Overview of Irradiation Experiment Planning

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Goal and Agenda

- This overview is designed to familiarize potential experimenters with the steps involved in planning and executing irradiation experiments
- Primary emphasis is structural materials experiments but unique aspects of fueled experiments will be addressed
- Focus is on neutron irradiation in reactors, not accelerator, ion, or gamma irradiation
- High-level topics
  - Irradiation Experiment Design
  - Irradiation Vehicle Design
  - Experiment Control and Monitoring

Irradiation Experiment Design

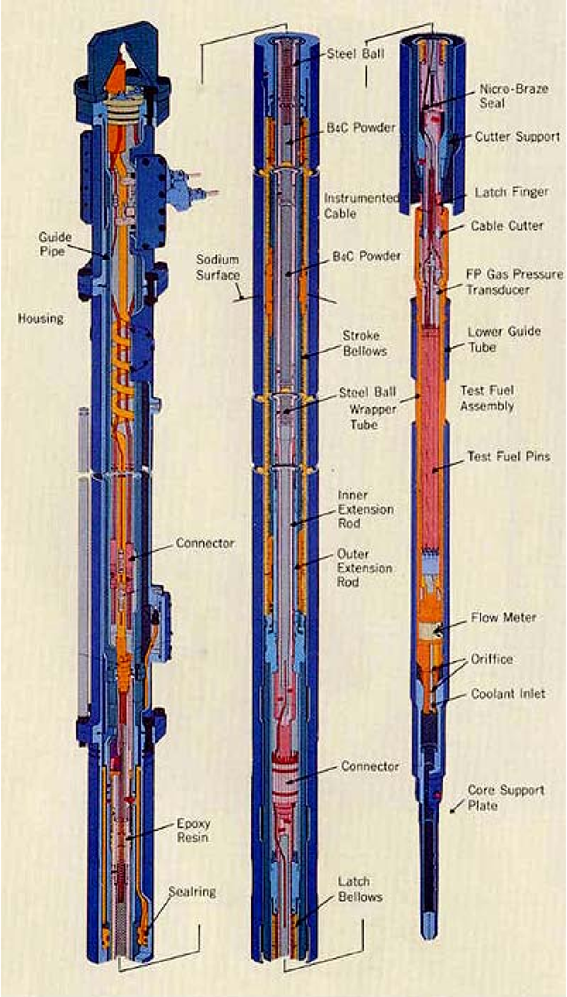
- Define Test Objectives
- Materials or Fuels?
- Define Test Conditions
- Reactor Selection
- Define Irradiation Position

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

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

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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

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

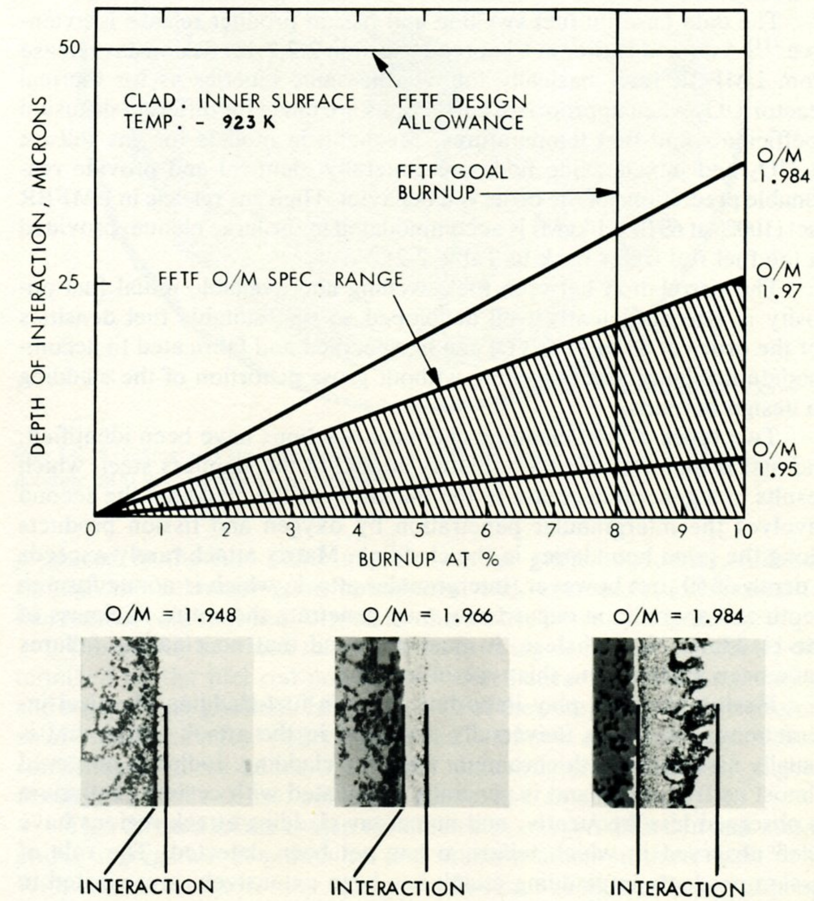

Fig. 3-8. Fuel–cladding chemical interaction (FCCI) in mixed oxide fuel irradiated in EBR-II (Ref. 11).

JTA Roberts. 1981. *Structural Materials in Nuclear Power Systems.*

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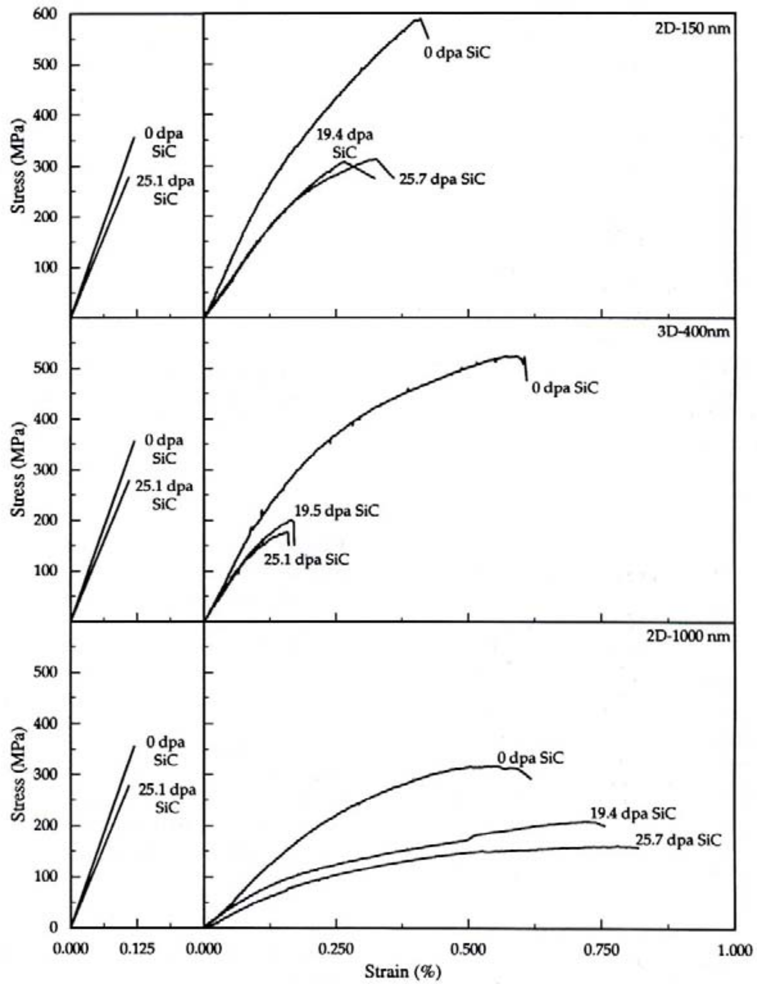
Define Test Conditions

- 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)



GW Hollenberg, et al. 1995. *JNM*, 219:70-86.

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Define Test Conditions

- 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.

