Materials Irradiation within the Nuclear Science and Technology Division

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U. S. DEPARTMENT OF ENERGY

Why do materials testing?

Why do materials testing?

- **Radiation exposure can produce large changes in structural materials**
  - **Radiation hardening and embrittlement**
  - **Irradiation creep**
  - **Volumetric swelling from void formation**
  - **High temperature He embrittlement**
  - **Transmutation**
- **Combination of radiation damage and transmutations produce major changes in physical properties and mechanical behavior**

Why do materials testing?

- **This type of graphite shows a remarkable 70% decrease in the coefficient of thermal expansion under irradiation**
- **One HFIR cycle in the target region provides about $2x10^{21}$ n/cm^2**

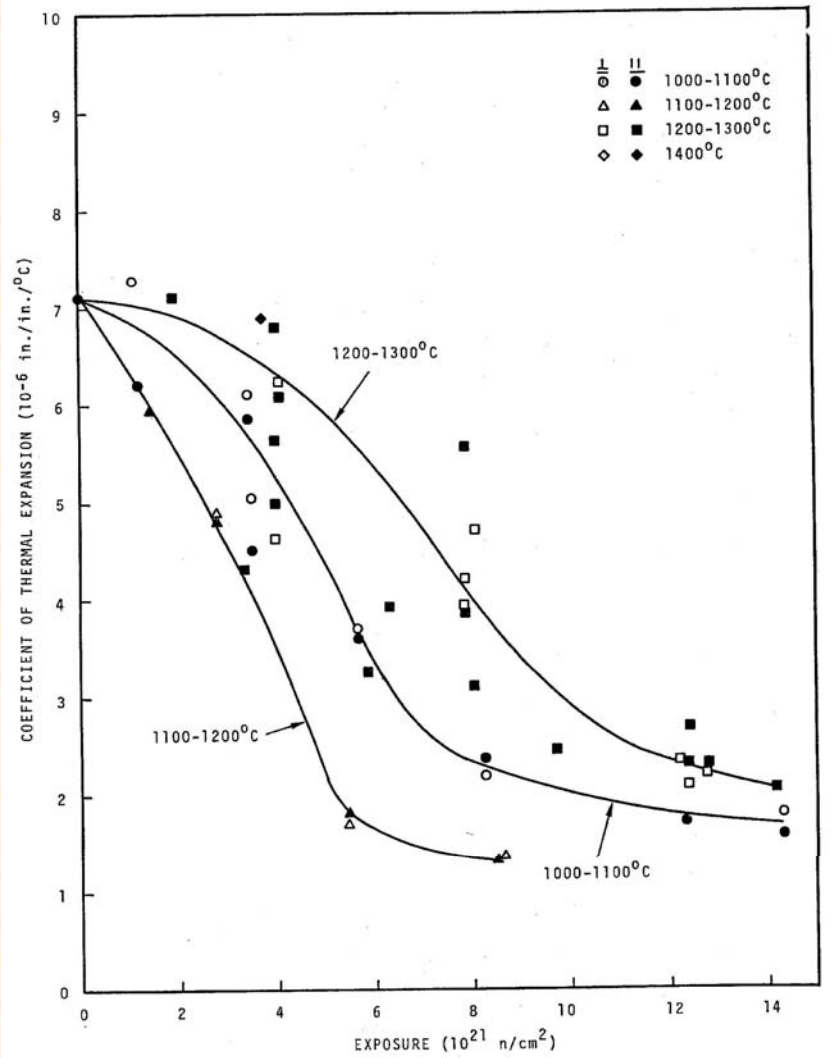


FIGURE 40. Coefficient of Thermal Expansion of AXF-8Q1.

Why do materials testing?

- **Many materials will swell or shrink under irradiation**
- **This graphite grade will simultaneously shrink parallel to the grain and swell perpendicular to the grain**
- **In the perpendicular direction, the graphite initially shrinks and then swells after about $6x10^{21}$ n/cm^2**

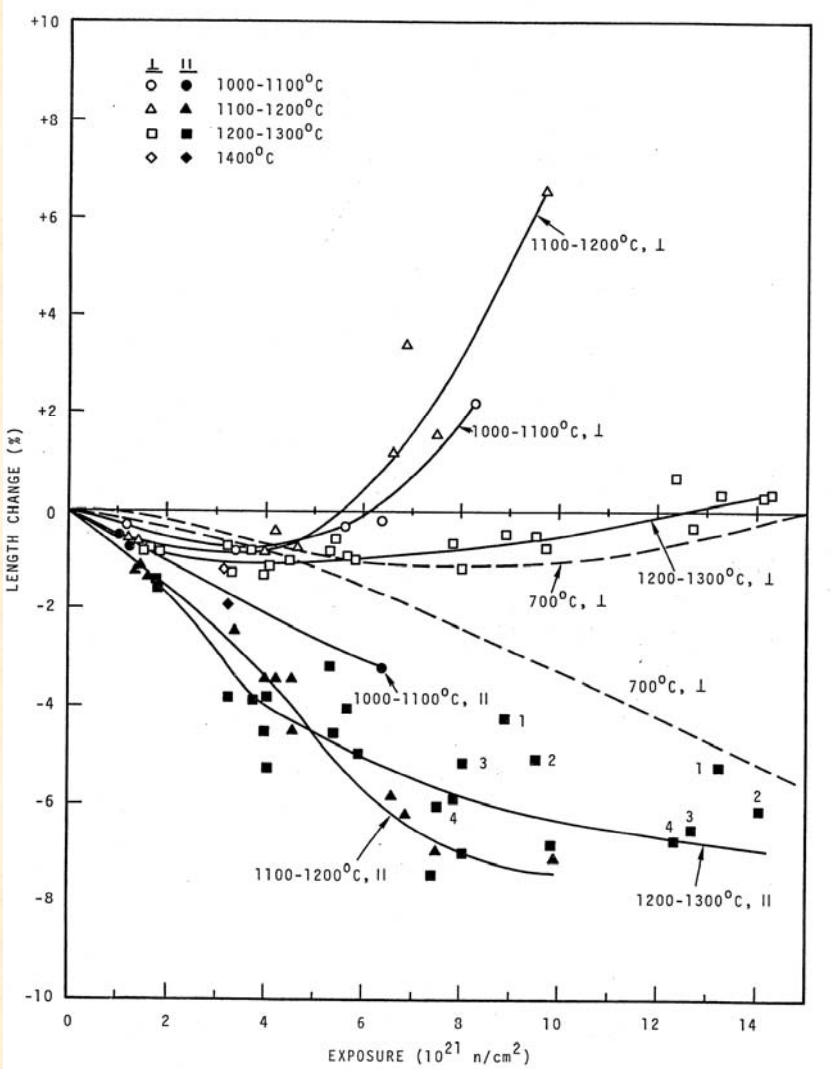


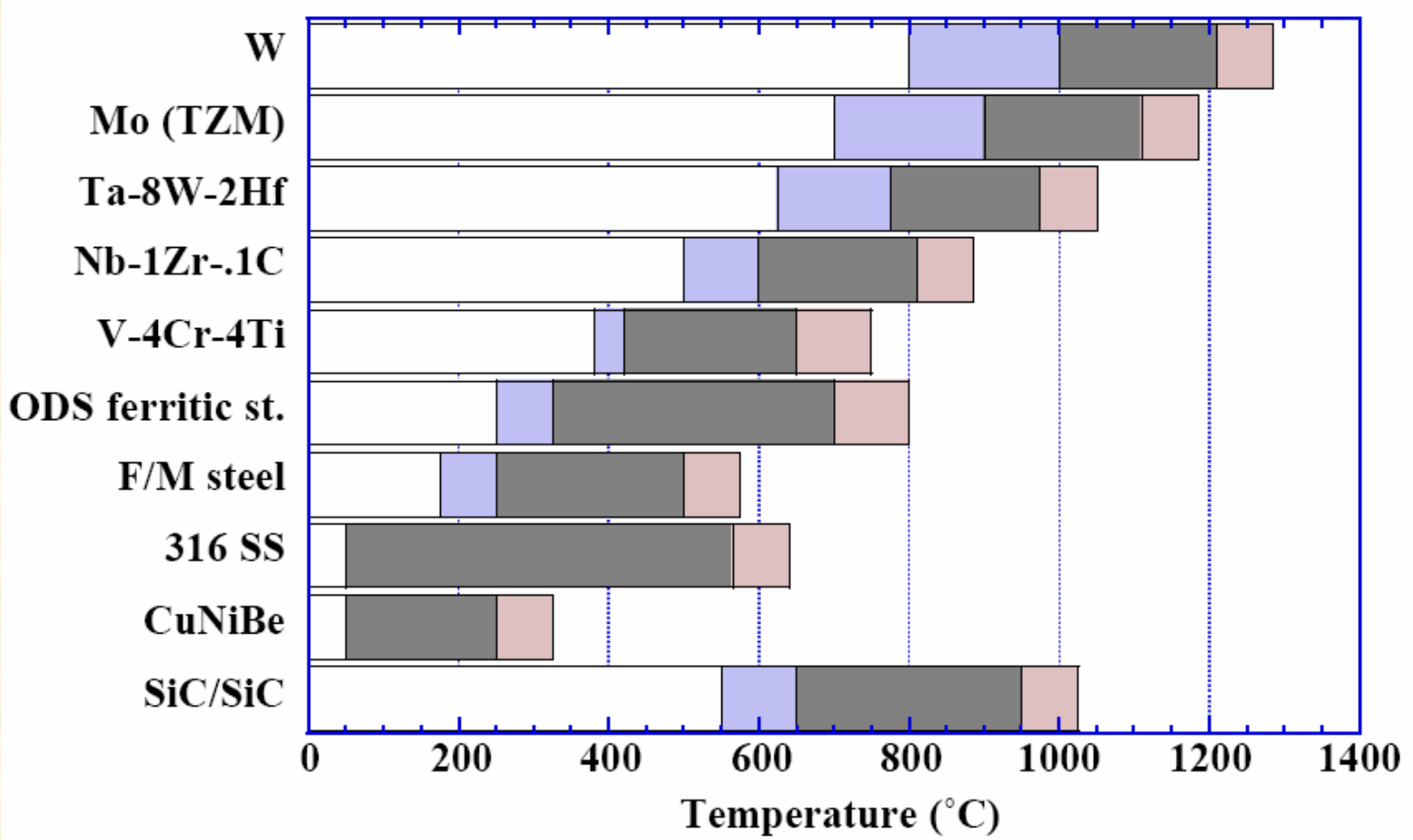
FIGURE 3. Length Change of EGCR.

