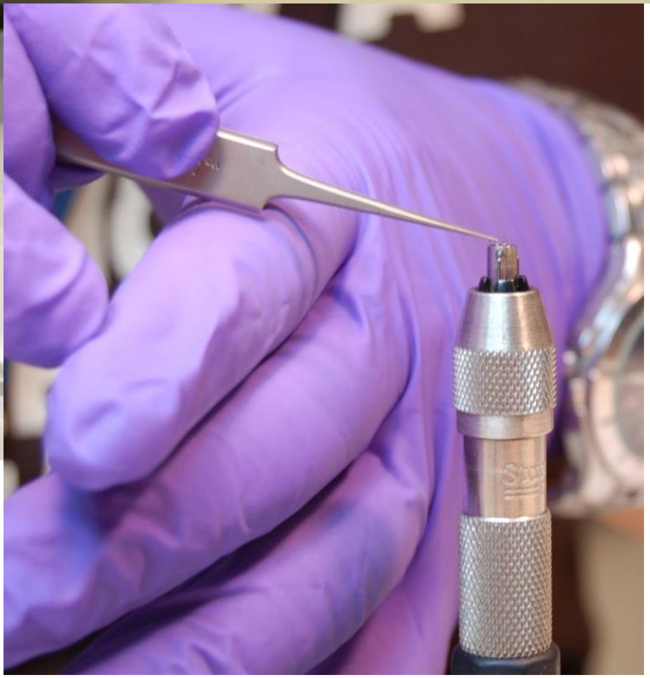
Sample Loading







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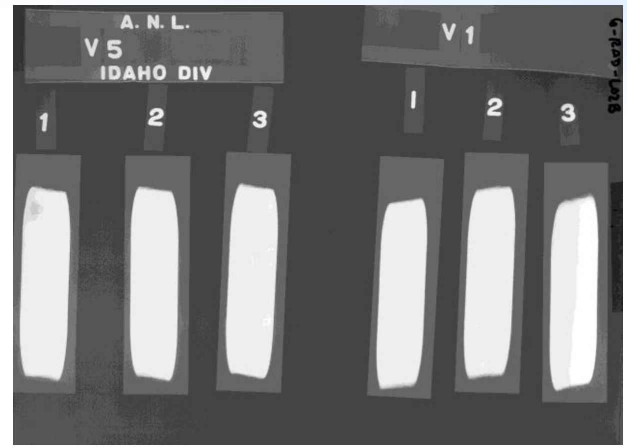
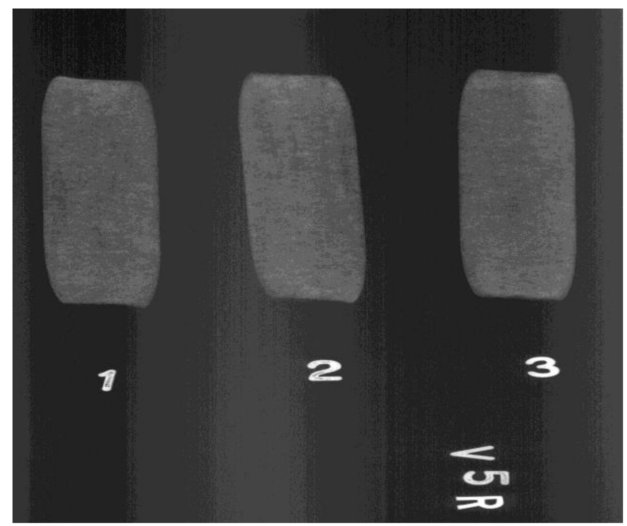
Quality Assurance on Finished Specimens

- Dimensional inspection
- Visual inspection
- Contamination
- Bond testing
- Blister testing
- Radiography
  - Fuel location
  - Fuel density