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Define Test Conditions

- 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

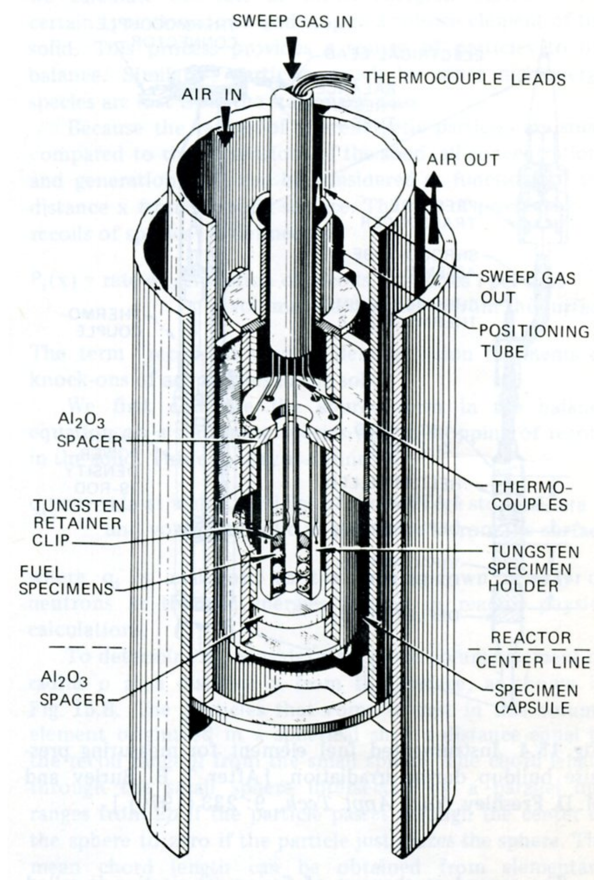

Fig. 15.3 Detail of capsule for in-pile fission-gas release investigation of fused crystal spheres of UO_2. [From R. M. Carroll et al., *Nucl. Sci. Eng.*, 38: 143 (1969).]

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

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Define Test Conditions

- 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

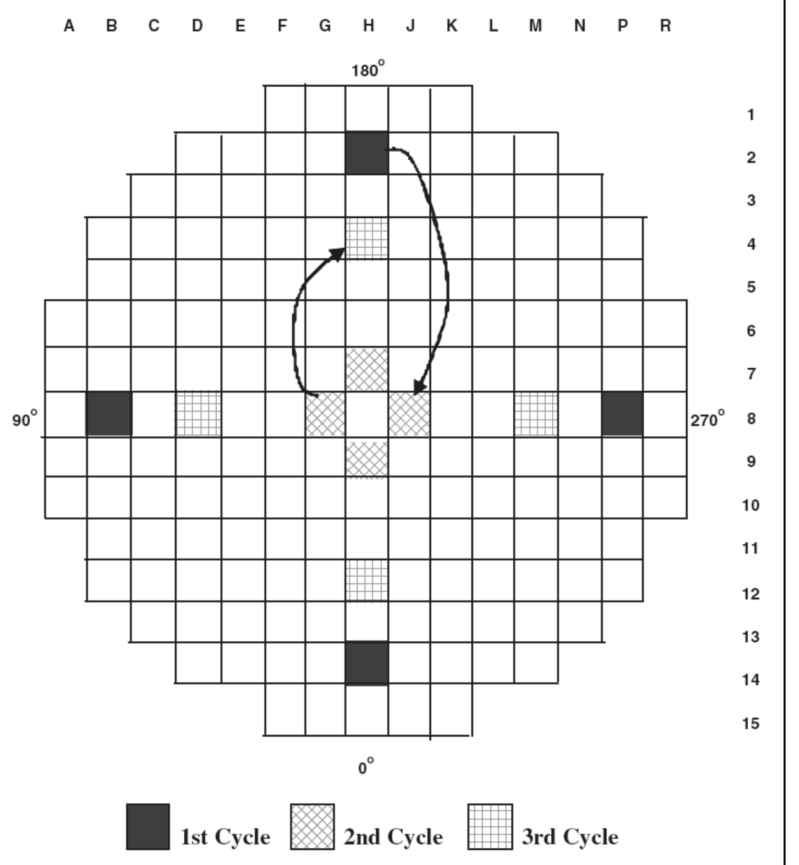

Fig. 7 PLUS7 LTA locations in the core

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

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Define Test Conditions

- 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), Design of Experiments is typically employed to some degree

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, filters can be employed to tailor the spectrum

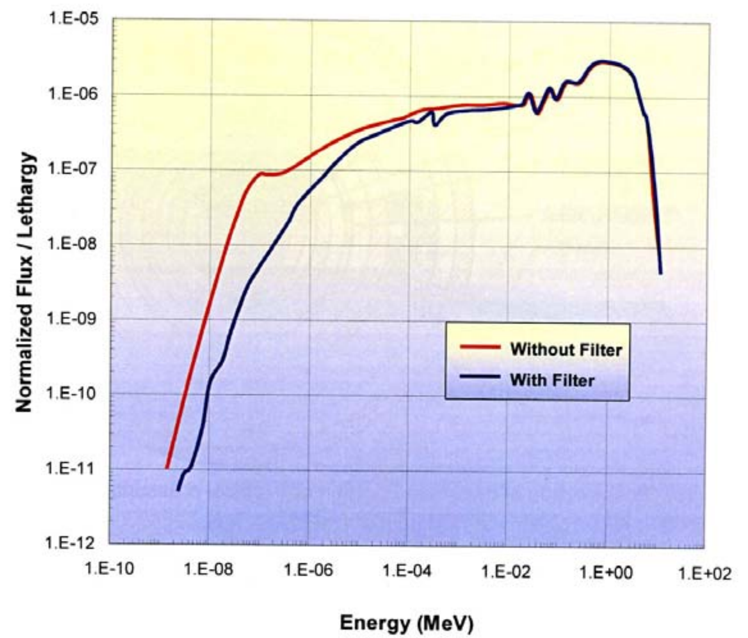

Figure 18. A filter may be used with the ITV to substantially reduce the thermal neutron flux density.

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Reactor Selection

Thermal Test Reactors

Reactor	Location	Rated Power (MW_t)	Peak Fast Flux $(10^{15}\ n/cm^2\text{-}s)$	Core Volume (l)
SM	Russia	100	2.0	48
Osiris	France	40	0.26	
Japan Materials Testing Reactor	Japan	50	0.40	244
High Flux Reactor	Netherlands	45	0.46	169
High Temperature Engineering Test Reactor	Japan	30	0.02	8856
FRM-II	Germany	20	0.50	18
Advanced Test Reactor (with fast flux boosting)	USA	250	0.20	275
High Flux Isotope Reactor	USA	85	1.7	51

Fast Test Reactors

Reactor	Location	Rated Power (MW_t)	Peak Fast Flux $(10^{15}\ n/cm^2\text{-}s)$	Core Volume (l)
Monju	Japan	714	6.0	2340
Phˇnix	France	563	7.2	1227
Joyo (Mk III)	Japan	140	4.0	227
BOR-60	Russia	60	3.5	60
Fast Breeder Test Reactor	India	17.4	1.4	24
Fast Flux Test Facility	USA	400	7.2	1040
Experimental Breeder Reactor II	USA	62.5	2.5	73

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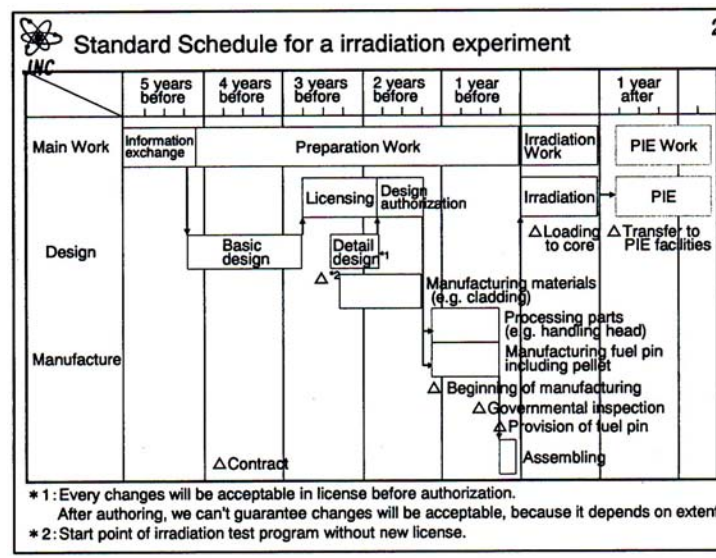
Reactor Selection