Why do materials testing?

- **Performance goals for structural materials**
  - **Compatibility with the operating environment**
    - **liquid metal, water, or helium coolants**
    - **hydrogen plasma**
  - **Adequate operating range (temperature and stress limits) under expected**
    - **neutron fluxes**
    - **heat fluxes**
    - **mechanical loads**
    - **load cycling**
  - **Reliable production, component fabrication, welding, and joining technologies**

Why do materials testing?

Operating Temperature Windows for Structural Alloys in Fusion Reactors



Why do materials testing?

- **No known material exists which can satisfactorily function in the hostile environment of a commercially viable fusion reactor**
  - **displacement damage**
  - **H, He generation**
  - **high temperatures**
  - **thermal & mechanical stress**
  - **coolant compatibility**

Designing a Materials Irradiation Experiment

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Advanced CAD and Thermal Modeling Tools Used for Experiment Design

- **Pro/Engineering CAD software used to develop 3-D models**
- **ANSYS multi-physics analysis code used for thermal design**

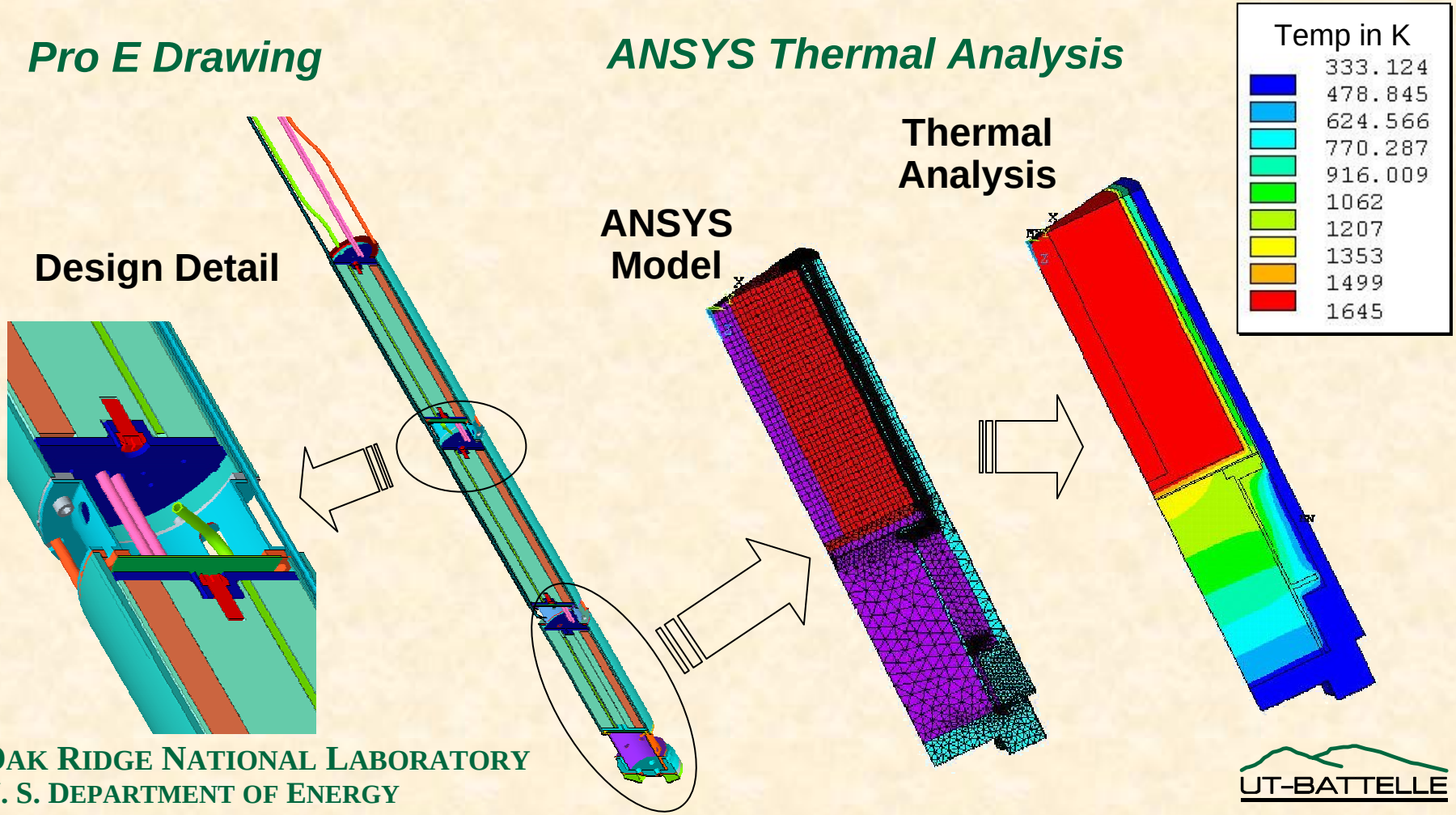
Pro E Drawing

ANSYS Thermal Analysis

Design Detail

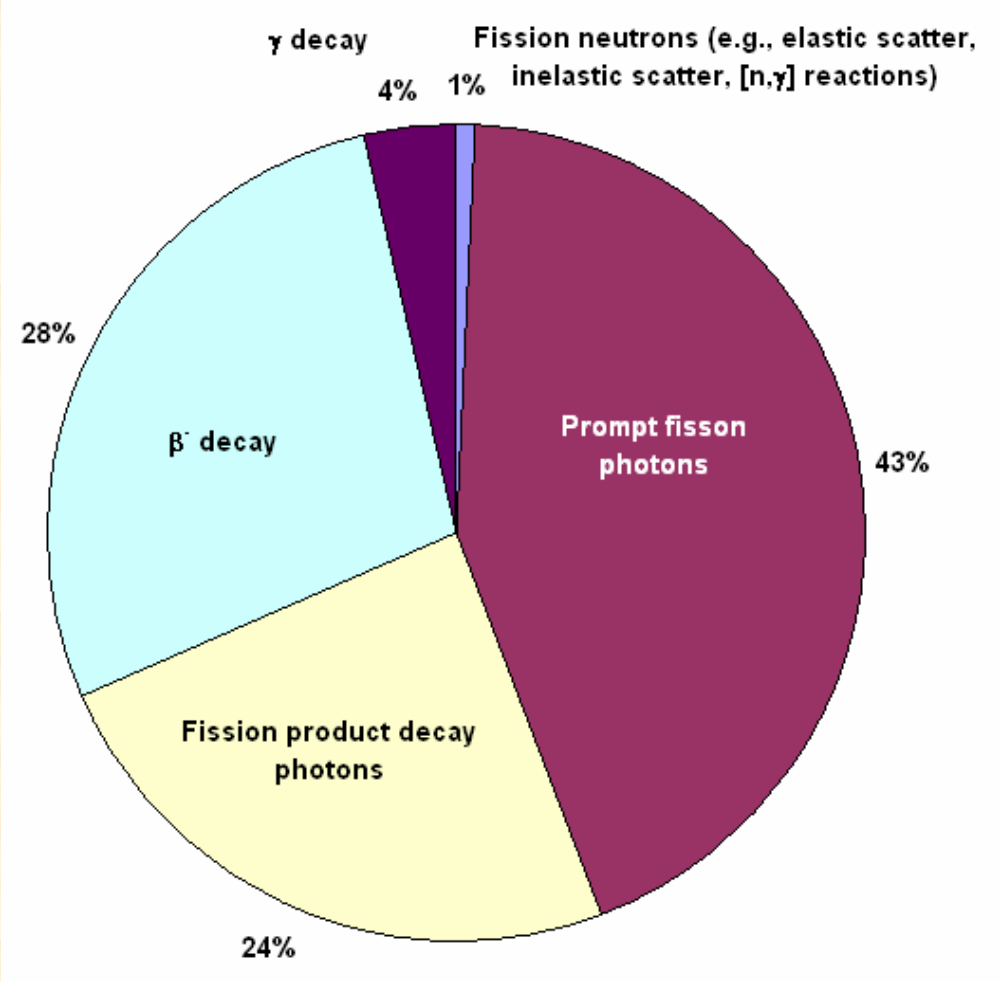
ANSYS Model

Thermal Analysis



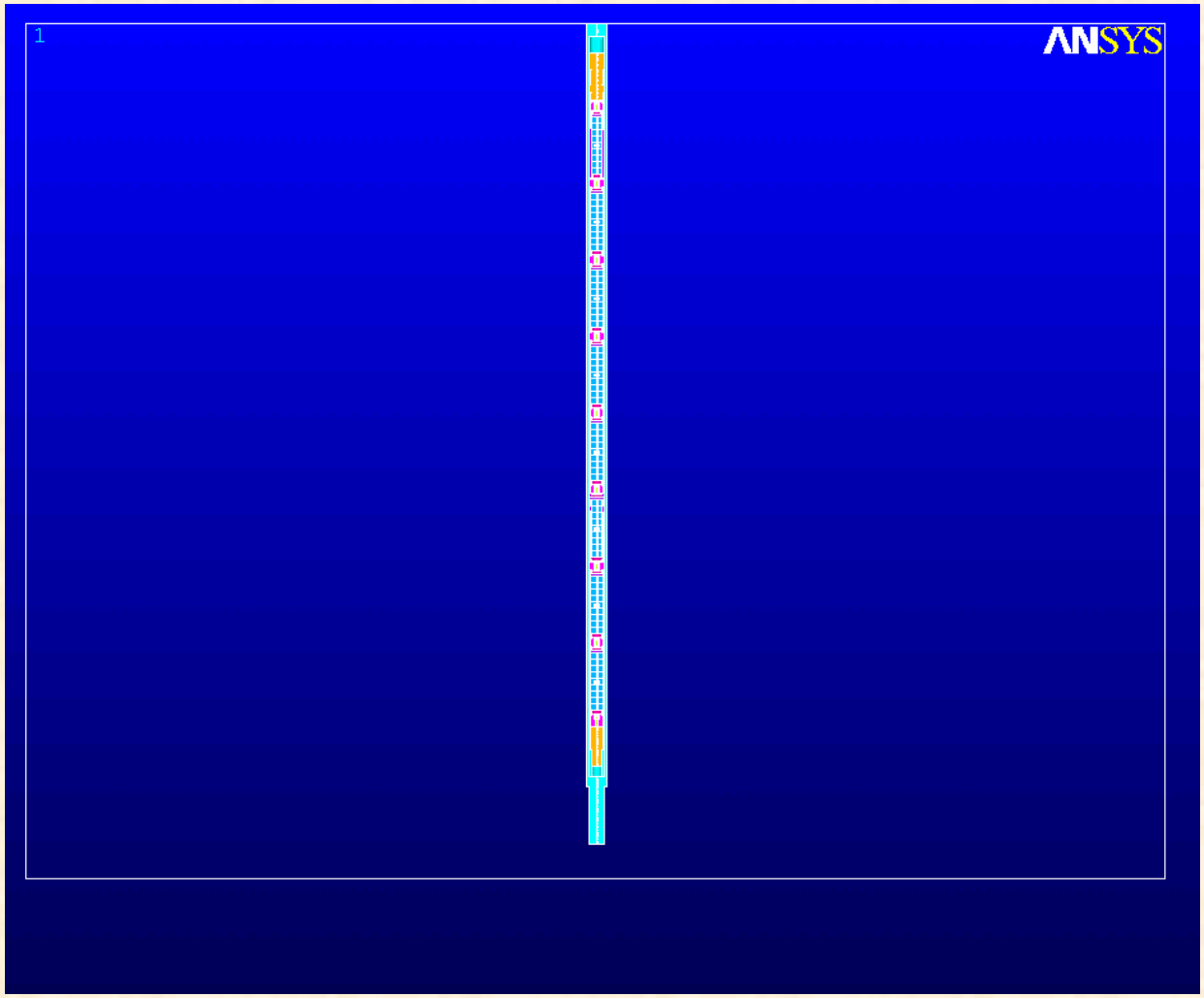
Material Heat Generation

- **Most of the heat generated is due to prompt and delayed photons from the reactor fuel**
- **Some materials also have significant heat generation from activation and decay**
- **MCNP, ORIGEN-S, and FISPACT are the primary software tools for evaluating heat generation rates for materials**
- **Because of large uncertainties, hand calculations based on previous experiments are also commonly used**



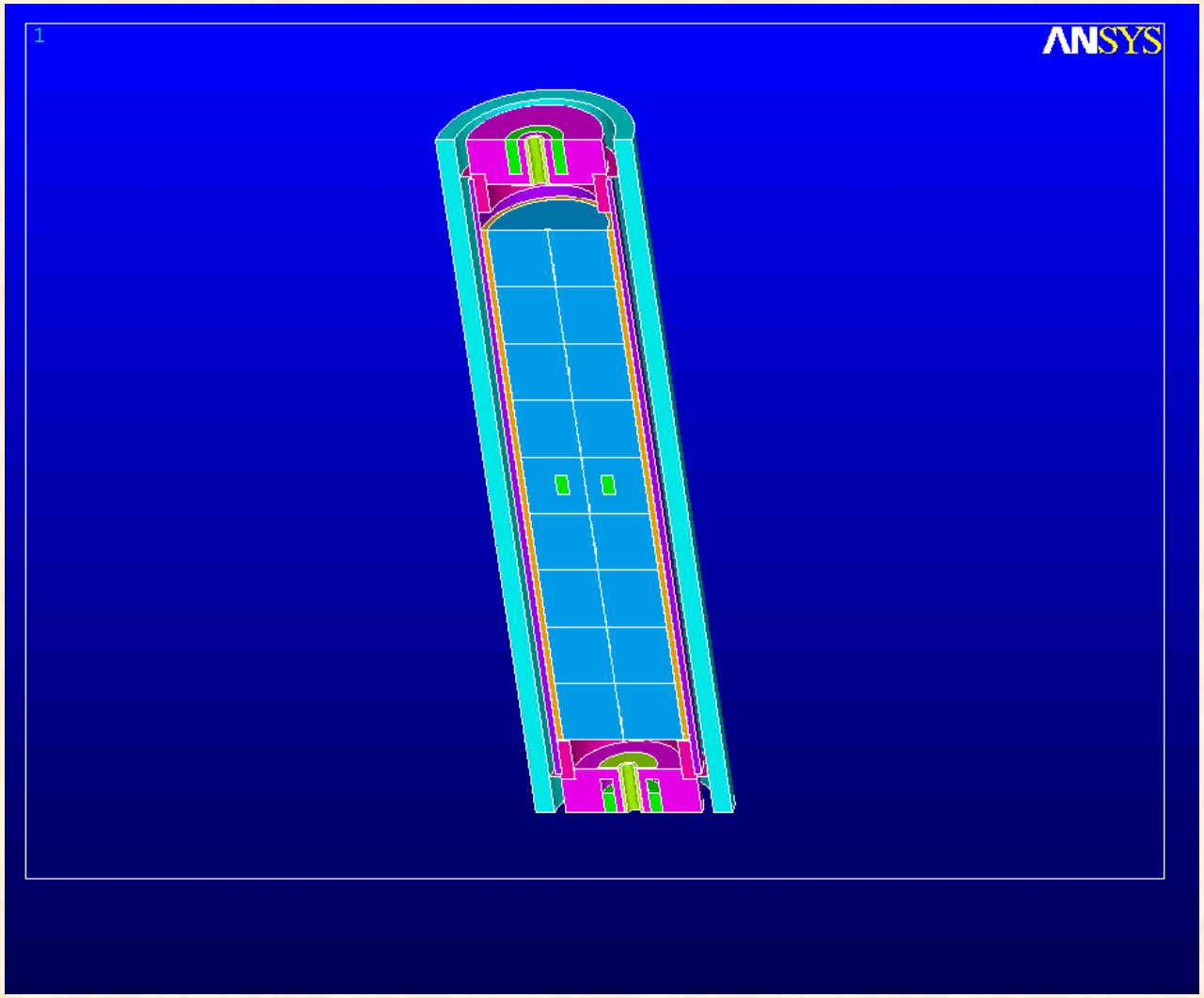
Thermal Modeling

- **The ANSYS finite element software is the primary analysis tool for thermal design**



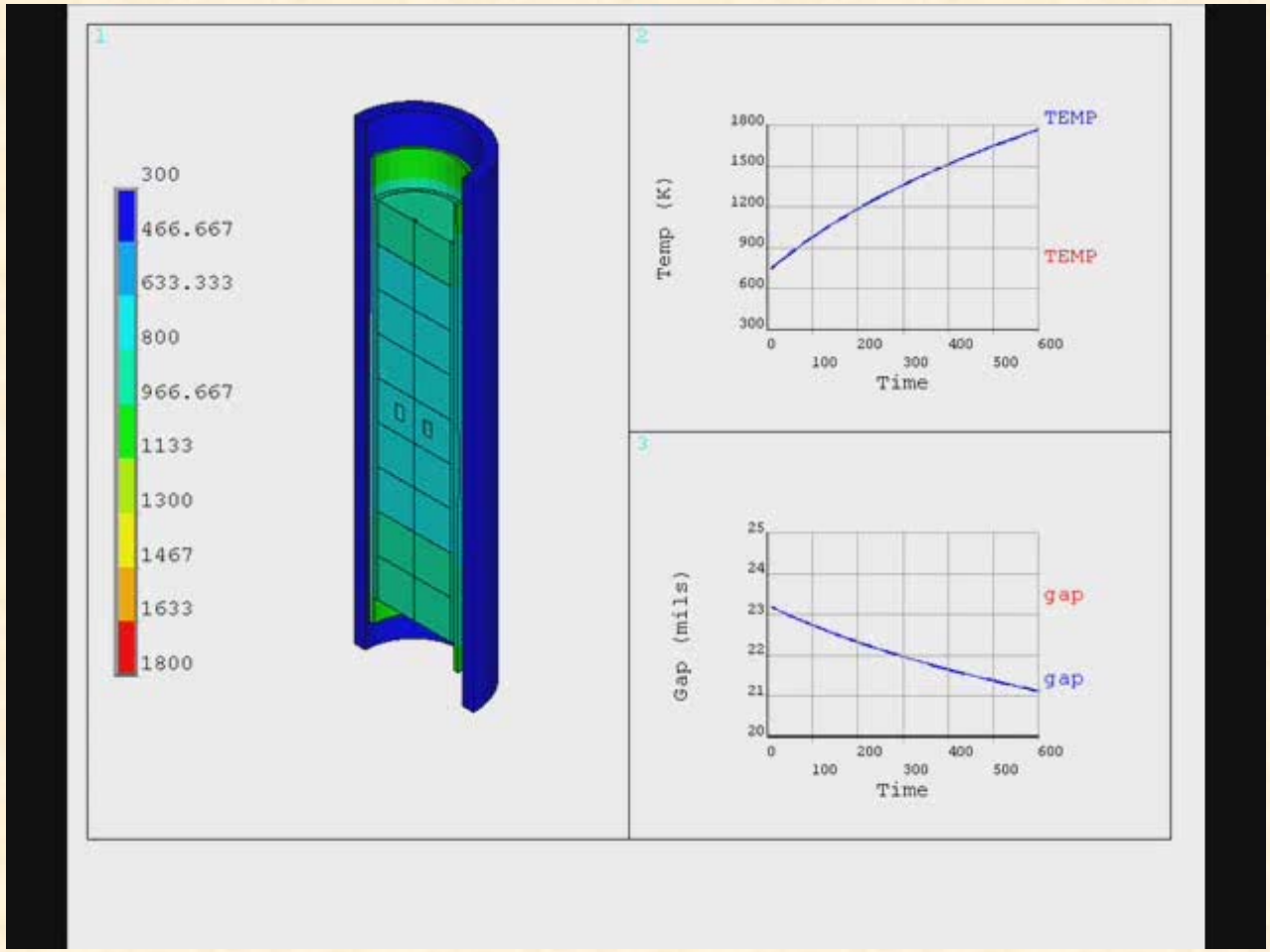
Thermal Modeling

- **The key design feature is the gas gap thickness that separates the specimen holder from the externally-cooled outer housing**



