Fission-Product Release and Transport in the RCS

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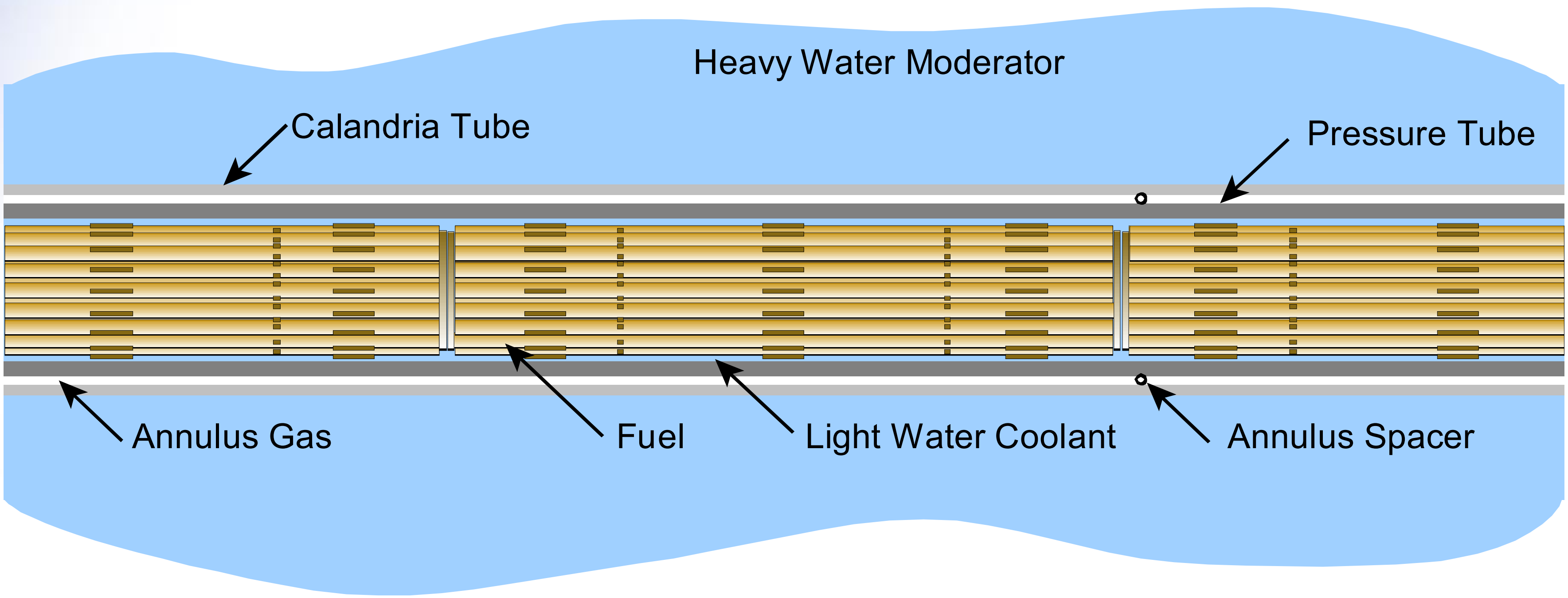
Outline

- ACR Fuel and RCS Design
- Fission-Product Release and Transport in Limited and Severe Core Damage Accidents
- Experimental Database
- Computer Codes