- 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 operations
    - Irradiation testing (ATR, JOYO)
    - Isotope production (NRX, HFIR)
    - Demonstration plant (Monju)
    - Power reactor



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Reactor Selection

- 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

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

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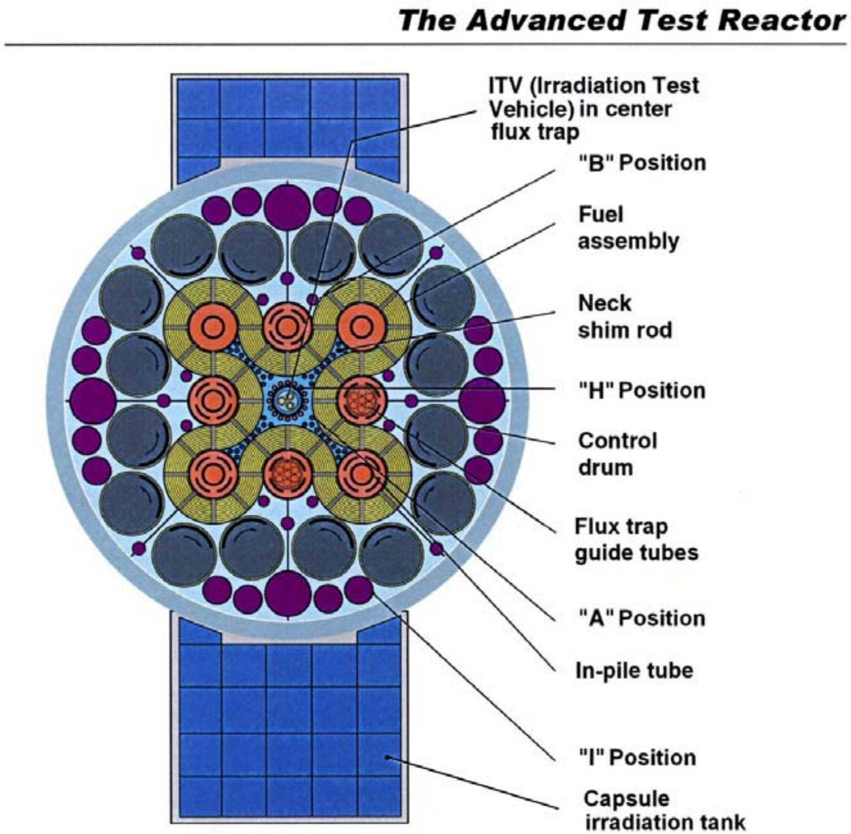
Define Irradiation Position

- 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



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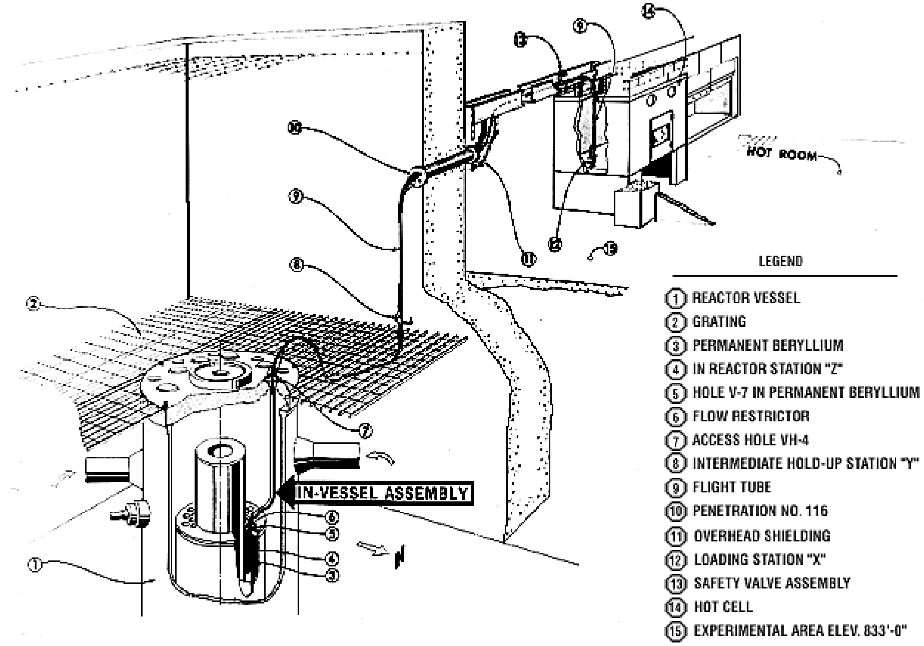
Define Irradiation Position

- Irradiation vehicles
  - Existing or custom?
  - Choices dictated by
    - Experimental needs
    - Budget
  - Rabbits
    - Good for short exposure
    - Least expensive option
    - Little to no temperature control
    - Passive temperature and fluence monitoring possible

Isometric illustration of the HFIR pneumatic facility in VXF-7



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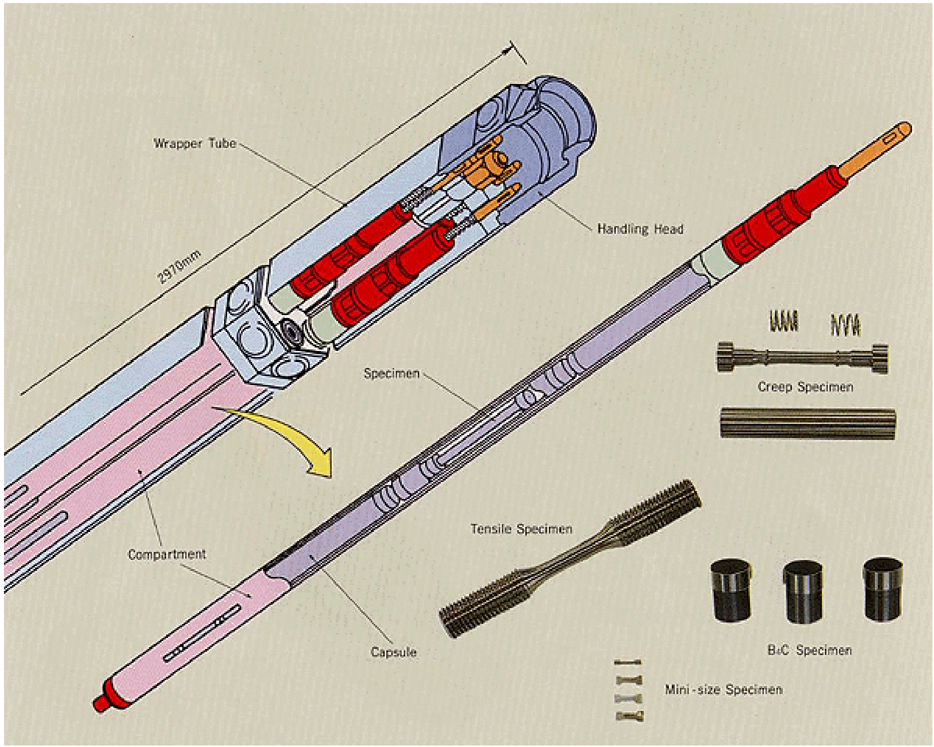
Define Irradiation Position