Thermal Modeling

- **As the reactor power level rises**
  - **local heat generation rises**
  - **temperature rises**
  - **gas gap narrows due to thermal expansion**



Thermal Modeling

- **In the experiment just described, the temperature drop through the gap is ~ 1000ºC over a ½ mm gap**
- **To control the specimen temperature to ±20ºC,**

$$\sigma_{gap} = \frac{(20^{\circ}\mathrm{C})}{\left(\frac{2000^{\circ}\mathrm{C}}{\mathrm{mm}}\right)} = 0.01\,\mathrm{mm} = 0.0004\,\mathrm{in}$$

- **We must control and predict the gas gap to within 10 µm, or 0.4 mil**
- **This is very close to current machining limits**

ORNL Irradiation Materials Testing Program

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ORNL Has Extensive Materials Irradiation Experience

- **50 years experience in design, assembly, and operation of irradiation experiments**
- **On-site reactor (High Flux Isotope Reactor)**
- **Experiments designed for other reactors**
  - **Advanced Test Reactor at Idaho National Laboratory**
  - **Ford Nuclear Reactor at University of Michigan**
  - **Others**
    - **High Flux Reactor at Petten, The Netherlands**
    - **Oak Ridge Research Reactor at ORNL**
    - **Oak Ridge Bulk Shielding Reactor**

ORNL Irradiation Experiments have Supported a Variety of Programs

- **Fusion materials**
- **High Temperature Gas-cooled Reactor**
- **Fissile Materials Disposition Program**
- **Pressure vessel steels for NRC**
- **Advanced Neutron Source**
- **Zircaloy creepdown for NRC**

A Variety of Materials and Specimen Types Have Been Irradiated

Structural Materials

Aluminum	Niobium/Niobium alloys
Aluminum oxide	Silicon carbide
Aluminum nitride	Silicon nitride
Beryllium oxide	Steels—austenitic/ carbon/ferritic/martensitic
Carbon	
Carbon/carbon composites	Spinel ($MgAl_2O_4$)
Carbon/silicon carbide composites	Tantalum alloys
Copper	Vanadium
Molybdenum	Zirconium
Mo-Re alloys	Zirconium oxide

Fuel Types

- Coated-particle (HTGR)
- Mixed oxide
- Uranium nitride
- Uranium oxide
- Uranium silicide (ANS)

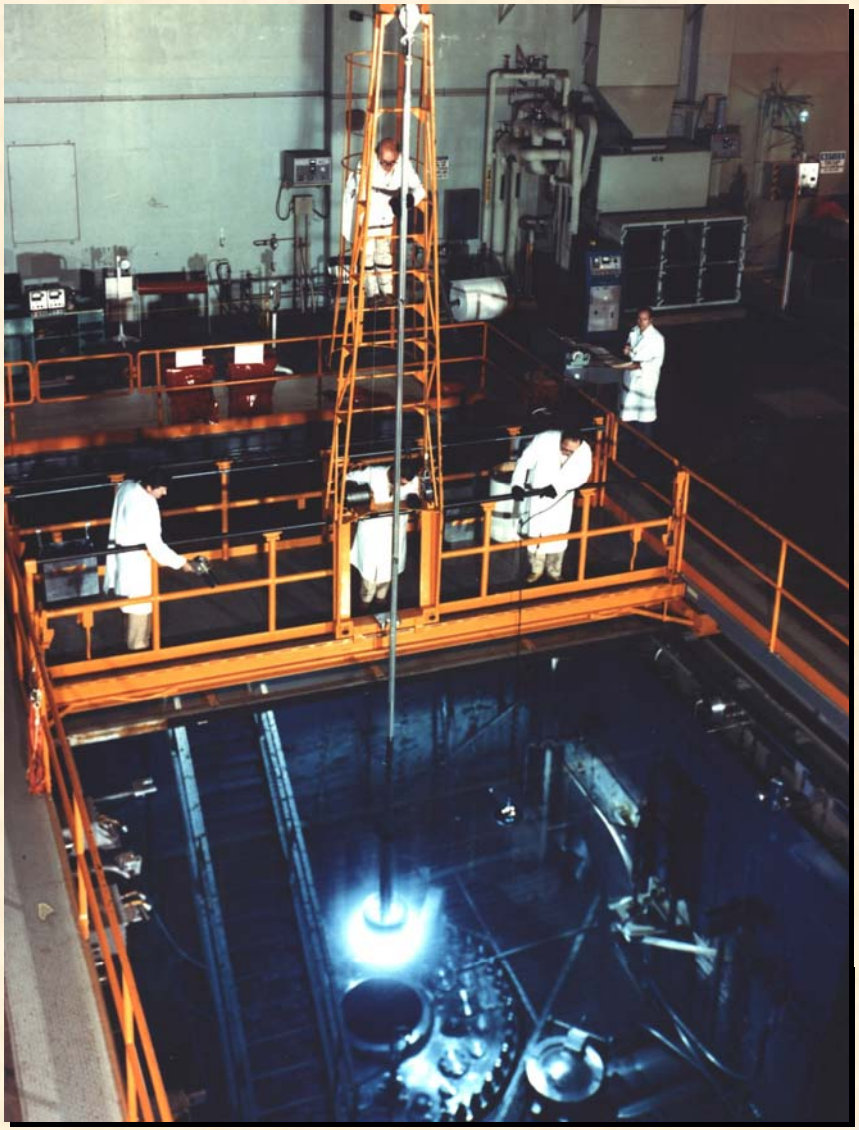
Specimen Types

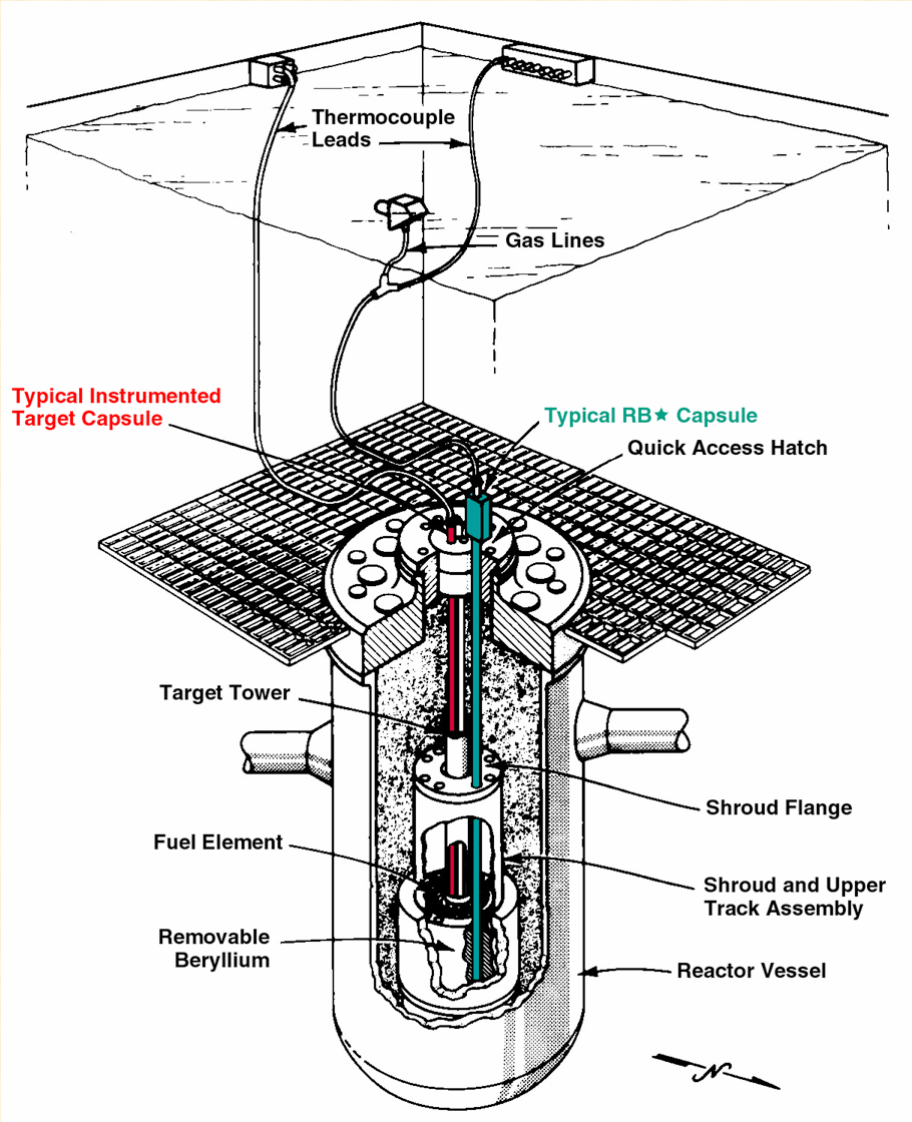
Atom probe	Fatigue
Bend bar	Pressurized tube (creep)
Charpy	Tensile
Compact tension	Thermal conductivity
Crack growth	Thermal diffusivity
Disk compact tension	Transmission electron microscopy
Electrical resistivity	