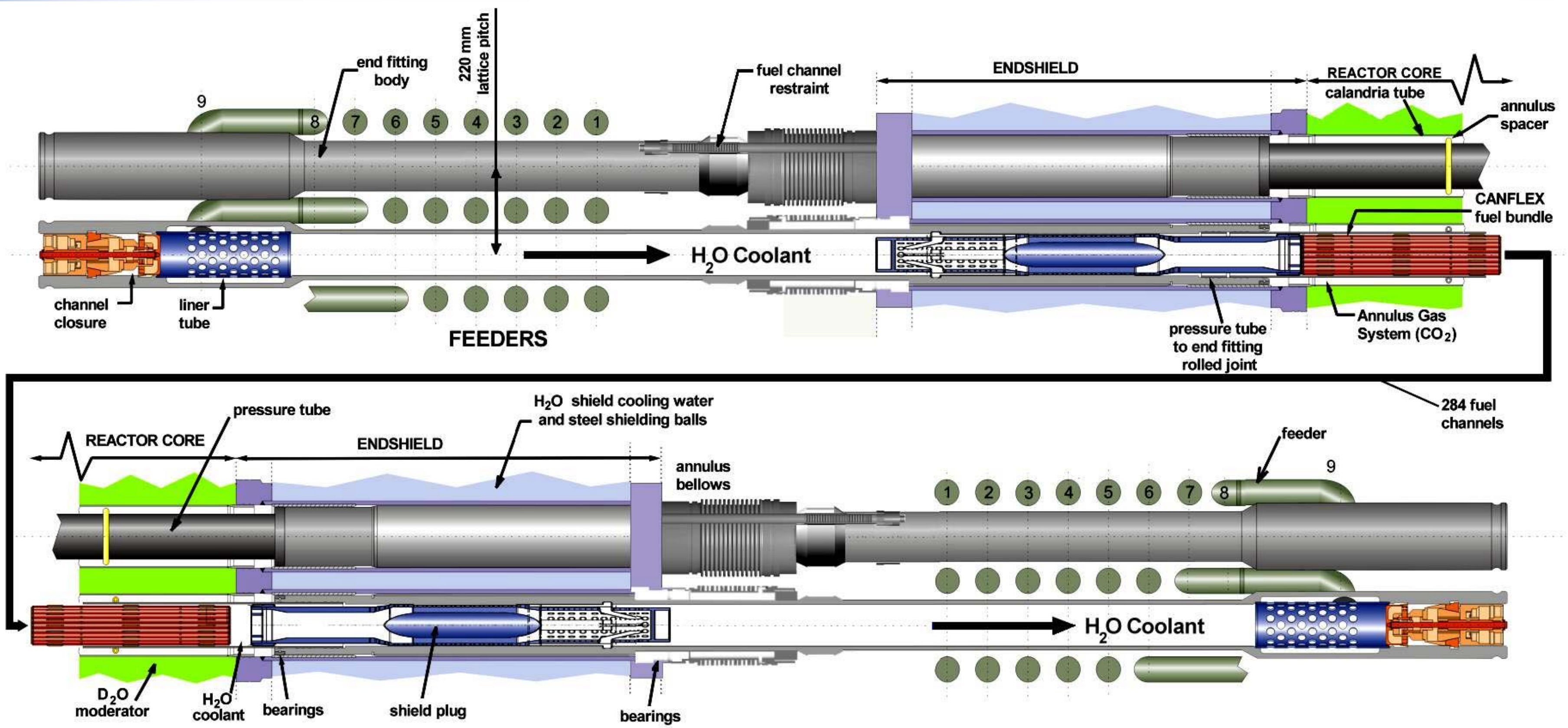
ACR Fuel Channel Details



Fuel is uranium oxide clad with Zircaloy-4

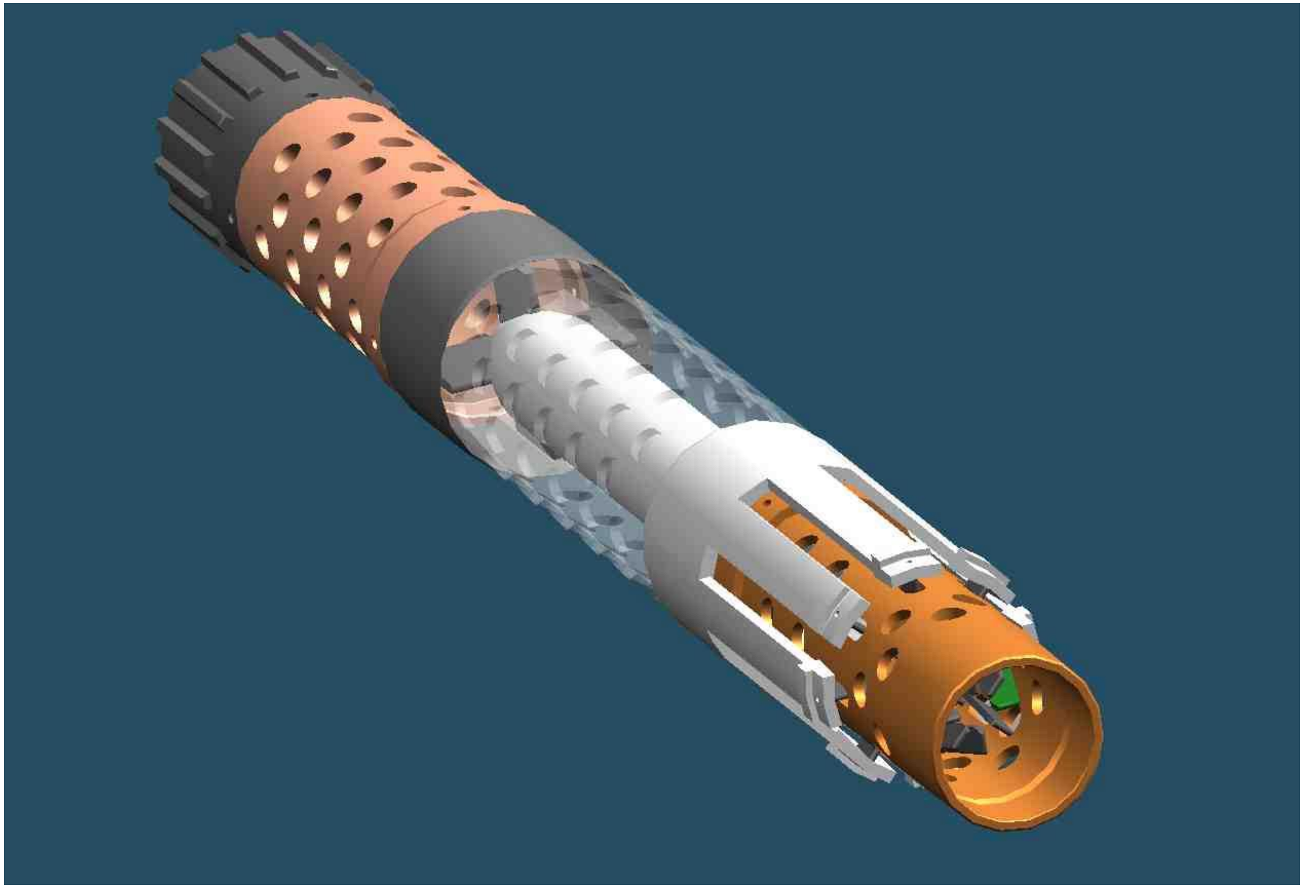
Moderator is unpressurized and below 100°C

ACR Fuel Channel

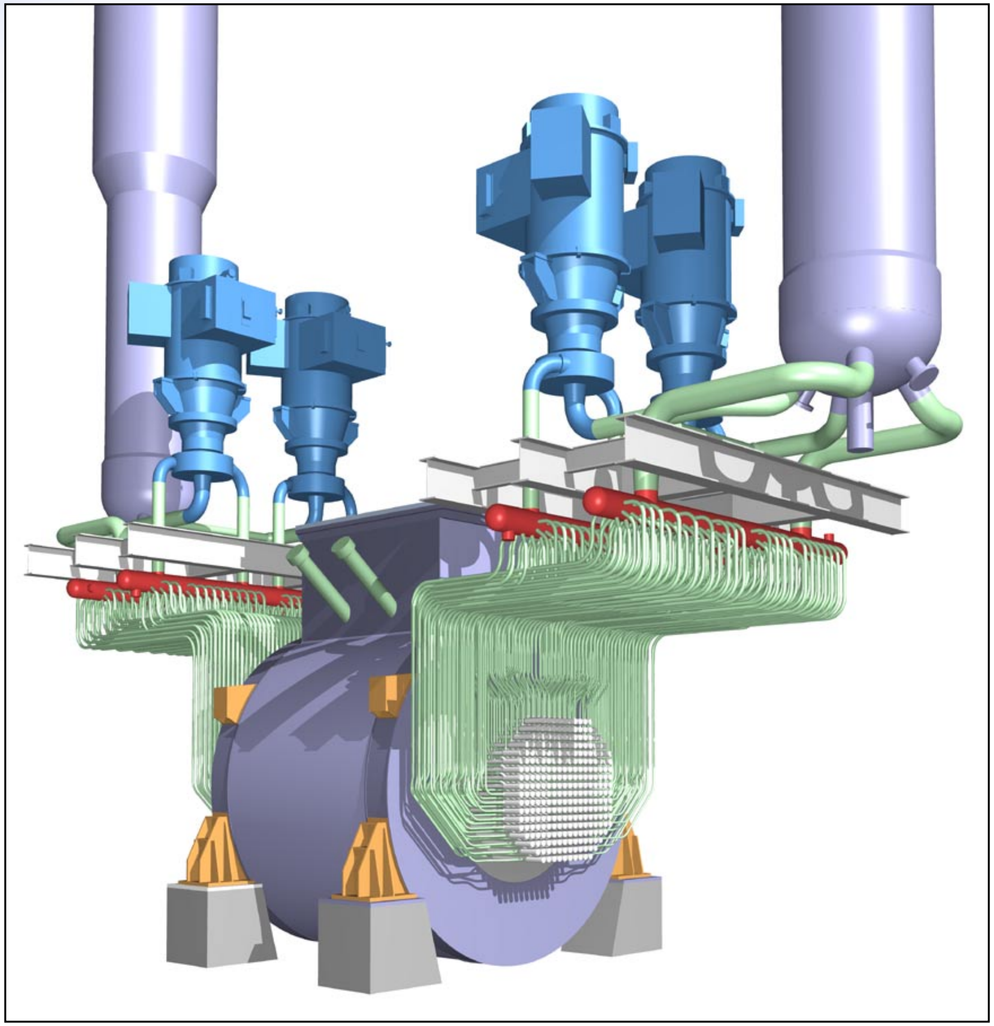


ACR Shield Plug

- The ACR shield plug is based on a flow through design
- The shield plug is attached in the bore of the end fitting to locate the fuel bundles and to provide shielding



ACR Reactor Coolant System Layout



Similar to LWR above the headers

Below headers, feeders and horizontal fuel channels instead of a pressure vessel

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Fission Product Release and Transport

- Fission product release from fuel and transport in the reactor coolant system are assessed to determine FP release into containment under accident conditions
- FP release and transport calculations are part of the source term analysis methodology
- FP release and transport simulations are used in estimating doses to the public, station staff and plant equipment

Fission-Product Release Behavior

- Diffusion in fuel grains
  - Fuel oxidation increases diffusion rate
- Accumulation and venting from grain boundaries
- Grain-boundary sweeping
- Accumulation on fuel surface and in fuel-clad gap
- Redox conditions (hydrogen vs. steam) of fuel environment after cladding failure affect volatility
  - Noble gases (Kr, Xe) and volatile elements (I, Cs, Te, etc.) are released from the fuel in significant amounts at high temps.
  - Other elements (e.g., Ru) may also be released if the fuel is exposed to oxidizing conditions for extended periods

FP Release Phenomena (1)

- Athermal Release (knockout, recoil and fission-spike)
- Diffusion (from fuel grains to grain boundaries)
- Grain-Boundary Sweeping / Grain Growth
- Grain-Boundary Bubble Coalescence / Tunnel Interlinkage
- Vapor Transport / Columnar Grains
- Fuel Cracking (thermal)
- Gap Transport (failed elements)
- Gap Retention