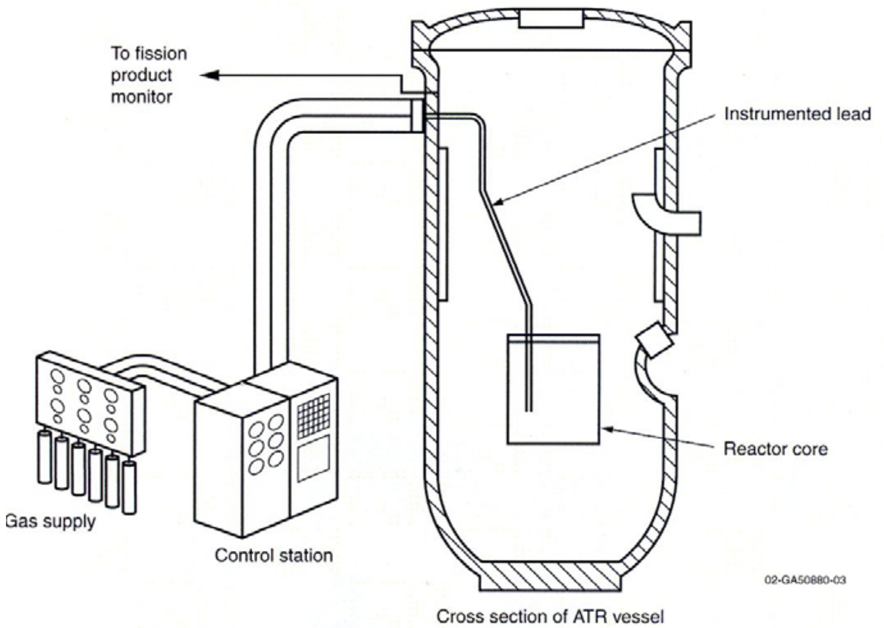
- Irradiation vehicles
  - Uninstrumented (drop-in) experiments
    - Relatively simple to design and fabricate
    - Usually located in specific reactor positions with well-defined spectrum/flux
    - No active temperature measurement or control
    - Passive temperature monitoring possible



Materials Irradiation Test Assembly (MITA) at JOYO

Define Irradiation Position

- Irradiation vehicles
  - Instrumented (lead) experiments
    - More complex 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



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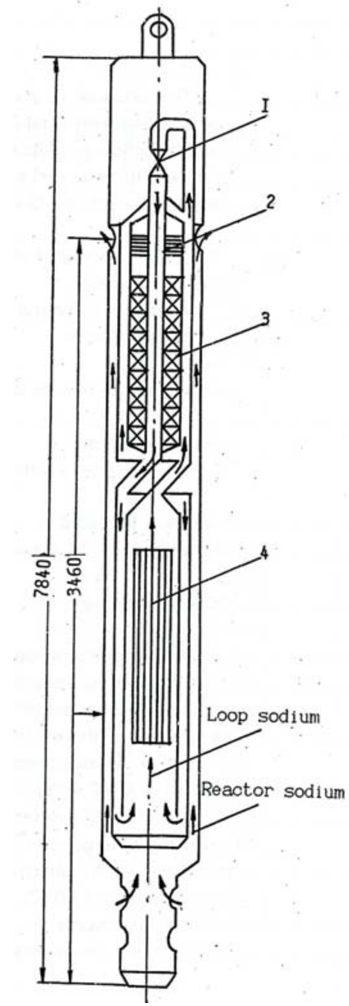
Define Irradiation Position

- 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



RIAR. 1995.

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Irradiation Vehicle Design

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

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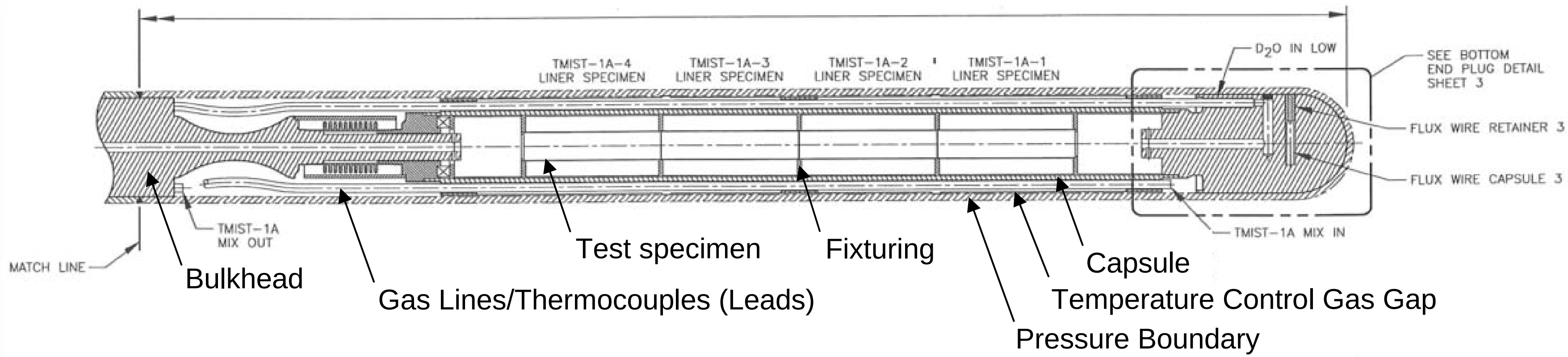
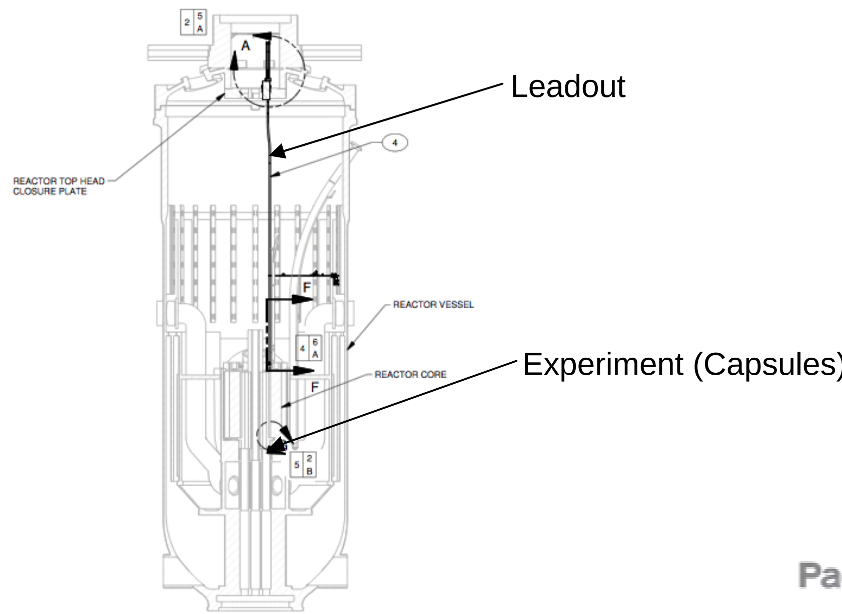
In-Reactor Components



Test Train



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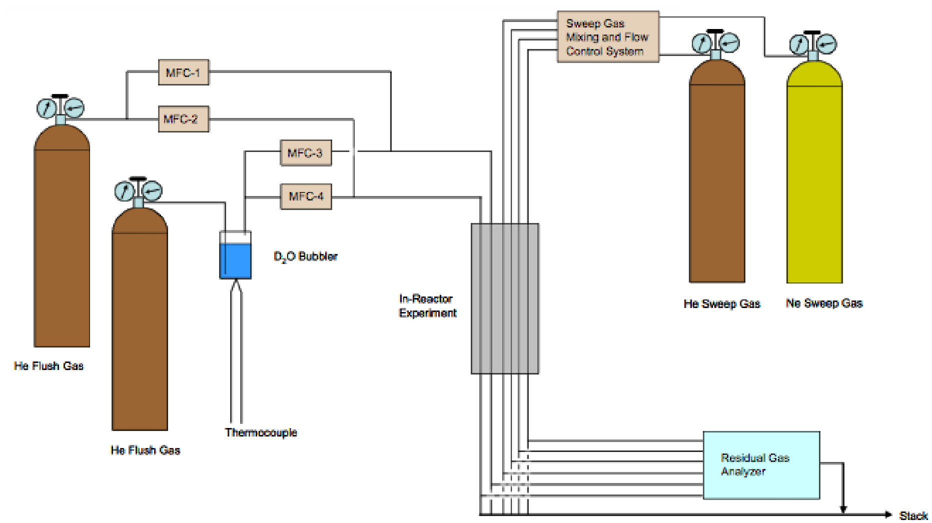
Ex-Reactor Systems (Lead Experiments Only)