The Oak Ridge High Flux Isotope Reactor (HFIR)

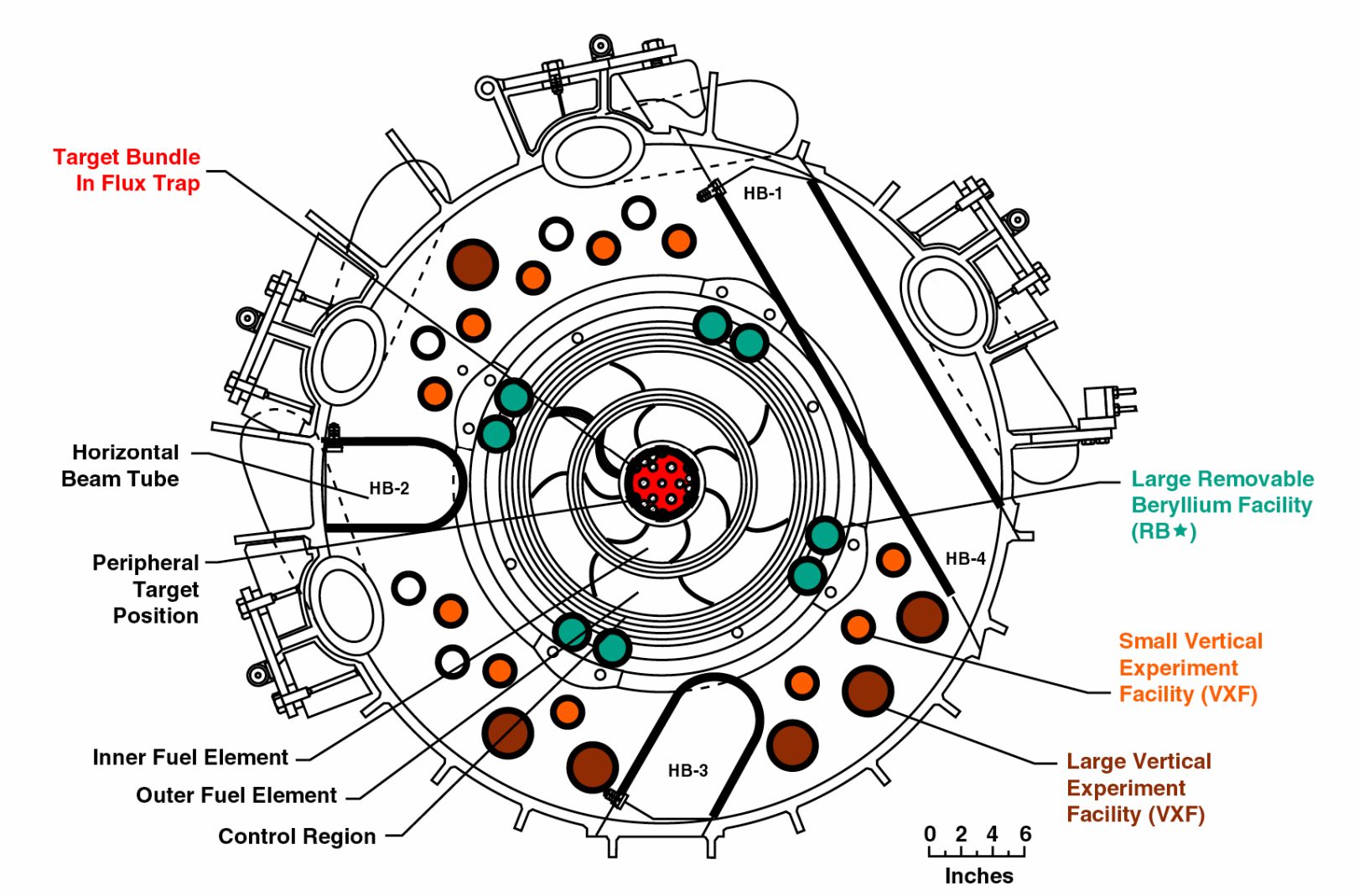
- **A pressurized, light-water-cooled, beryllium-reflected, 85-MW research reactor**
- **22 to 26 day fuel cycle depending on experiment loading**
- **Repetitive fuel loading and cycle operation**
- **Constant power operation**
  - **~30 minutes from N_L to full power**
  - **85 MW continuous operation**
  - **Cycles terminated by manual scram**
- **Numerous experiment positions available**

The Oak Ridge High Flux Isotope Reactor





Cross Section Through HFIR Midplane



Characteristics of Major Irradiation Facilities in HFIR

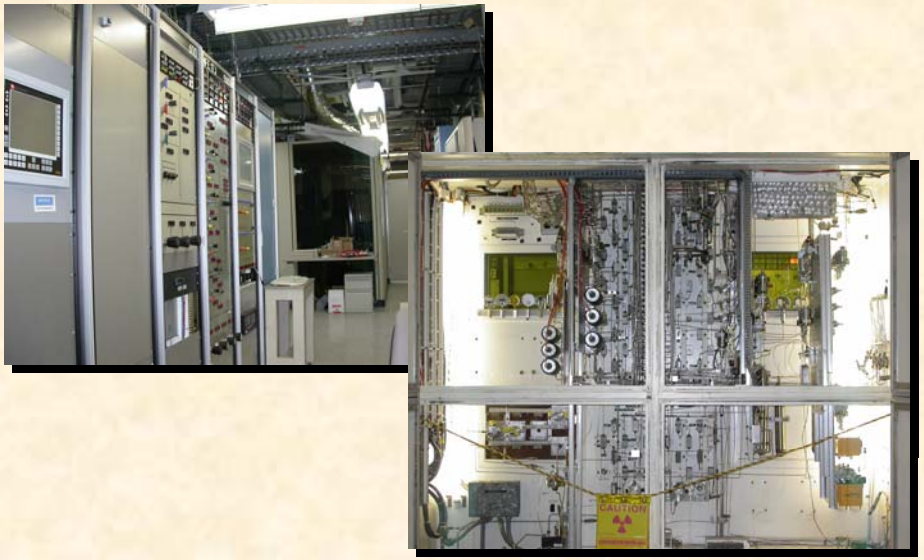
Characteristics	Target	RB★	Small VXF	Large VXF
Fast flux, E > 0.1 MeV (10^{14} neutrons/cm^2-s)	11	5.3	0.5	0.13
Peak displacements per atom (dpa) per calendar year, stainless steel (65% DF)	18	6.7		
Thermal flux (10^{14} neutrons/cm^2-s)	20	9.7	7.5	4.3
Gamma heating (W/g SS)	46	16	3.3	1.7
Typical capsule diameter (mm)	16	43	37	69
Number of available positions	36	8	16	6

Spectrum Tailoring Enhances Versatility of RB★ Facilities

Characteristics	RB★ Unshielded	RB★ Hf Shield	RB★ Eu_2O_3 Shield
Fast flux, E > 0.1 MeV (10^{18} neutrons $m^{-2}s^{-1}$)	5.3	4.6	4.9
Peak displacements per atom (dpa) per calendar year, stainless steel (65% DF)	6.7	5.6	5.8
Thermal flux (10^{18} neutrons $m^{-2}s^{-1}$)	9.7	1.0	0.19
Gamma heating (W/g SS)	16	9	13
Typical capsule diameter (mm)	43	38	38

NSTD Operates Two Major Facilities to Support Irradiation Programs

- **Materials Irradiation Facility**
  - **Monitor and control of experiment conditions in real time during irradiation at ORNL High Flux Isotope Reactor**
  - **Web-based interface allows PIs to view progress of the experiment**



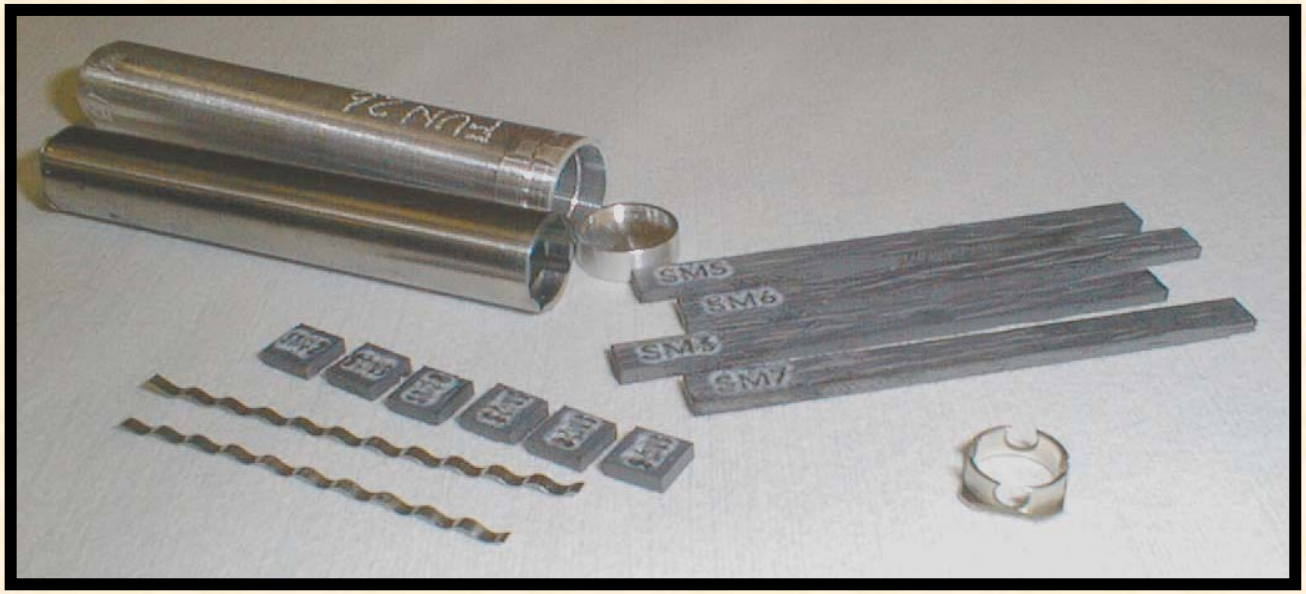
- **Capsule Assembly Laboratory**
  - **Facilities for assembling and performing acceptance testing of irradiation experiments**
  - **Integrated welding facility**
  - **Vacuum test equipment**
  - **Hydrotest equipment**
  - **Test pit for acceptance testing of long experiments**