FP Release Phenomena (2)

- Uranium Oxidation State
  - $UO_{2-x} \leftrightarrow UO_2 \leftrightarrow UO_{2+x} \leftrightarrow U_4O_9 \leftrightarrow U_3O_8$
- UO_2 – Zircaloy Interaction
- UO_2 Dissolution in Molten Zircaloy
- Fuel Melting
- Fission Product Vaporization / Volatilization
- Matrix Stripping
- Temperature Transients
- Grain-Boundary Separation
- Fission-Product Leaching

Fission-Product Transport Behavior

- Noble gases transported to the break
- Retention of other fission products can occur in the reactor coolant system between the fuel and the break location
- Aerosol deposition, especially in
  - Complex geometries (e.g., end fittings)
  - Condensing steam (e.g., in feeder pipes)
  - Water-filled components (e.g., headers and steam generators)
- Fission-product vapor condensation
- Fission-product vapor reactions with piping surfaces

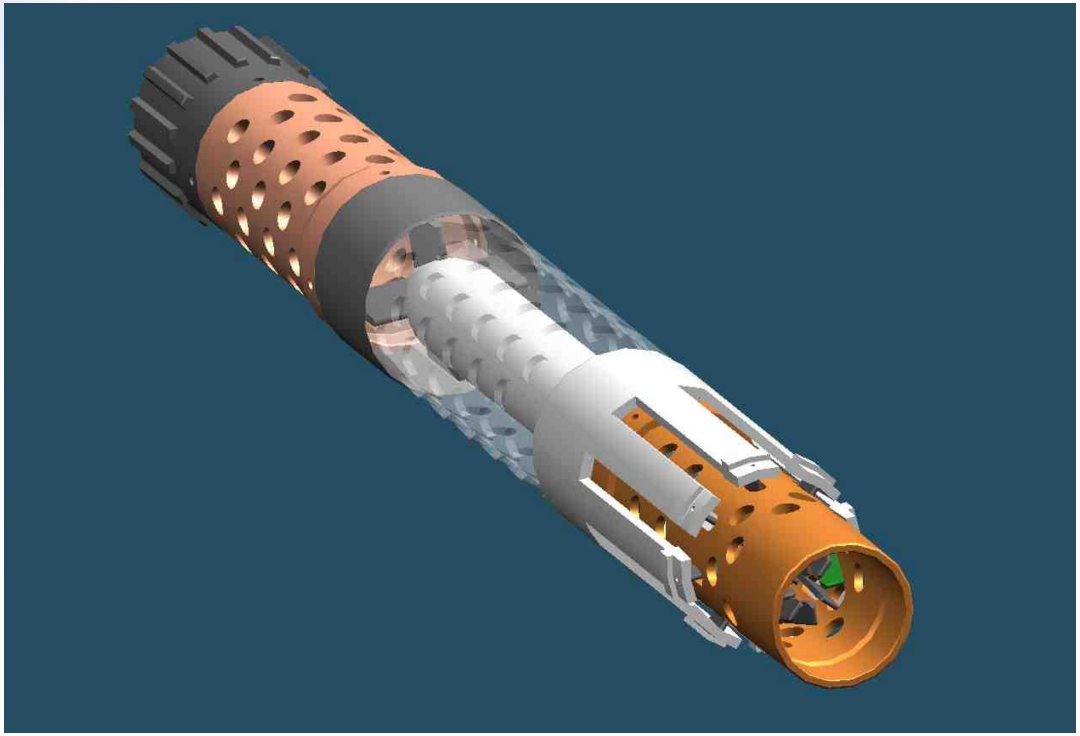
RCS FP Transport Phenomena (1)

- Fuel Particulate Suspension
- Vapor Deposition and Revaporization of Deposits
- Vapor / Structure Interaction
- Aerosol Nucleation
- Aerosol Agglomeration
  - Gravitational, Brownian motion (diffusional), turbulent, laminar, and electrostatic mechanisms
- Aerosol Growth / Revaporization

RCS FP Transport Phenomena (2)

- Aerosol Deposition
  - Thermophoresis, diffusiophoresis (Stefan flow), gravitational deposition, Brownian motion deposition, turbulent deposition, laminar deposition, electrophoresis, inertial deposition and photophoresis
- Aerosol Resuspension
- Pool Scrubbing
- Transport of Deposits by Water
- Chemical Speciation
- Transport of Structural Materials

ACR Shield Plug



Fission products will be deposited in complex flow paths such as through the shield plug.

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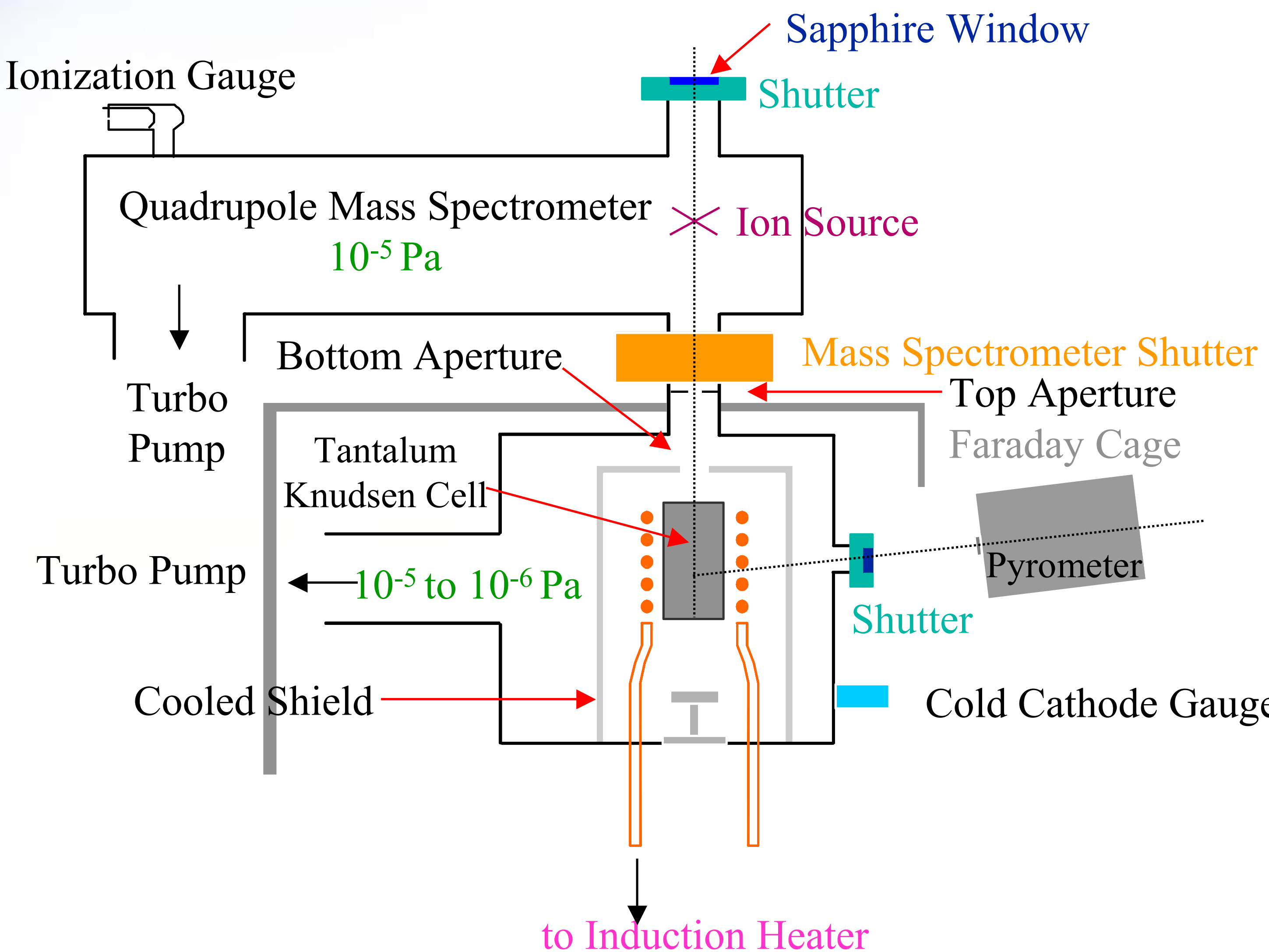
FPR&T Experimental Database