- 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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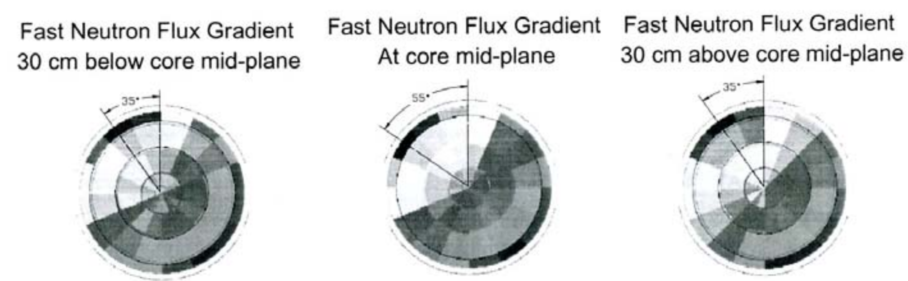
Test Specimen Design

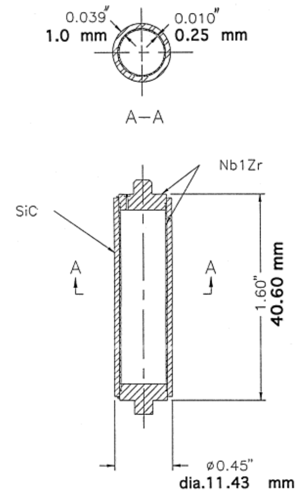
- Geometry influences irradiation characteristics
  - Temperature
    - Radial temperature profile
    - Gamma or neutron heating
    - Internal heat generation for fuels or strong absorbers
    - Self-shielding
  - Fluence
- Adjacent test specimens (within same holder or capsule) must be chemically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



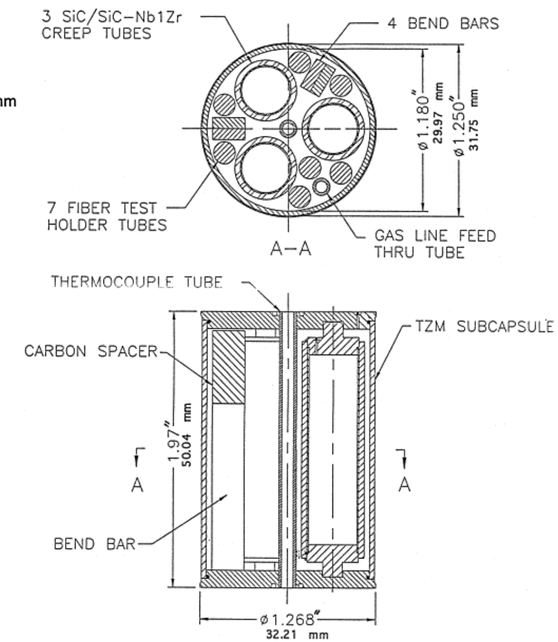
Fast flux gradients across small B position in ATR (Parry 2007)

Test Specimen Design

- 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



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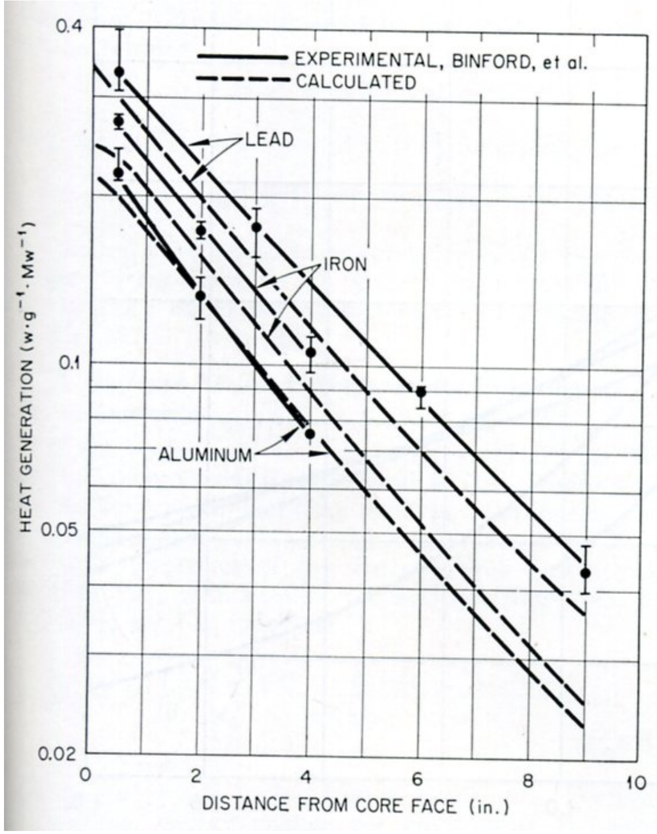
Capsule Design

- Achieving Desired Temperatures
  - 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 (e.g. W)



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

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Capsule Design

- Achieving Desired Temperatures
  - 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
    - Stepped or tapered gas gaps can be used to offset axial variations in flux
    - Small gaps (≤ 0.010 in.) will cause difficulties in assembly and will be very sensitive to dimensional variations

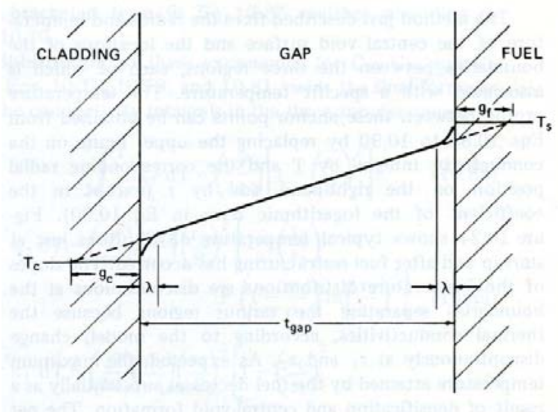
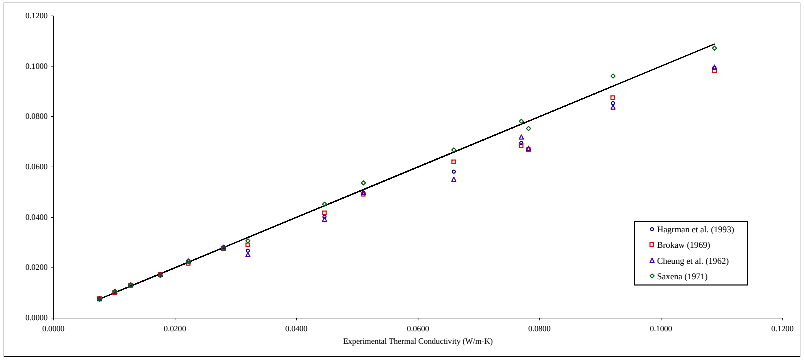


Fig. 10.25 Temperature profile in a gas between two plane surfaces.

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



MATPRO Gas Mixing Model Compared to Data

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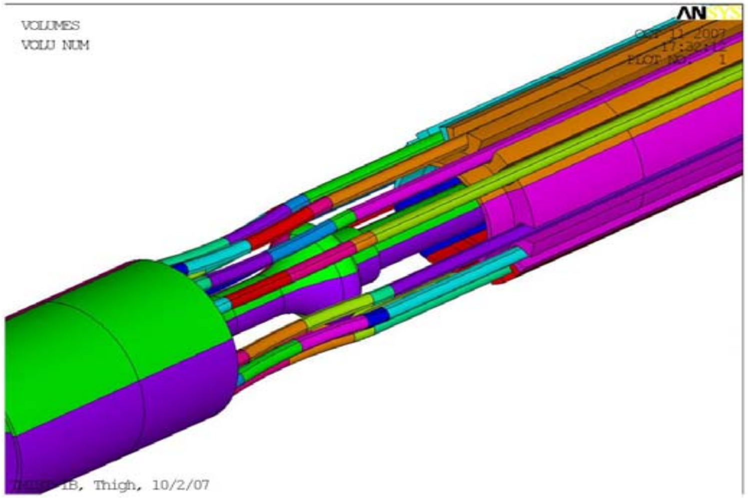
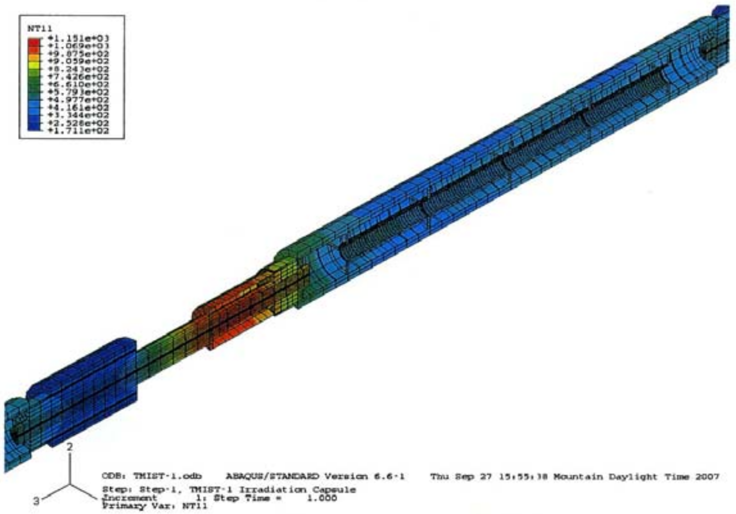
Capsule Design