Experiment Designs Vary From Simple to Highly Complex

- **Uninstrumented Experiments**
  - **Rabbit Capsules**
  - **Target Capsules**
- **Instrumented Experiments**
  - **Temperature monitoring and control**
  - **In-situ Measurements**

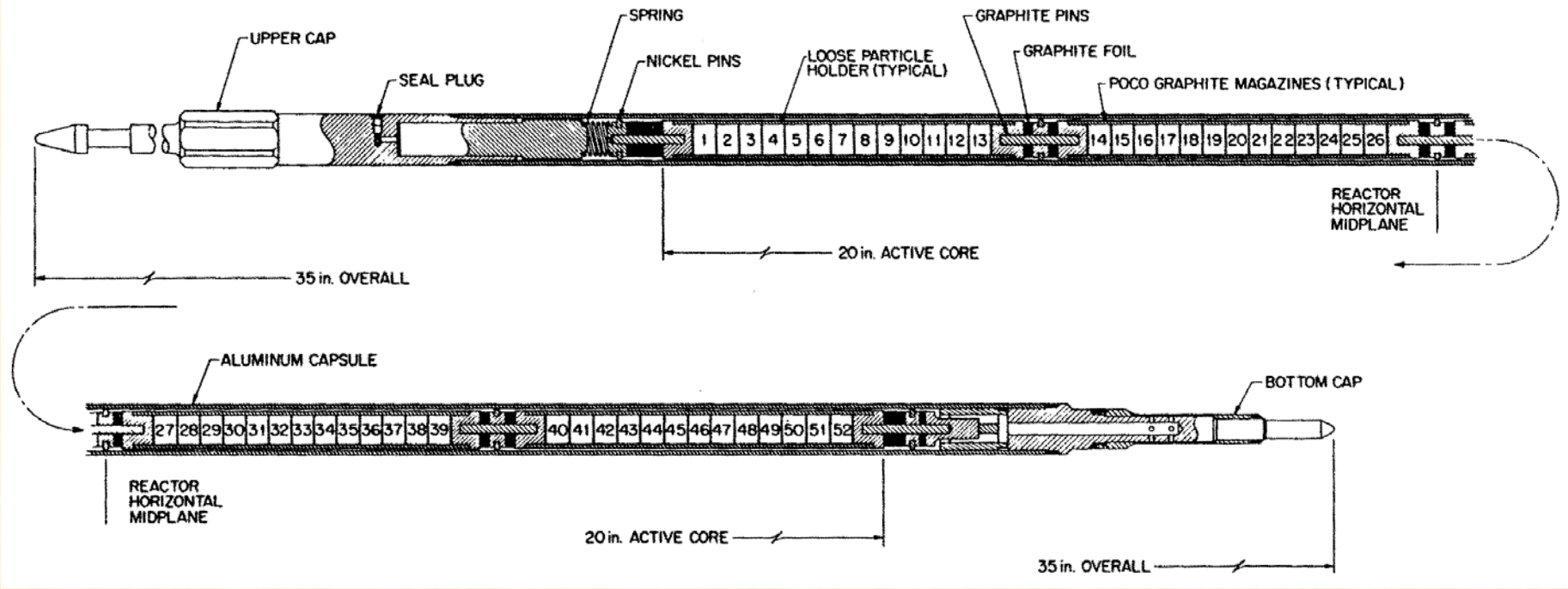
Rabbit Capsules Ideal for Scoping Tests

- **Small (0.375-in. ID by 2.3 in. long)**
- **Relatively Inexpensive**
- **Infinitely Variable Irradiation Times**
- **Temperatures up to 1500°C**



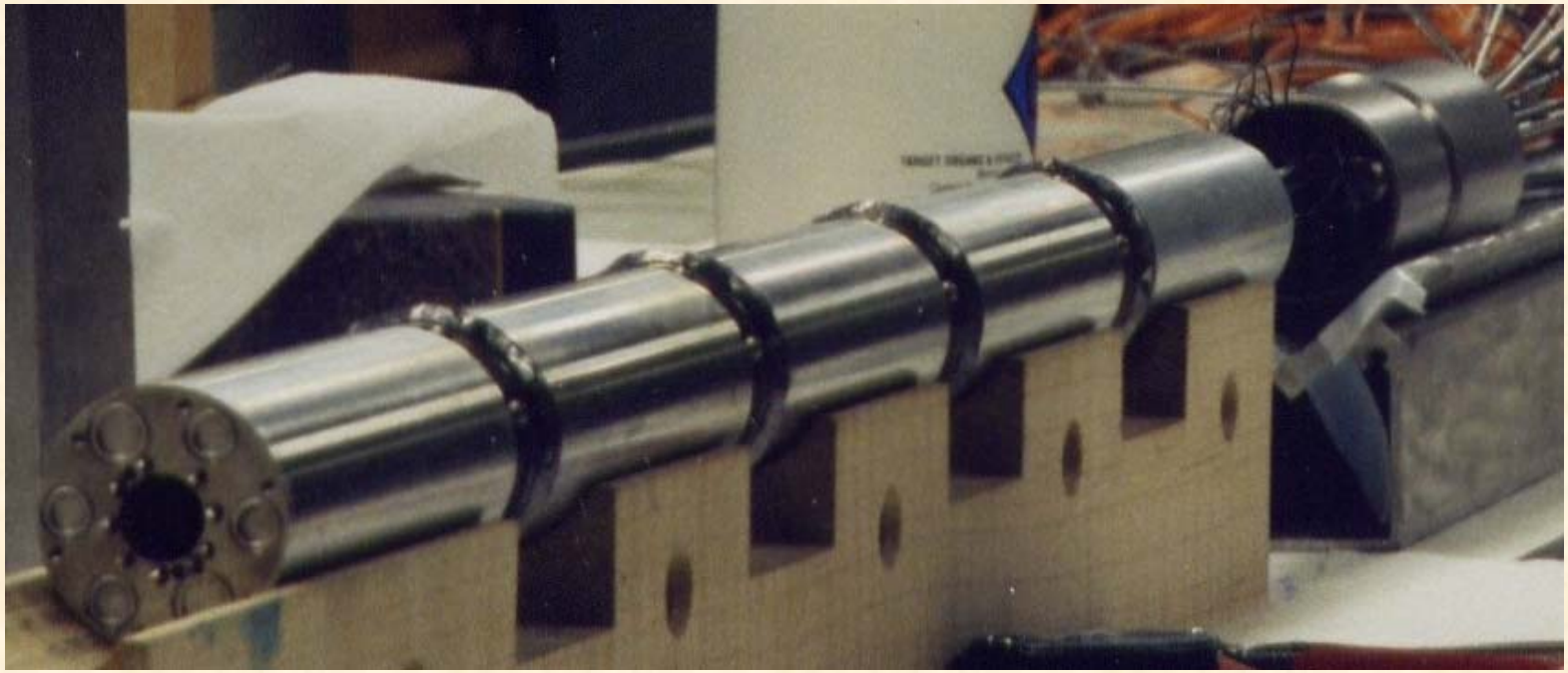
Target Capsules Offer Larger Volumes

- **Two standard designs – 0.444 in. or 0.531 in. ID by 20 in. long**
- **Irradiation temperatures up to 1500°C**



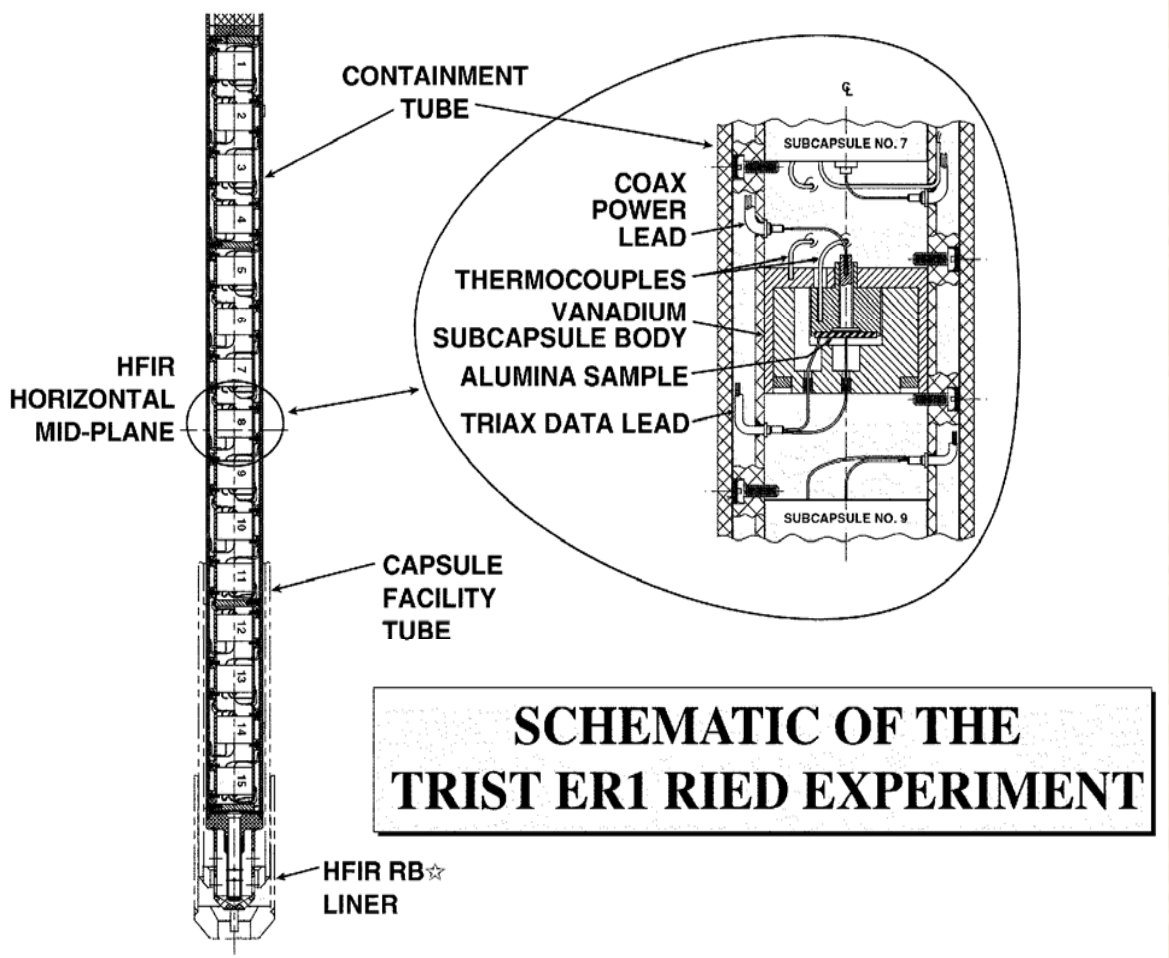
Instrumented Experiments Offer Many Options