- **Laboratory separate-effects tests**
  - UO_2 oxidation-volatilization studies
  - Fission-product thermochemistry
  - Aerosol deposition in CANDU fuel channel end fitting
- **Hot-cell fission-product release tests**
  - FP release and transport from clad and unclad fuel samples under accident conditions (Canadian, ORNL VI, Vercors)
  - Grain boundary inventory measurements
  - Direct-electric-heating tests
- **In-reactor tests under accident conditions**
  - Canadian severe-fuel-damage tests (BTF)
  - International severe accident tests (ACRR ST, Phebus FP)

Knudsen Cell – Mass Spectrometer

- Used to measure vapor pressures and other thermodynamic properties of fuel and fission-product compounds at high temperatures

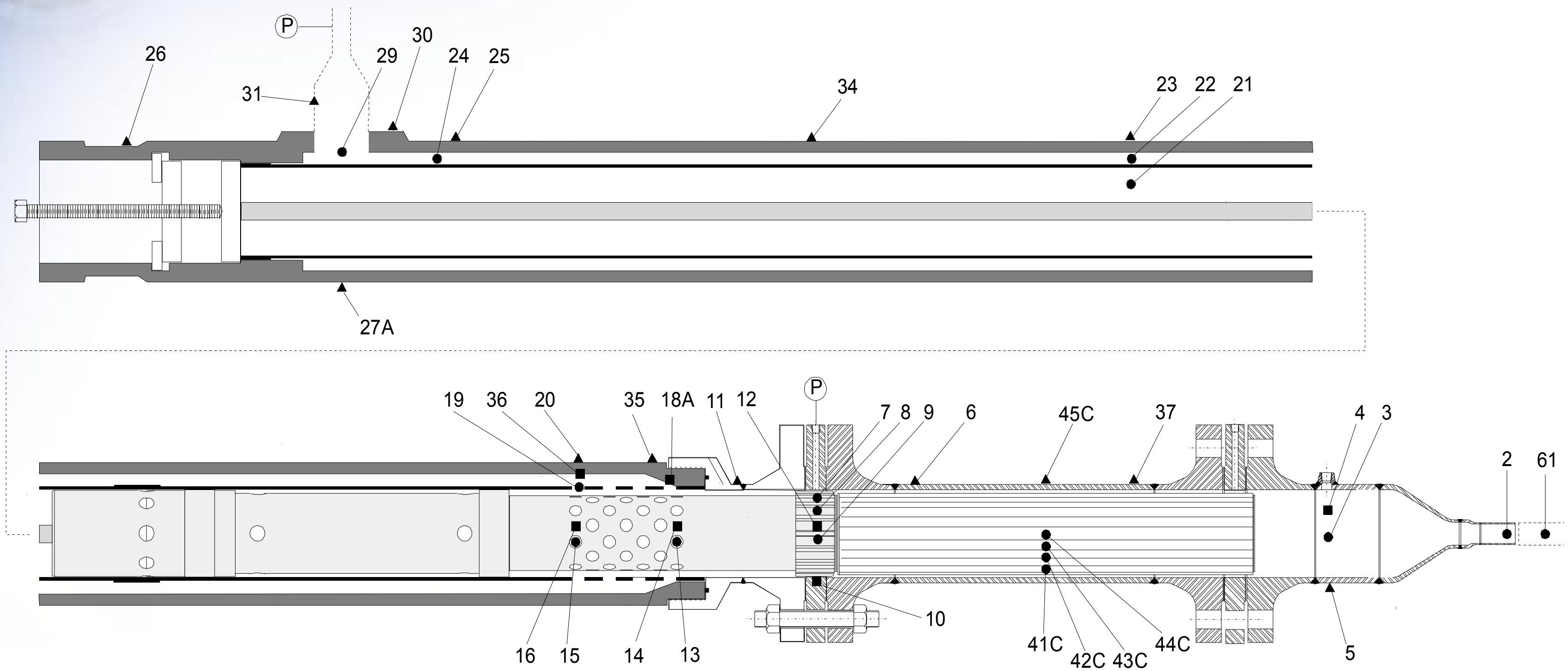
Knudsen Cell - Mass Spectrometer



Systems Investigated with KC-MS

- Iodine volatility over CsI / UO_2 / MoO_x and CsI / U_3O_8
- Lanthanum volatility over lanthanum oxide / uranium dioxide solid solutions
- FP simulant volatility over SIMFUEL
- Vapor pressure and stability of cesium molybdate

End Fitting Aerosol Deposition Rig



32 condenser - inlet steam temp.
33 condensate temp.
57 superheater -steam temp. at inlet
58 superheater -steam temp. at CsI injection point
59 superheater -surface temp
60 superheater -surface temp at outlet
61 superheater -steam temp at outlet