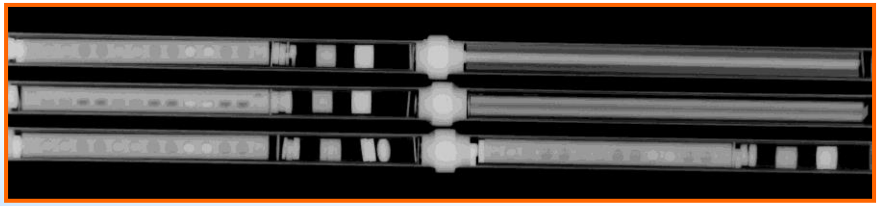


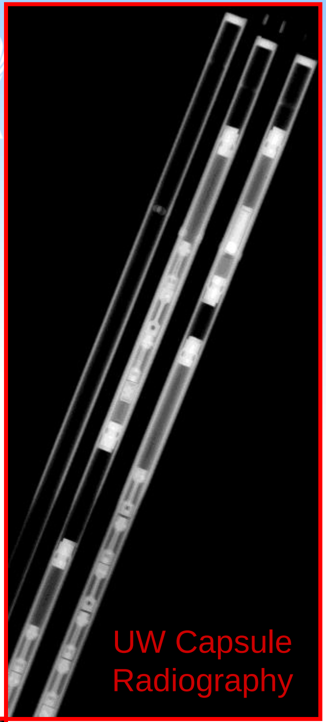


Fabrication Inspection

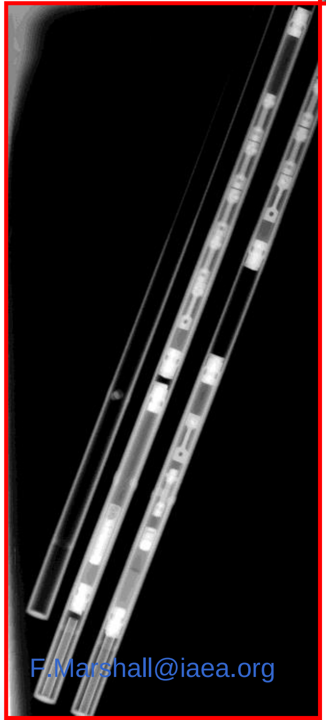
- Weld inspection
  - Visual
  - Radiography
  - Liquid penetrant
  - Helium leak test
- Loading verification
- Dimensional inspection, straightness
- Material / sample chemistry verification or analysis

U Florida Capsule Radiography

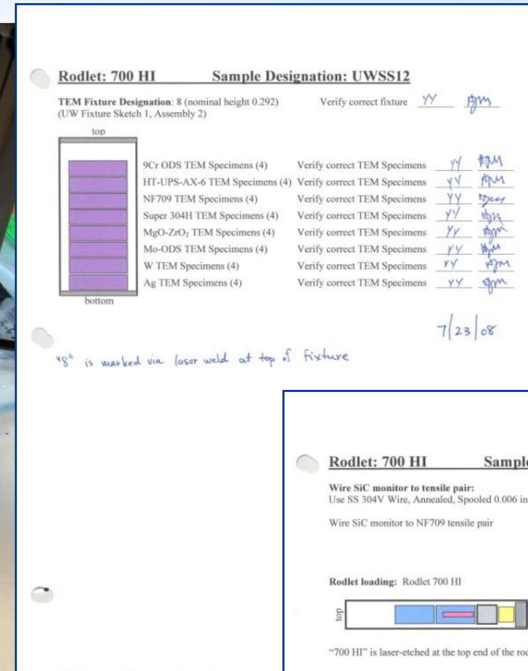




UW Capsule Radiography



Experiment Quality Assurance



Rodlet: 700 HI Sample Designation: UWSS12

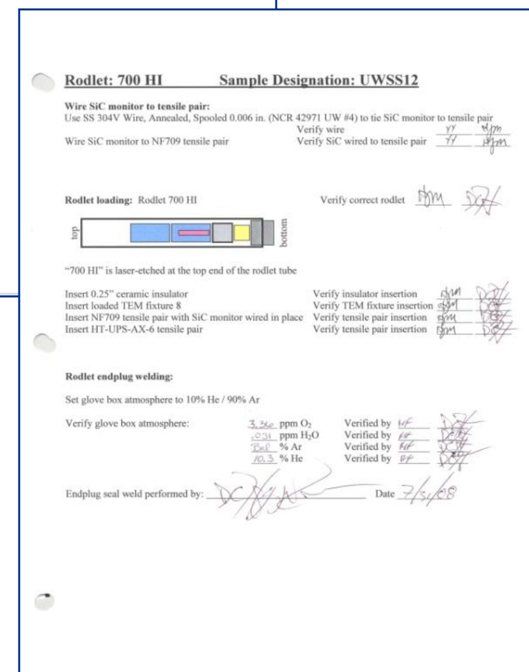
TEM Fixture Designation: 8 (nominal height 0.292) (UW Fixture Sketch 1, Assembly 2) — Verify correct fixture YY

top / bottom

Specimens	Verification		
9Cr ODS TEM Specimens (4)	Verify correct TEM Specimens	YY	
HT-UPS-AX-6 TEM Specimens (4)	Verify correct TEM Specimens	YY	
NF709 TEM Specimens (4)	Verify correct TEM Specimens	YY	
Super 304H TEM Specimens (4)	Verify correct TEM Specimens	YY	
$MgO-ZrO_2$ TEM Specimens (4)	Verify correct TEM Specimens	YY	
Mo-ODS TEM Specimens (4)	Verify correct TEM Specimens	YY	
W TEM Specimens (4)	Verify correct TEM Specimens	YY	
Ag TEM Specimens (4)	Verify correct TEM Specimens	YY	