- **Precise temperature control independent of reactor power**



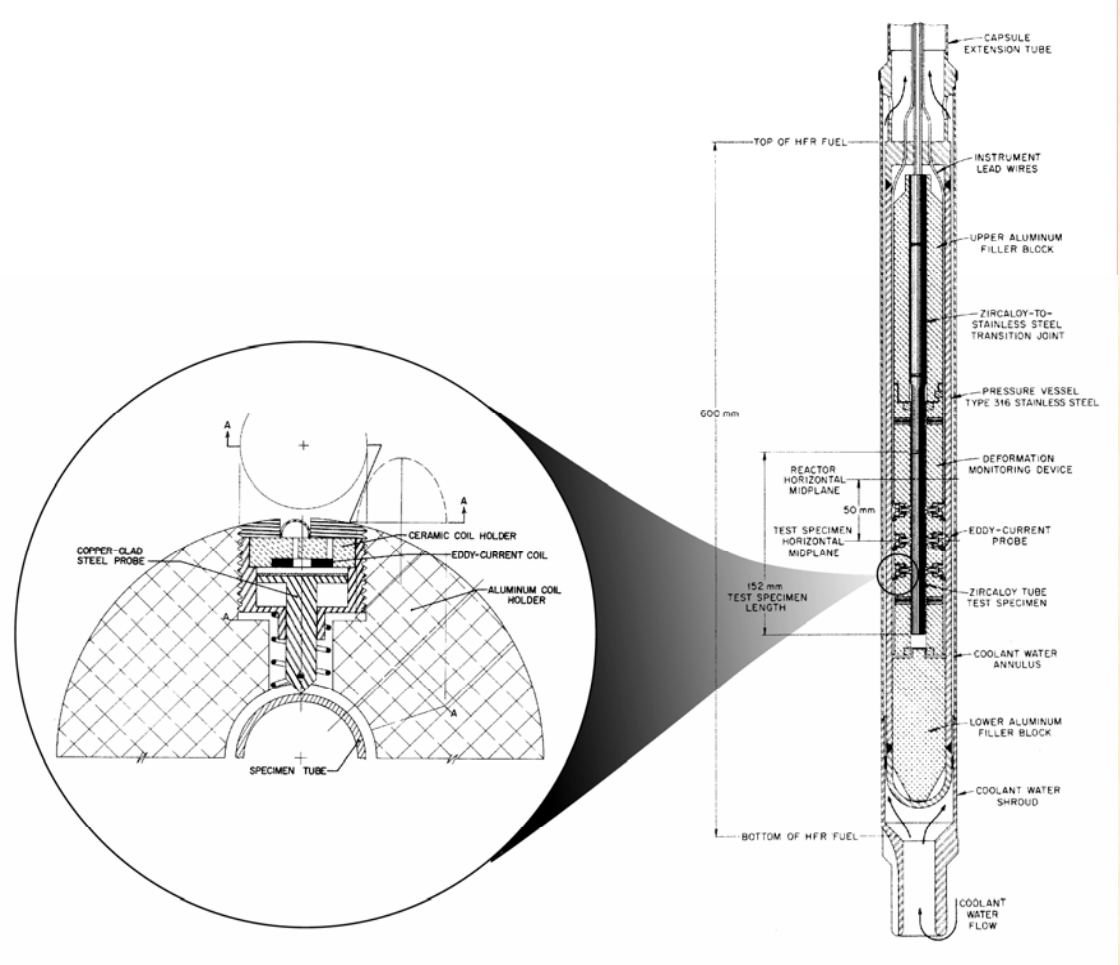
Instrumented Experiments Offer Many Options (cont'd)

- **In-situ material property measurements**



Instrumented Experiments Offer Many Options (cont'd)

- **In-situ measurement of fuel cladding creepdown**

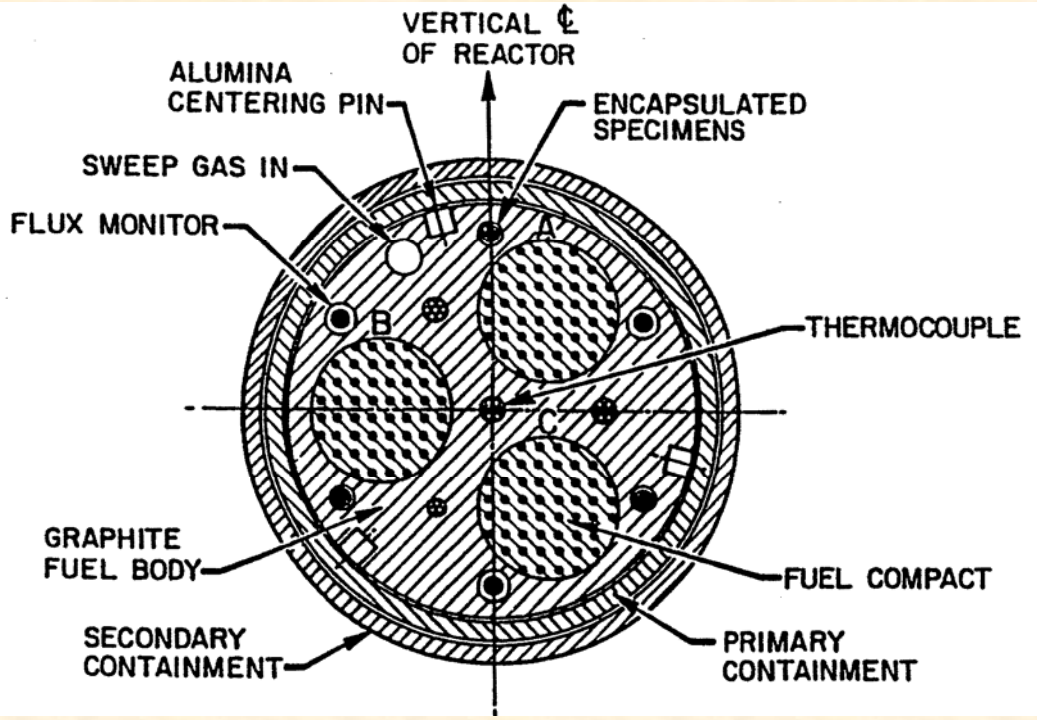


Instrumented Experiments Offer Many Options (cont'd)

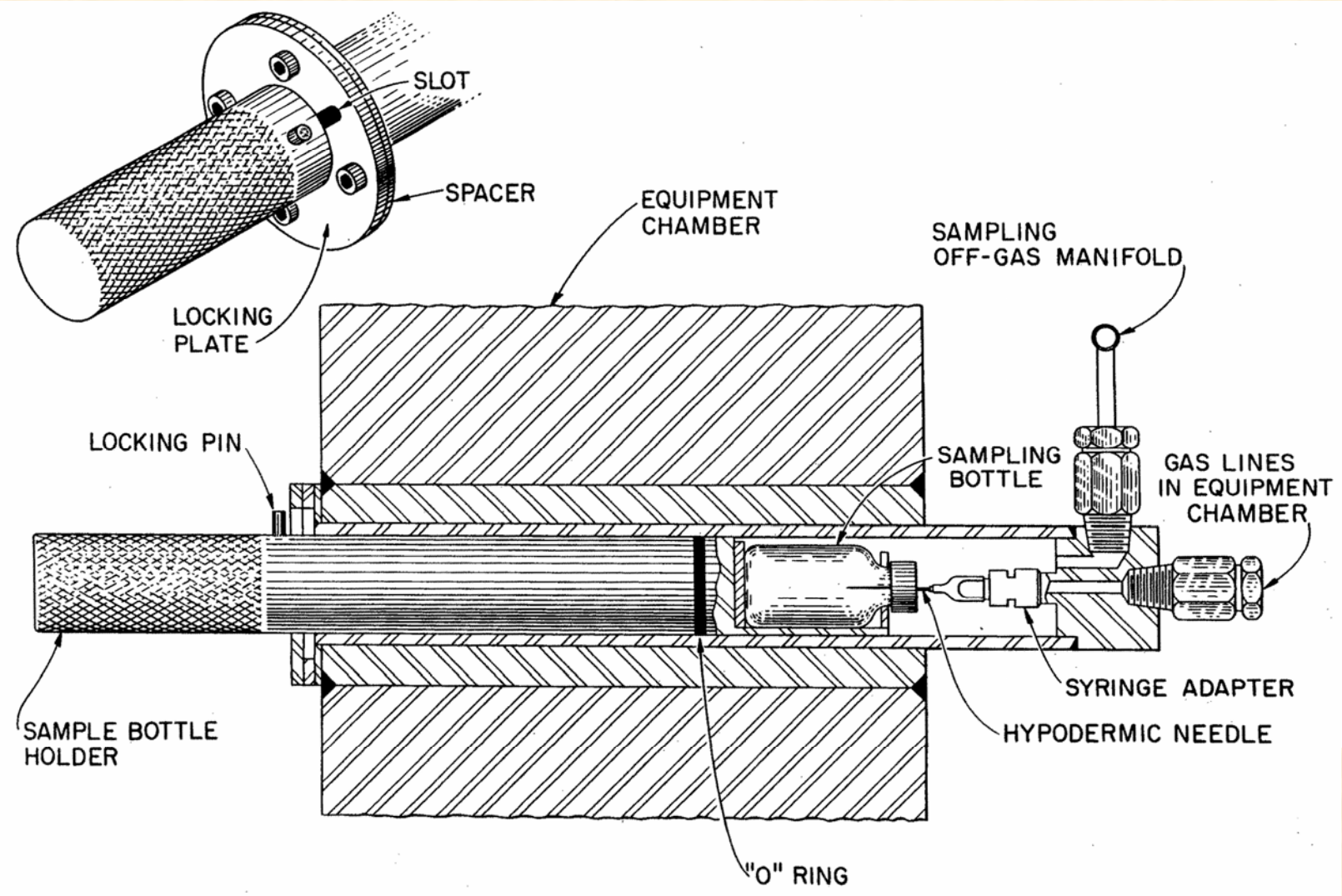
- **Lithium-filled subcapsules can accommodate multiple specimen geometries, and minimize temperature gradients**