- 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)
    - Circumferential variability in mass distribution (e.g. gas lines or thermocouples)
    - Axial effects
  - Radiation
    - Important for high-temperature (>800°C) experiments
    - Can be significant for lower-temperature experiments where very precise temperature control is desired





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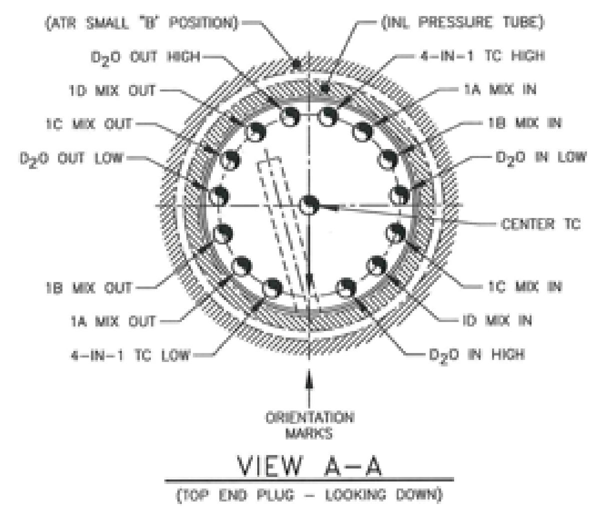
Capsule Design

- 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
    - Common outlet lines can be accommodated with appropriate back-pressure control
  - Materials/Sizes
    - Typically 304 or 316 SS (0.062 in. OD x 0.015 in. 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



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Capsule Design

- Bulkheads
  - Used to isolate independent temperature control gas volumes
  - Typically welded to the pressure boundary tube
  - Piston rings can be used in lieu of welding to the pressure boundary, but will experience some degree of cross-talk
  - 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

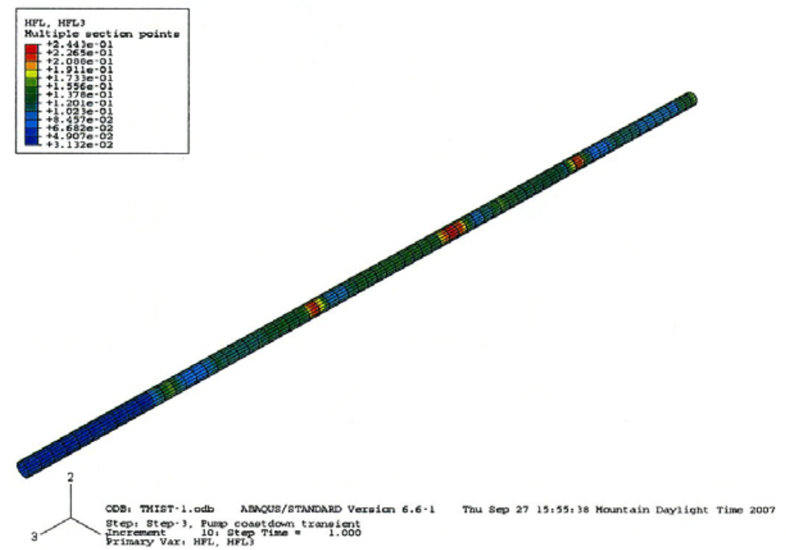
Capsule Design

- Differential Strain Relief
  - Differential axial strain will occur in lead experiments
    - If bulkheads are welded to pressure boundary
    - If gas lines/thermocouples are brazed into bulkheads
    - 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

- Reactor Safety Analyses
  - Required by the reactor to ensure no risk to plant or personnel due to experiment
  - 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



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Capsule Design

- Other Design Considerations
  - Fabricability
    - Clearances/straightness
    - Weld/braze joint design
    - Handling/cleanliness
    - Glovebox assembly for fuel?
  - Post-Irradiation Examination
    - Ease of disassembly
    - Activation/dose effects
    - Specimen identification
  - Shipping/handling
    - DOT regs (over-the-road)
    - Closed road
    - International
  - Waste disposal
    - Activation/waste stream

Capsule Design

- Documentation typically required during design and fabrication
  - Interface agreements between design/fab/testing organizations
  - Test plan and/or test specification
  - Technical and functional requirements
  - Design calculations
  - Design drawings
  - Design reviews
  - Assembly specifications/procedures
  - Fabrication travelers
  - Material and/or design certification
  - Qualification of special processes (welding, brazing, heat treatment)
  - Inspection reports (receiving, in-process, acceptance testing)
  - Non-conformance reports, deficiency reports
- Irradiation experiment design and fabrication is a highly rigorous process that requires significant QA infrastructure

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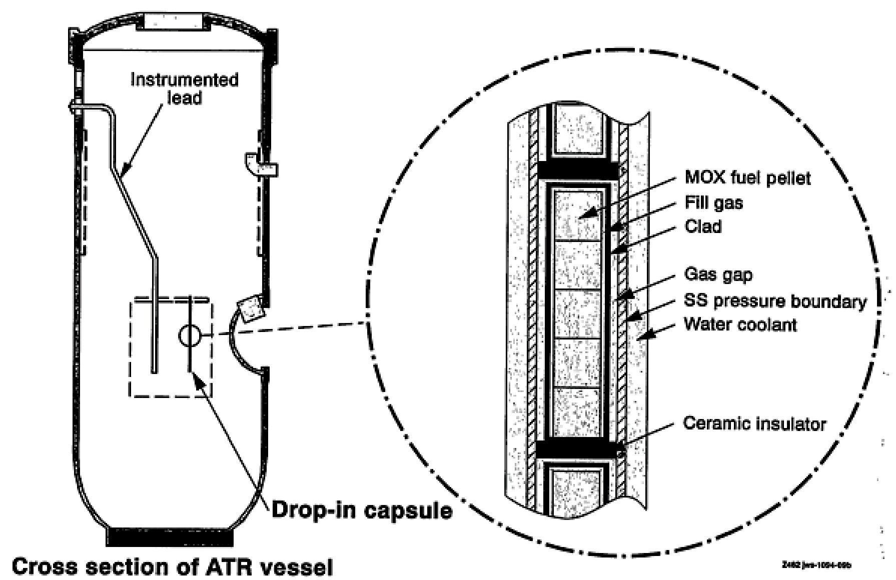
Experiment Control and Monitoring

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

Temperature Control

- Passive
  - Relies on neutronic and thermal analyses to specify a fixed temperature control gas mixture during assembly
  - Final capsule closure welds are made in a chamber with the appropriate He-Ne or He-Ar mixture
  - Thermocouples could be used for monitoring (lead experiment), but usually passive methods are used (drop-in capsules)



Chang et al. 1996. INEL-96/0369.