● steam temp.
■ wall temp.
▲ outside wall temp.
Ⓟ pressure sensor

EF11-7F.DRW

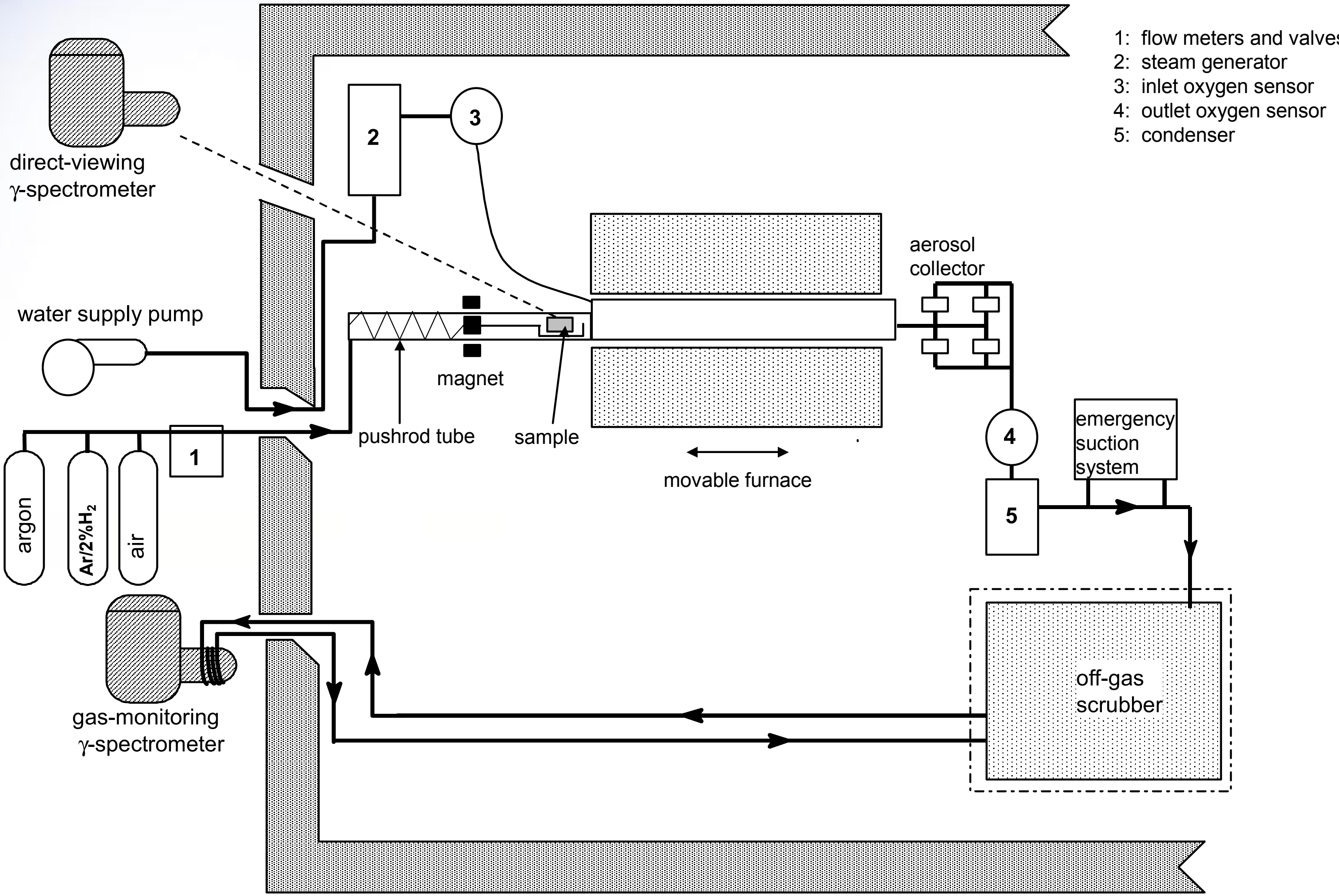
Hot-Cell FP Release Tests

- FP release and transport from clad and unclad fuel samples under accident conditions
  - > 300 tests performed
  - Maximum temperatures: 670 to 2300 K
  - Environments: H_2, Ar/H_2, steam/H_2, steam, air
  - Heating rates: 0.2 to 50 K/s
  - On-line gamma-spectroscopy for FP release measurements
  - Post-test gamma-scanning for FP deposition measurements

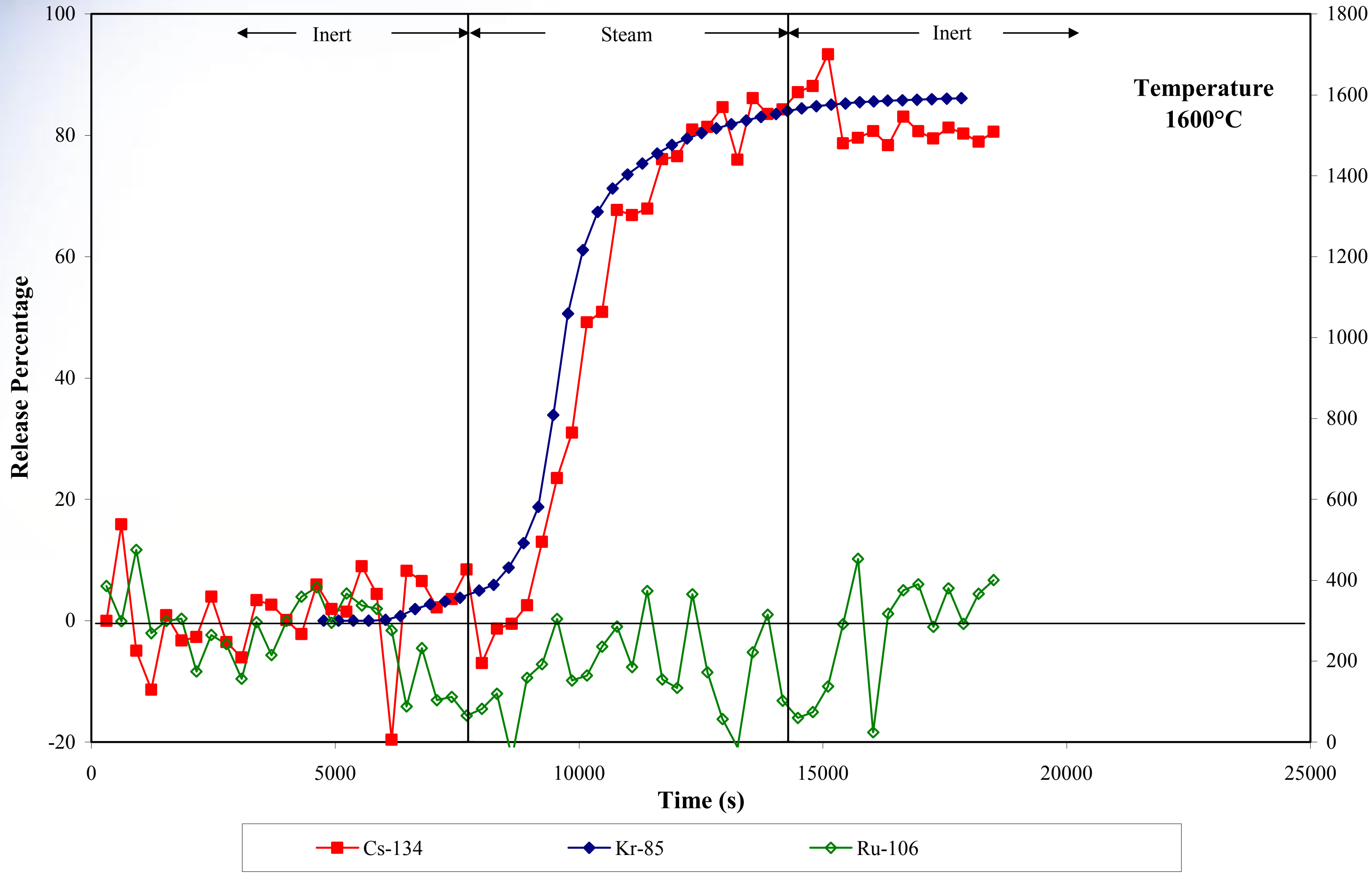
HCE4 Experiment Objectives

- Hot-Cell Experiment #4 (HCE4) was performed to provide data on fission-product releases (FPR) from CANDU fuel at 1650°C for validation of CANDU reactor safety codes
- Three sets of tests were performed to assess the effects of the following parameters on FPR:
  - Gaseous environment (Ar/2%H_2, steam/0.5%H_2 and air)
  - Fuel sample length (20 and 100 mm)
  - Heating rate (0.2, 1-2 and 6 K/s)

Schematic of HCE4 Hot-Cell Apparatus



Fission-Product Release in J03 Test



% FP Release (±1σ Uncertainties)

Test	J01	J02	J03	J04
Environ.	$Ar/2\%H_2$	Air	$Steam/H_2$	$Steam/H_2$
Temp /°C	1620	1645	1640	1650
Time /s	5733	6712	6360	6462
^{85}Kr	8 ± 1	100 ± 11	74 ± 10	73 ± 8
^{106}Ru	0 ± 4	13 ± 3	1 ± 3	0 ± 3
^{131}I	11 ± 4	100 ± 10	79 ± 3	100 ± 10
^{134}Cs	2 ± 5	75 ± 1	84 ± 1	82 ± 2
^{137}Cs	0 ± 6	74 ± 2	86 ± 1	84 ± 2