7/23/08

"8" is marked via laser weld at top of fixture



Rodlet: 700 HI Sample Designation: UWSS12

Wire SiC monitor to tensile pair:
Use SS 304V Wire, Annealed, Spooled 0.006 in. (NCR 42971 UW #4) to tie SiC monitor to tensile pair
Verify wire YY
Wire SiC monitor to NF709 tensile pair — Verify SiC wired to tensile pair YY

Rodlet loading: Rodlet 700 HI — Verify correct rodlet

top / bottom

"700 HI" is laser-etched at the top end of the rodlet tube

Insert 0.25" ceramic insulator — Verify insulator insertion
Insert loaded TEM fixture 8 — Verify TEM fixture insertion
Insert NF709 tensile pair with SiC monitor wired in place — Verify tensile pair insertion
Insert HT-UPS-AX-6 tensile pair — Verify tensile pair insertion

Rodlet endplug welding:

Set glove box atmosphere to 10% He / 90% Ar

Verify glove box atmosphere:
3.36 ppm O_2 — Verified by
.031 ppm H_2O — Verified by
Bal % Ar — Verified by
10.3 % He — Verified by

Endplug seal weld performed by: ______ Date 7/31/08

Material/parts green tag

416.22
03/29/2007
Rev. 03

W.O./Purchase Order No.	Revision No.	Receipt No.	Quality Level
PLN-2790	0	N/A	1 (2) 3

Line Item No.	Quantity Inspected	Catalog I.D.	QA/UTC No.
1	1	N/A	N/A

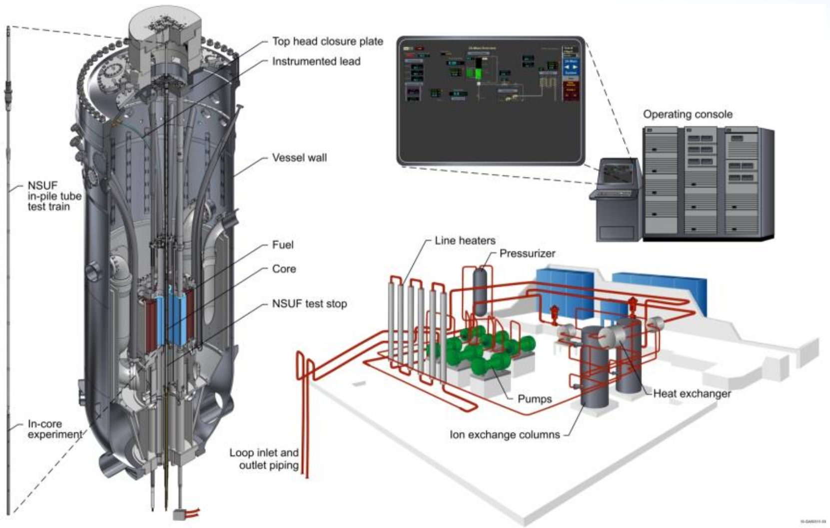
Item Description: University of Wisconsin Loaded Capsule

Specification/Drawing	Rev.	Work Order No.	Serial No.
PLN 2790	0	N/A	UW-1

Facility/Area/System	Inspector	Date
NSUF	C.W. Cooper	8-21-08

Experiment Control and Monitoring

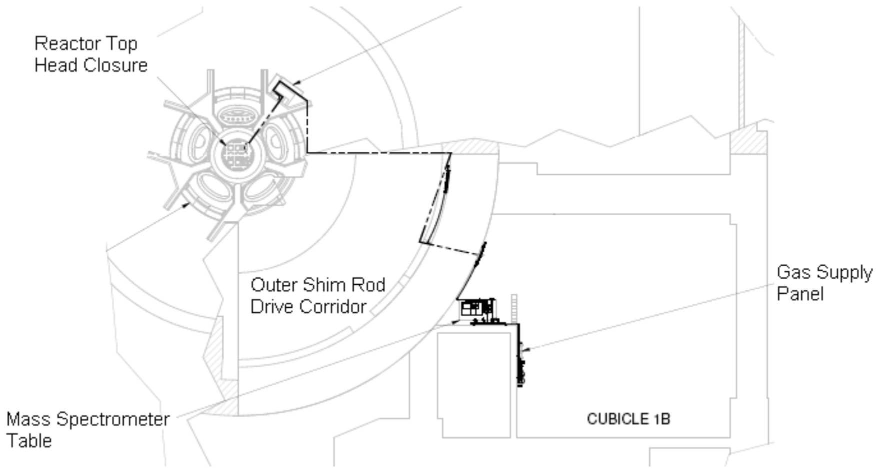
- Temperature Control
- Temperature Measurement
- Dosimetry
- Ex-Reactor Systems Control
- Remote Data Viewing
- Operating Procedures