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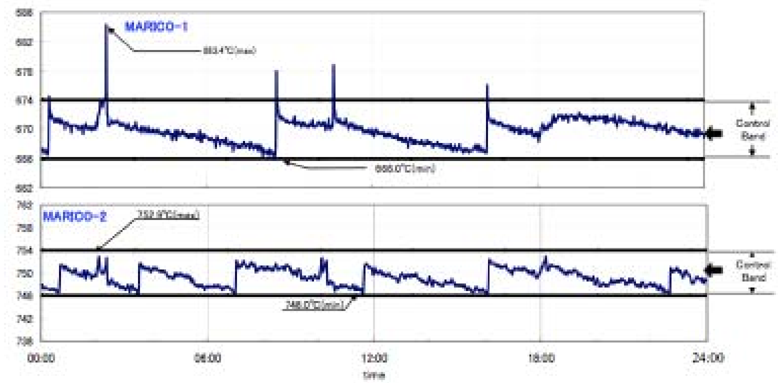
Temperature Control

- Active
  - Uses inlet/outlet gas lines to actively control the He-Ne or He-Ar mixture based on feedback from thermocouples
  - Control methodology
    - Manual - Manual flow rate adjustments on the two gases
    - Semi-automated - Control algorithm specifies He flow, but manual control used for Ne
    - Automated - Control algorithm specifies changes and makes the changes automatically, with pre-programmed setpoints and alarms
  - Relatively slow response times (minutes) at normal flow rates (~30 sccm)
  - Depending on capsule design, control band can be wide (~200°F)



Ito et al. 2008. *J. Power Ener. Sys.*, 2(2):620.

Temperature Control

- Active
  - Electric heaters
    - Provide additional heating beyond temperature control gas capability
    - Can be used to tailor thermal profile
    - Requires extra leads
    - Reliability/lifetime issues

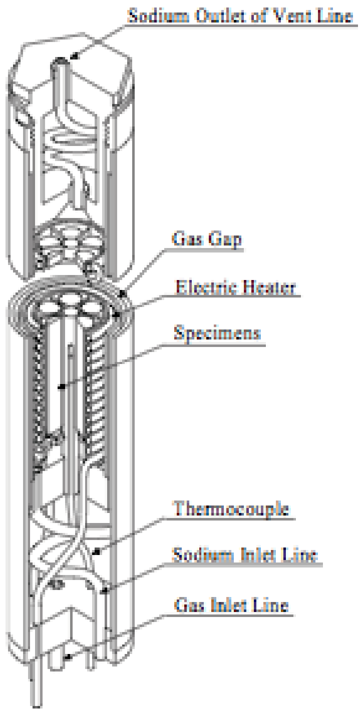


Fig. 6 Structure of Electric Heater Type Irradiation Capsule

Ito et al. 2008. *J. Power Ener. Sys.*, 2(2):620.

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Temperature Measurement

- Passive Techniques
  - Melt wires - usually several included to bracket exposure temperatures
    - Only indicates range of peak temperature achieved
  - Differential thermal expansion devices (TEDs)
    - Stainless steel capsules filled with Na or other appropriate liquid metal
    - Measurement of capsule strain after irradiation indicates peak temperature achieved

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Temperature Measurement

- Passive techniques
  - SiC temperature monitors
    - Swelling of SiC is a well-known function of irradiation temperature from 300-800°C
    - Measurement of swelling after irradiation indicates effective temperature
    - Effective temperature reflects the average temperature achieved during the last 1 dpa (or so)
    - Equilibration times long for thermal irradiation, but short for fast irradiation - late transients can significantly affect effective temperature

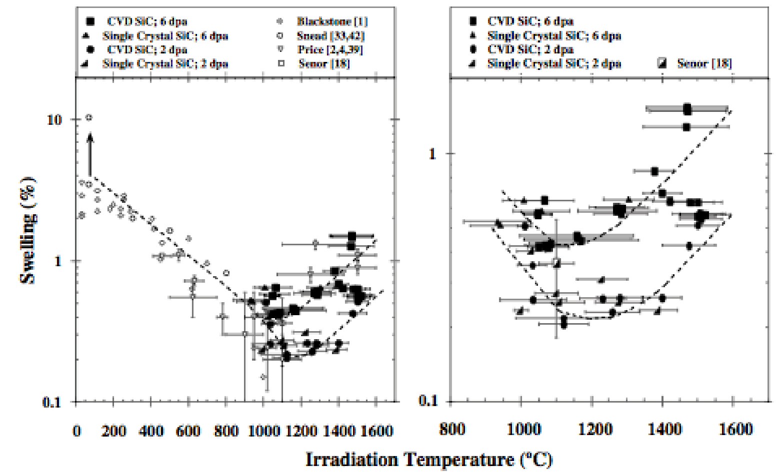
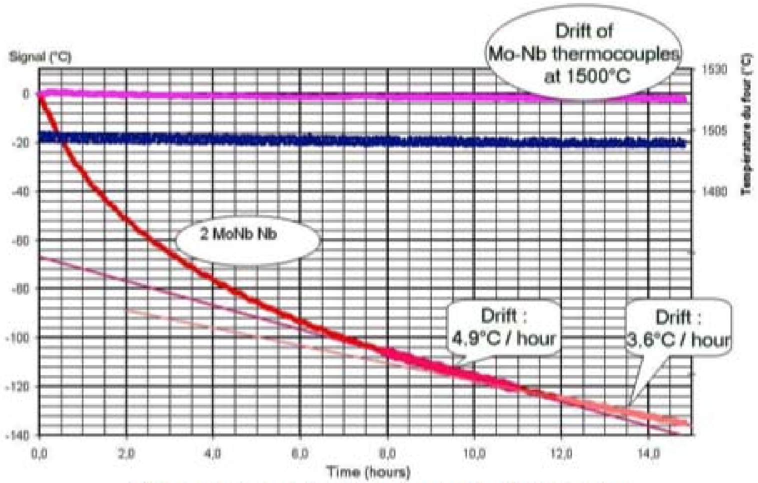


Fig. 1. Volumetric swelling of SiC as a function of neutron irradiation temperature.

Snead et al. 2007. *JNM*, 376-370:677.

Temperature Measurement

- Thermocouples
  - Typically used in lead experiments with active temperature control
    - Type K (chromel-alumel) are the most common and cover most temperatures of interest (RT-1100°C)
    - Other thermocouples can be used at higher temperatures (Pt/Mo for 1100-1500°C)
    - Sheath diameters as small as 0.062 in.
  - Thermocouple performance will degrade with irradiation
    - Radiation damage will cause changes in resistivity at high fluence
    - Materials with high cross-sections (e.g. Rh) must be avoided

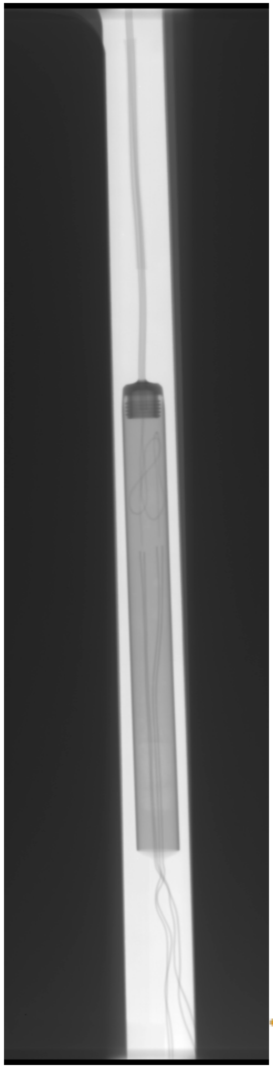


Measured thermal drift of Mo-Nb thermocouples at 1500°C

Villard and Fourrez. 2005. PTB Workshop, Berlin.