Conclusions from Hot-Cell FPR Tests

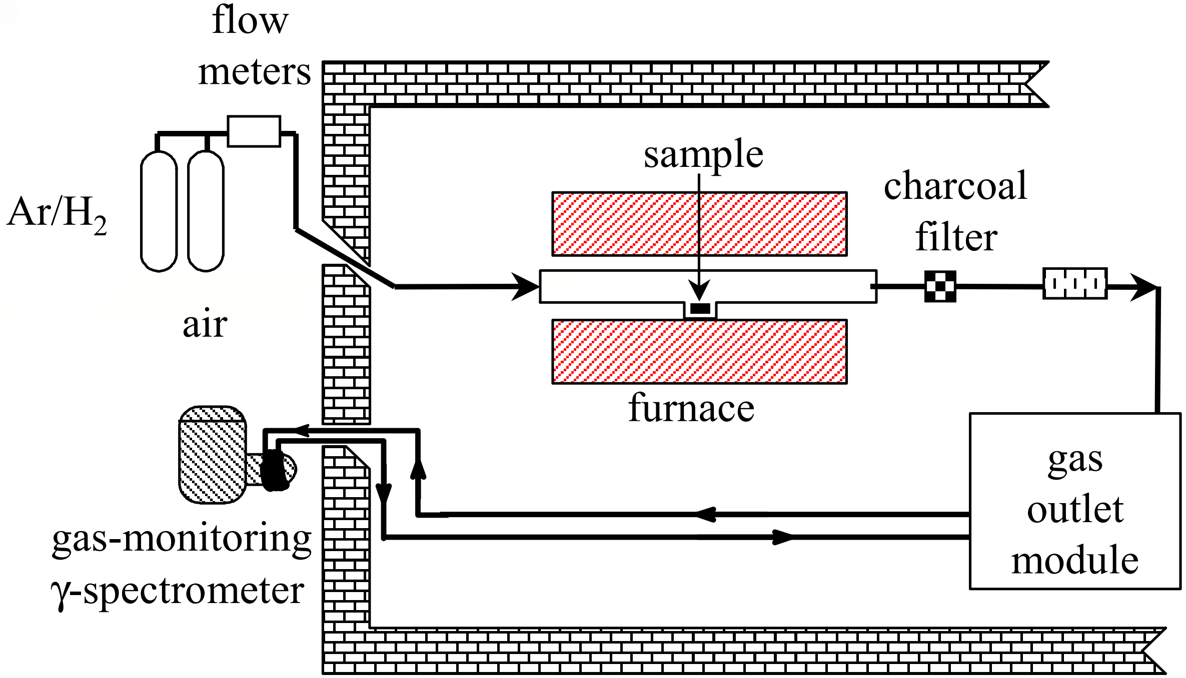
- **FP releases increase with increasing temperature**
- **FP releases depend on oxygen potential of the environment (hydrogen, steam, air)**
  - **Noble gases and volatile FP (I, Cs, Te, etc.) are released rapidly under oxidizing conditions**
  - **Releases of other FP (Ru, Ba, Nb, Sr, etc.) depend on the volatility of the stable condensed-phase species formed in the environment, e.g., Ru released under oxidizing conditions**
  - **Non-volatile FP and actinides released by vaporization of the UO_2 matrix**

Grain Boundary Inventory Tests

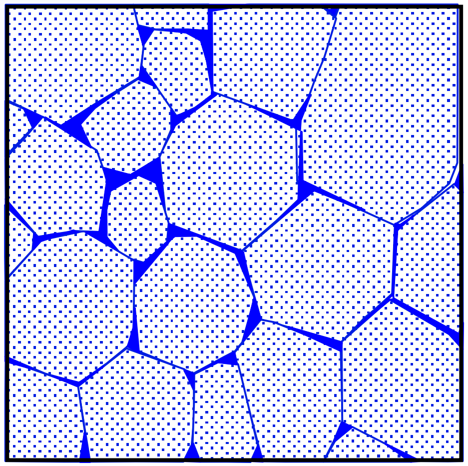
- **Motivation**
  - Data for validation of fuel performance codes
    - normal operating conditions
  - GBI is released more rapidly under accident conditions
    - safety analysis

GBI Measurement Technique

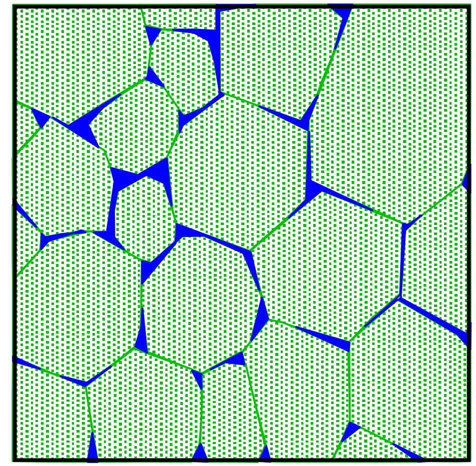
- **Heat to 500°C in Ar/H_2, add air flow**
  - **Kr-85 GBI plus Kr-85 and Xe-133 500°C grain releases**
- **Heat to 1100°C in air**
  - **Release remaining Kr-85 and Xe-133 in grain**