ATR Loop Experiment

Ex-Reactor System Control

- Temperature Control
  - Gas analyzers to distinguish He, Ne, Ar
  - Automated or manual mixing via mass flow controllers
  - Back pressure control
- Environment Control (e.g., oxidation experiment)
  - Oxidants usually in low concentration within an inert carrier gas (e.g., He)
  - For a water vapor, the dewpoint can be controlled via bubblers and mass flow controllers or by dewpoint generators
  - Similar mass flow control methods can be used for other oxidizing gases
  - Mass spectrometers can be used to monitor partial pressures and depletion



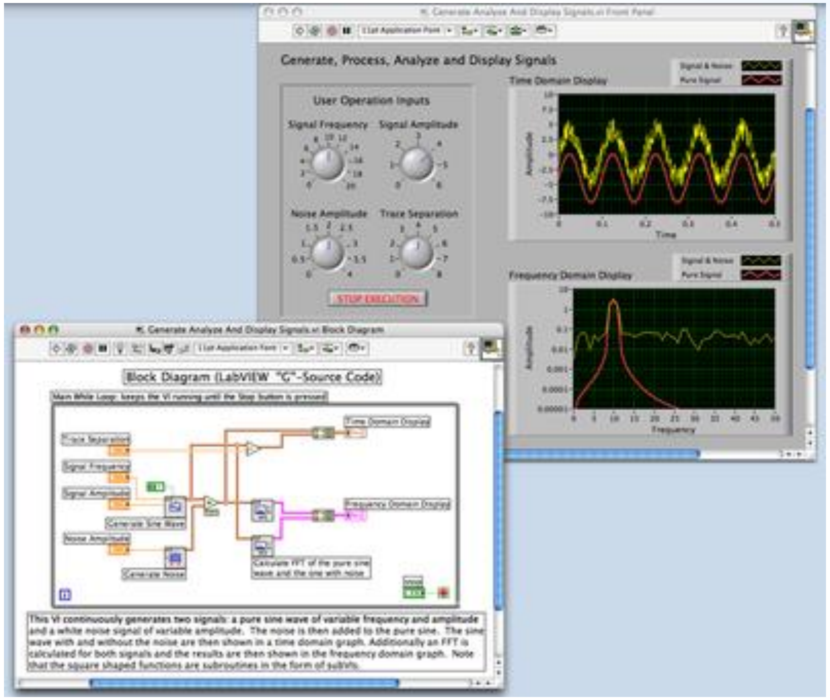
Longhurst and Sprenger. 2008. *TFG Meeting*, Richland, WA

Ex-Reactor System Control

- Sweep Gas Control
  - Shielding, contamination control, and effluent processing for systems sweeping radioactive species (e.g., tritium, fission gases)
  - Must consider possibility of chemical interactions over long tubing runs (typically > 15 m)
  - Measurement methods will depend on species (ion gage, scintillation counter, gamma spec)
- In-situ Experiment Control
  - Degradation of thermocouple or electrical wiring with dose
  - Moving parts in mechanical systems for in-situ loading

Remote Data Collection and Viewing

- Use of data acquisition software (e.g., LabVIEW) and high-speed internet communication protocols makes remote data viewing (but not experiment control) possible
  - Reduces travel expenses and data manipulation time at reactor site
- Consider data archive requirements for system design
  - Frequency of collection
  - Retention time



Experiment Control Documentation

- Safety analyses must be completed and accepted by reactor operator before experiment can be inserted
  - QA documentation must be complete, including closure of all non conformance reports, deficiency reports, unresolved safety questions, etc.
- Operating guidance from experimenter to reactor operator
- Operating procedures for experiment systems
  - Experiments generally controlled by reactor operators or dedicated experiment operators at reactor site

MTR Test Design Summary

- Irradiation testing requires a thoughtful, methodical approach
  - Reactor safety
  - QA culture
  - Expensive experiments with long lead times
- A proactive approach with Safety and QA organizations is necessary to avoid surprises (i.e., unexpected costs and delays)
- Careful planning and good communications between experimenter, designer, fabricator, reactor operator, safety analyst, and hot cell operator (for PIE) are vital

IAEA 60 Years

Atoms for Peace and Development

Thank you!

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