Temperature Measurement

- Thermocouples
  - It is possible to obtain thermocouples with multiple junctions in a single 0.062 in. sheath
  - Location of thermocouples in capsules is critical to understanding temperature profiles
    - In general, it is good practice to have redundant control thermocouples in each capsule
    - Having at least two thermocouples at different radial locations at the same axial location increases confidence in thermal model and estimates of specimen temperatures
    - Attaching thermocouples to specimens via welding or pressure is typically not successful due to thermal strains



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Dosimetry

- Flux wires
  - A combination of mg-size pieces of very pure metals that have (n,γ) reactions
    - Distinct gammas
    - Covers the spectrum of interest
  - Typically encased in a low-activation capsule (e.g. V) so they can be counted via gamma spectroscopy without disassembly after irradiation
    - Typical dimensions 0.050 in. diameter x 0.250 in. long
  - Using appropriate codes (e.g. STAYSL) along with good spectra, the energy-dependent fluence can be reconstructed from flux wire activation
  - Subsequent calculations (e.g. SPECTER) can be done to convert fluence to dpa

Table 6. Relative activation rates obtained with a stack configuration for reducing the uncertainties from flux gradient variations

Monitor nuclide	Energy, keV	Position	Relative activation rate			Standard deviation	Counting error
			1	2	3		
^{59}Fe	1099	B	0.9872	1.0171	1.0033	± 0.0117	± 0.011
		M	1.0048	1.0011	0.9956		
^{60}Co	1173	B	1.0132	0.9844	1.0049	± 0.0105	± 0.010
		M	0.9921	0.9941	1.0113		
^{198}Au	411	B	0.9988	1.0000	1.0046	± 0.0024	± 0.009
		M	0.9970	1.0013	0.9984		
^{124}Sb	1691	B				± 0.0142	± 0.019
		M	0.9877	0.9923	1.0199		
^{117m}Sn	159	B	0.9997	1.0009	0.9939	± 0.0071	± 0.005
		M	0.9922	1.0142	0.9991		
^{97}Zr	743	B	1.0260	0.9654	1.0213	± 0.0235	± 0.025
		M	0.9740	1.0146	1.0118		
^{58}Co	810	B	0.9735	0.9920	0.9991	± 0.0161	± 0.004
		M	1.0029	1.0045	1.0276		
With Cd-cover							
^{59}Fe	1099	B		1.0358	0.9861	± 0.0190	± 0.018
		M	0.9933	1.0002	0.9829		
^{60}Co	1173	B		1.0133	0.9974	± 0.0071	± 0.014
		M	1.0003	0.9961	0.9928		
^{198}Au	411	B		1.0057	0.9953	± 0.0060	± 0.007
		M	1.0012	0.9912	1.0066		
^{124}Sb	1691	B				± 0.0081	± 0.013
		M	0.9963	1.0112	0.9925		
^{117m}Sn	159	B		0.9906	1.0128	± 0.0083	± 0.003
		M	0.9912	1.0030	1.0024		
^{97}Zr	743	B		1.0191	0.9739	± 0.0195	± 0.014
		M	0.9983	1.0113	0.9707		
^{58}Co	810	B	1.0071	0.9690	1.0161	± 0.0349	± 0.003
		M	1.0112	0.9475	1.0563		

Matsushita et al. 1997. *J Radio Nuc Chem*, 216(1):95.

Dosimetry

- Retrospective Dosimetry
  - In the absence of flux wires (or in addition to them) sections of the irradiation capsule can be cut to provide dosimetry data
  - Purity of capsule material is less-controlled than flux wires so resolution will be lower
  - Useful if there is a significant gradient in flux across or around a capsule

Table 6
Neutron fluences (n/cm^2 × 10^{21}) with 1σ uncertainties for the top guide samples

Reaction	Sample 1	Sample 2
Thermal[a]		
^{62}Ni (n,γ) ^{63}Ni	2.30, 5%	2.12, 5%
^{54}Fe (n,γ) ^{55}Fe	2.08, 5%	2.12, 5%
^{59}Co (n,γ) ^{60}Co	2.27, 8%	2.47, 8%
Average	2.22	2.19
Std. Dev.	±6%	±8%
Fast >0.1 MeV		
^{54}Fe(n,p) ^{54}Mn	2.47, 10%	2.03, 10%
Fast >1.0 MeV		
^{54}Fe(n,p) ^{54}Mn	1.04, 10%	0.859, 10%

[a] Thermal fluence using 2200 m/s cross-sections with an adjusted epithermal fluence ratio of 0.35 (see text, and Table 3). Thermal group fluences <0.5 eV at reactor operating temperature are about a factor of 1.52 higher than the 2200 m/s value.

Greenwood et al. 2007. *JNM*, 361:1.

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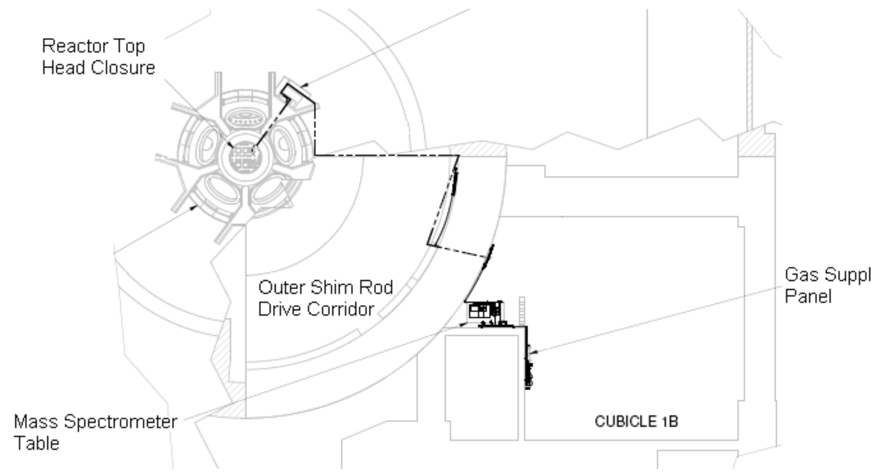
Ex-Reactor System Control

- 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 > 50 ft)
  - 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

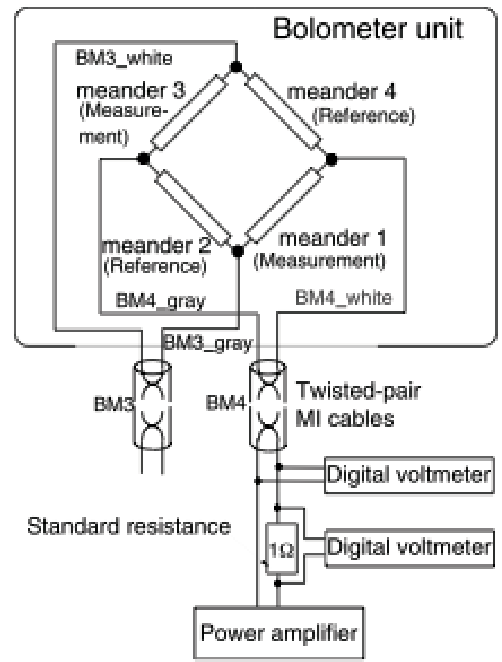


Fig. 1. Block diagram of the sensitivity measurements for the bolometer during irradiation.

Nishitani et al. 2002. *Fusion Eng Des*, 63-64:437.

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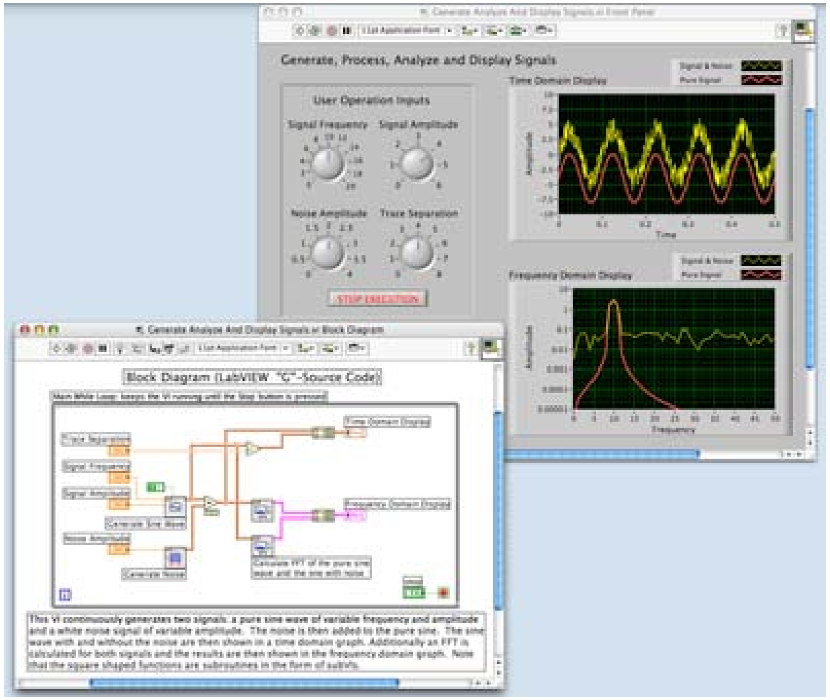
Remote Data Viewing

- 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



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 NCRs, DRs, USQs, 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

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, and hot cell operator (for PIE) are vital