Instrumented Experiments Offer Many Options (cont'd)

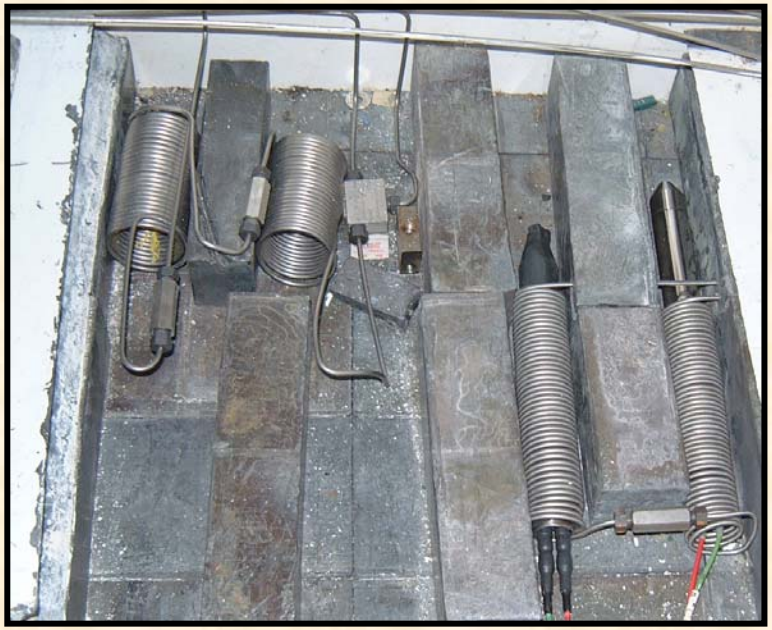
- **Double containment capsules have been used to irradiate coated-particle fuels**



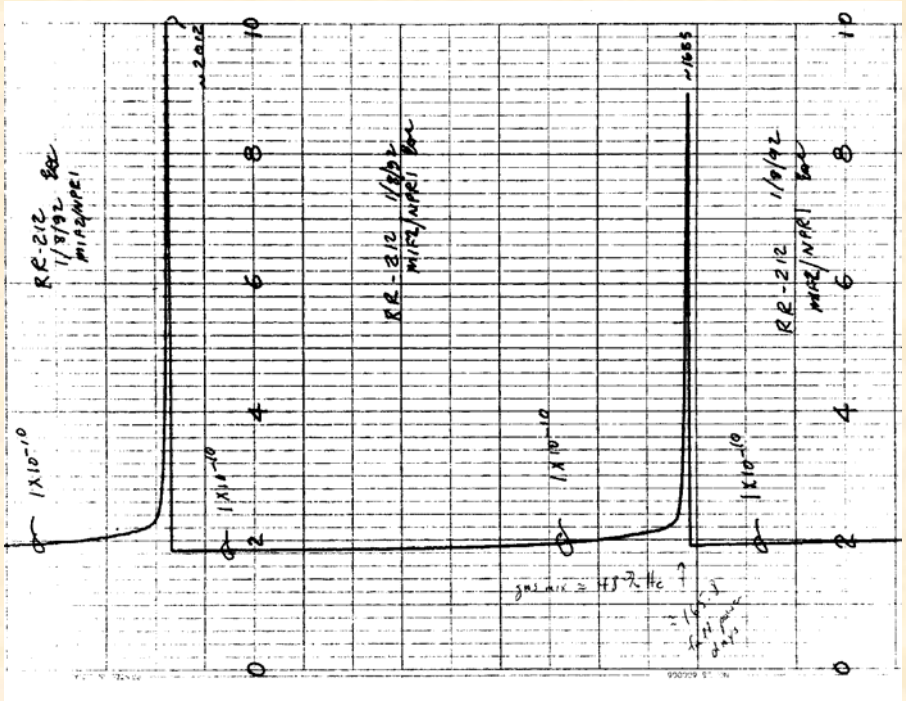
Fission Gas Sampling Station Used at HFIR

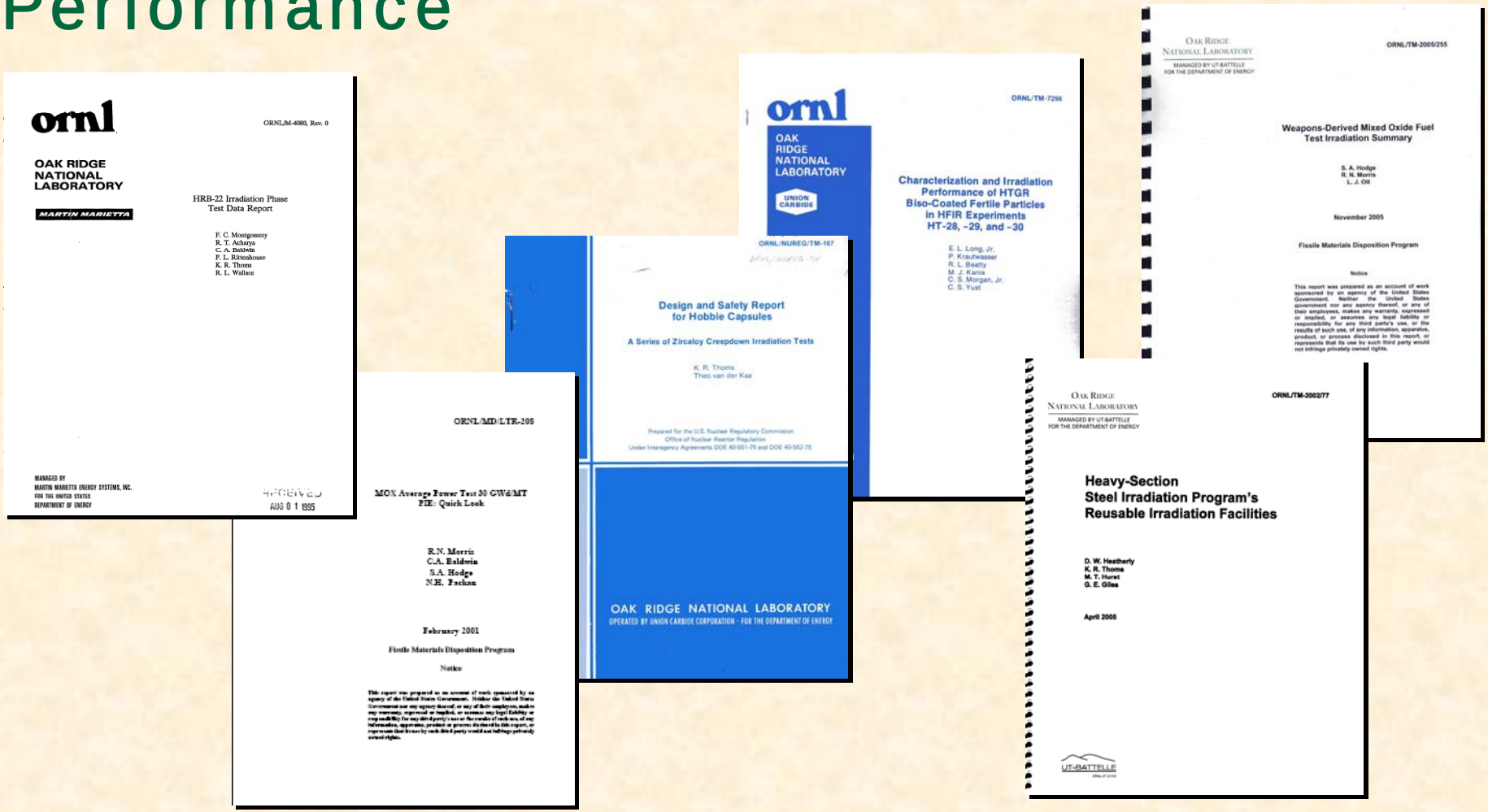


Radiation Monitors Are Used to Determine Individual Particle Failures in Coated-Particle Fuels



Monitor Arrangement



Response for Typical Particle Failure

ORNL Irradiation Programs Have Made Significant Contributions to World Knowledge Base of Materials Irradiation Performance