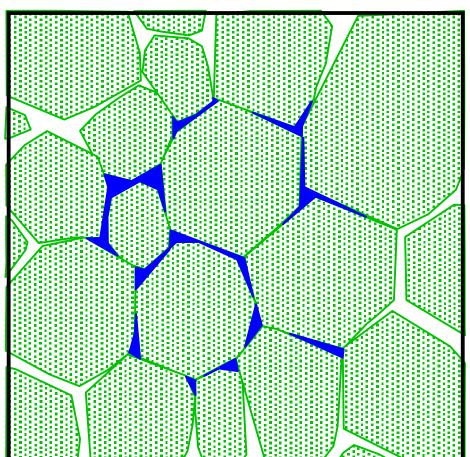
GBI Measurement Technique



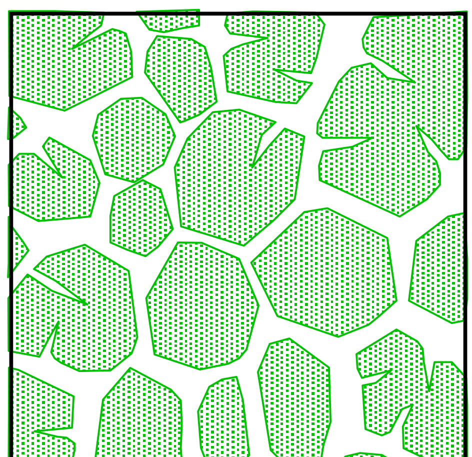
As-received



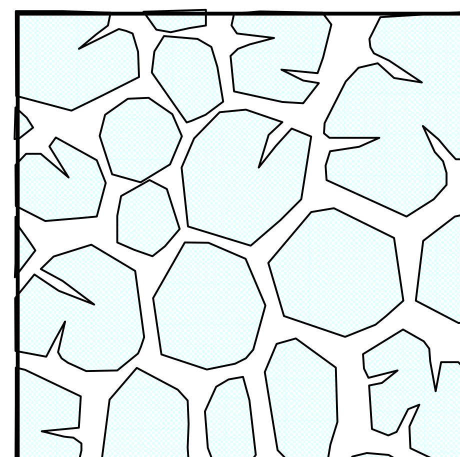
Trace-reirradiated



Start of 500°C air

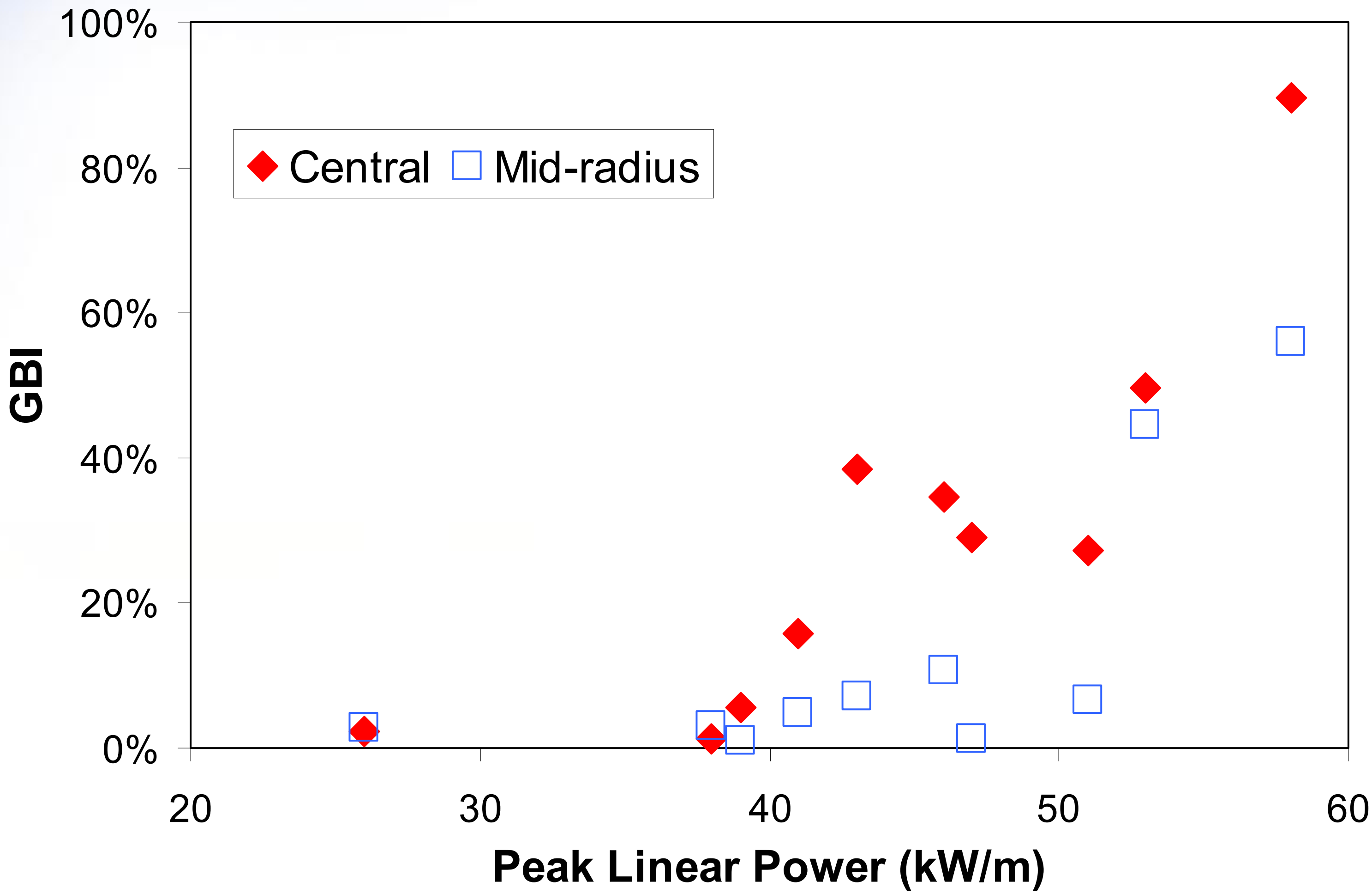


500°C air



1100°C air

Central and Mid-Radial GBI



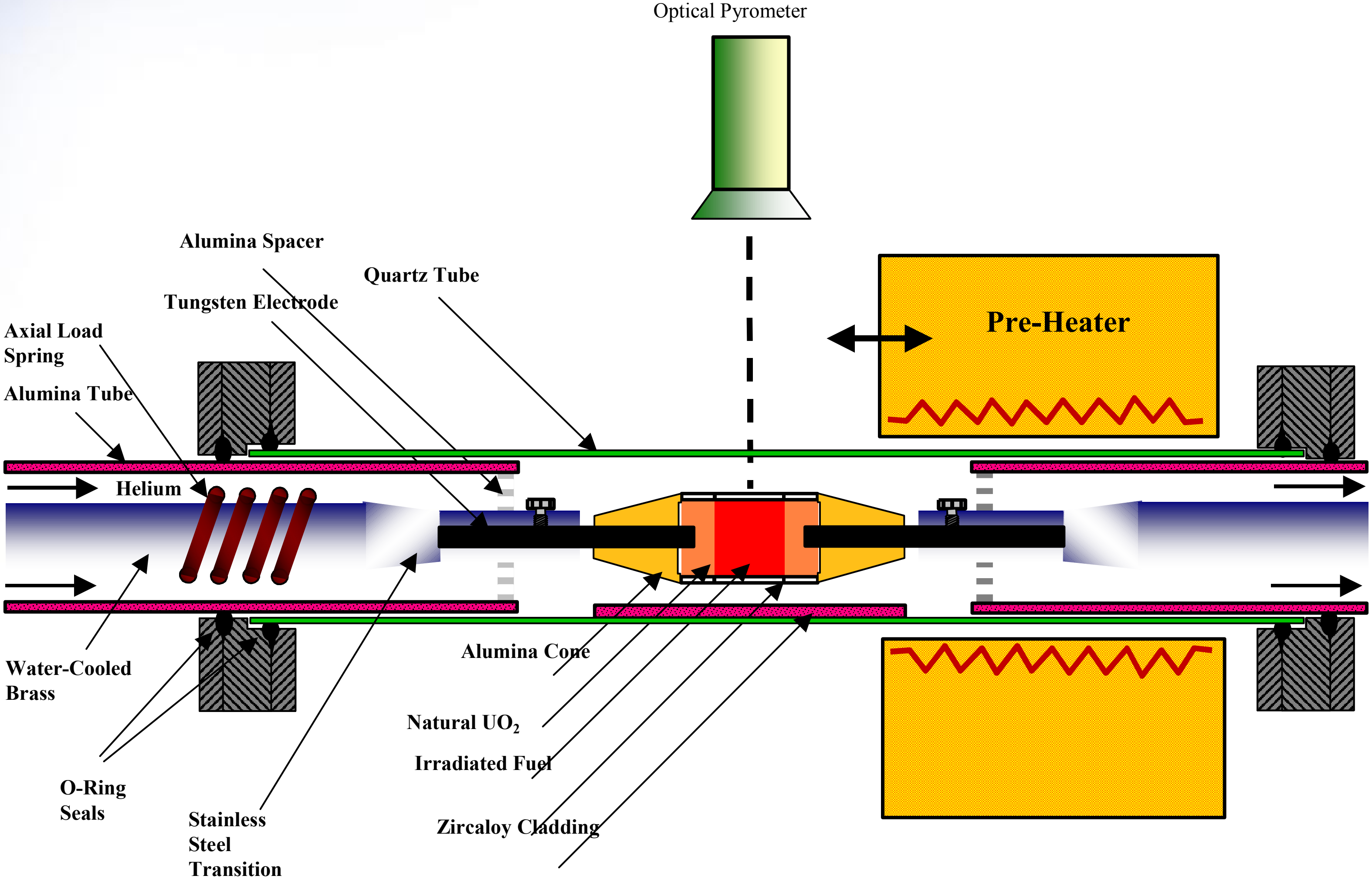
GBI Conclusions

- GBI and total inventory show radial variation
- Peripheral GBI < 5%
- Central GBI starts to rise at 38 kW/m
  - maximum of 90% for 58 kW/m high-burnup fuel
- High-GBI region expands with increasing power
- Absolute GBI saturates at center of fuel above 41 kW/m

Direct-Electric-Heating Experiments

- Fuel heated using direct electrical current to obtain conditions expected in reactor accident scenarios:
  - Rapid heating rates
  - Large radial temperature gradients
  - Original Zircaloy cladding

Direct-Electric-Heating Apparatus



Observations in DEH Tests

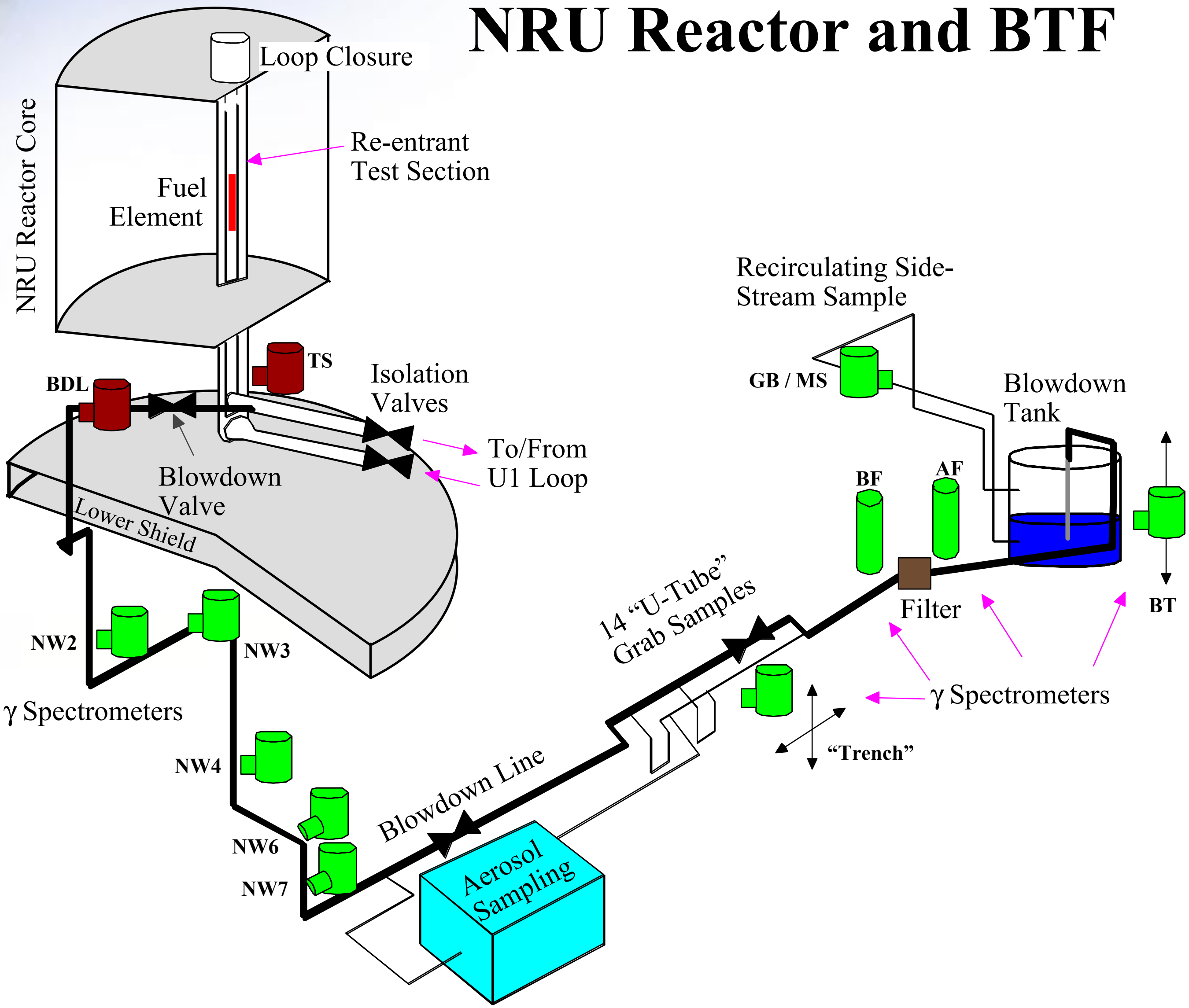
- Electric current flows mainly along fuel pellet axis
  - Exaggerates radial fuel temperature gradients
- Switched DC current (0.5 Hz) used to minimize electrolysis
- Some noble gas FP releases observed
- Volatile FP (e.g., Cs) redistribute from pellet center to periphery but are not actually released

Blowdown Test Facility

Research Program Goals

- Verify our understanding of fuel behavior and FP release and transport under high temperature conditions representative of severe-fuel-damage accident scenarios
- Provide data from integral in-reactor experiments for use in the validation of computer codes used for safety analyses and licensing of CANDU reactors

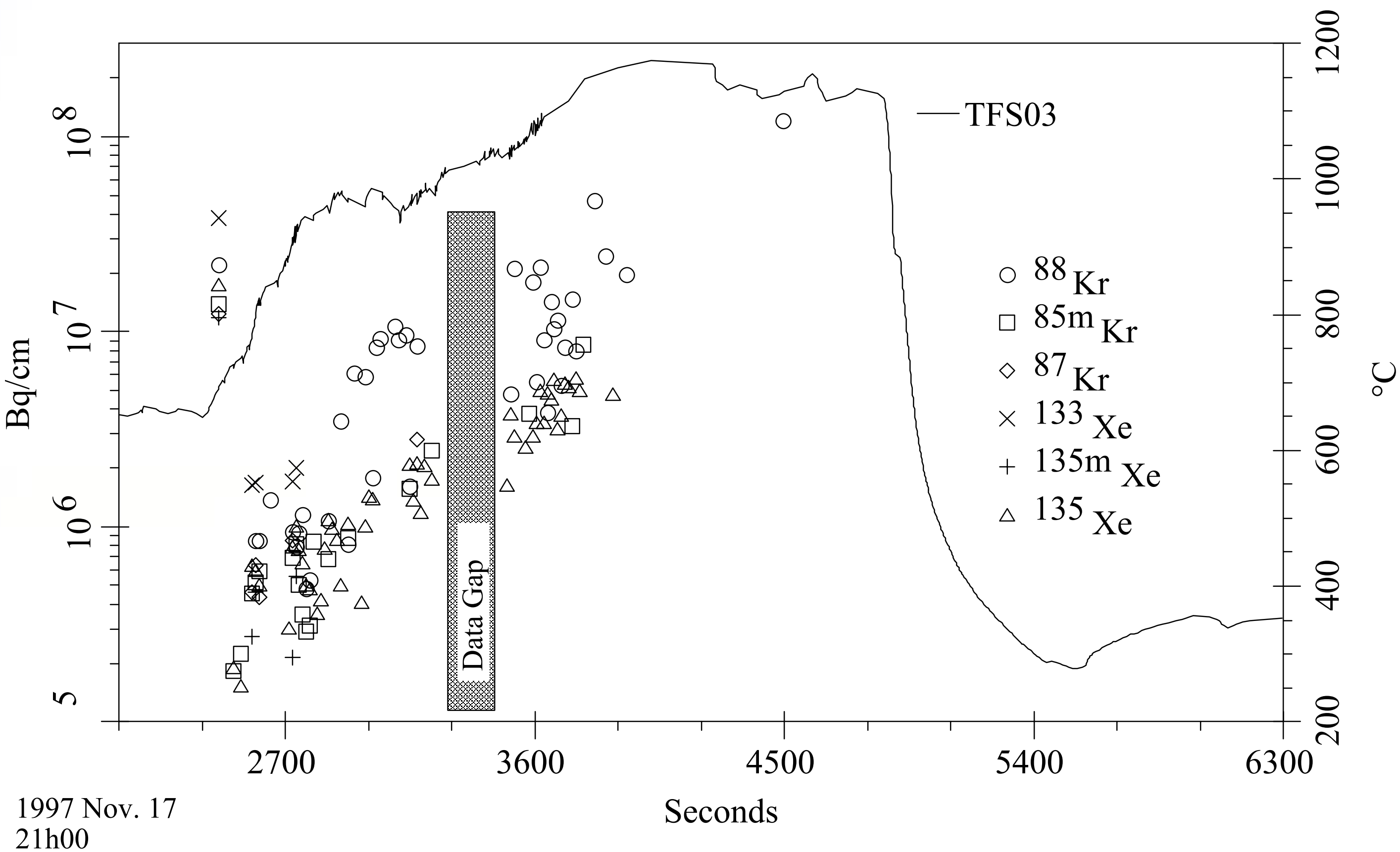
NRU Reactor and BTF



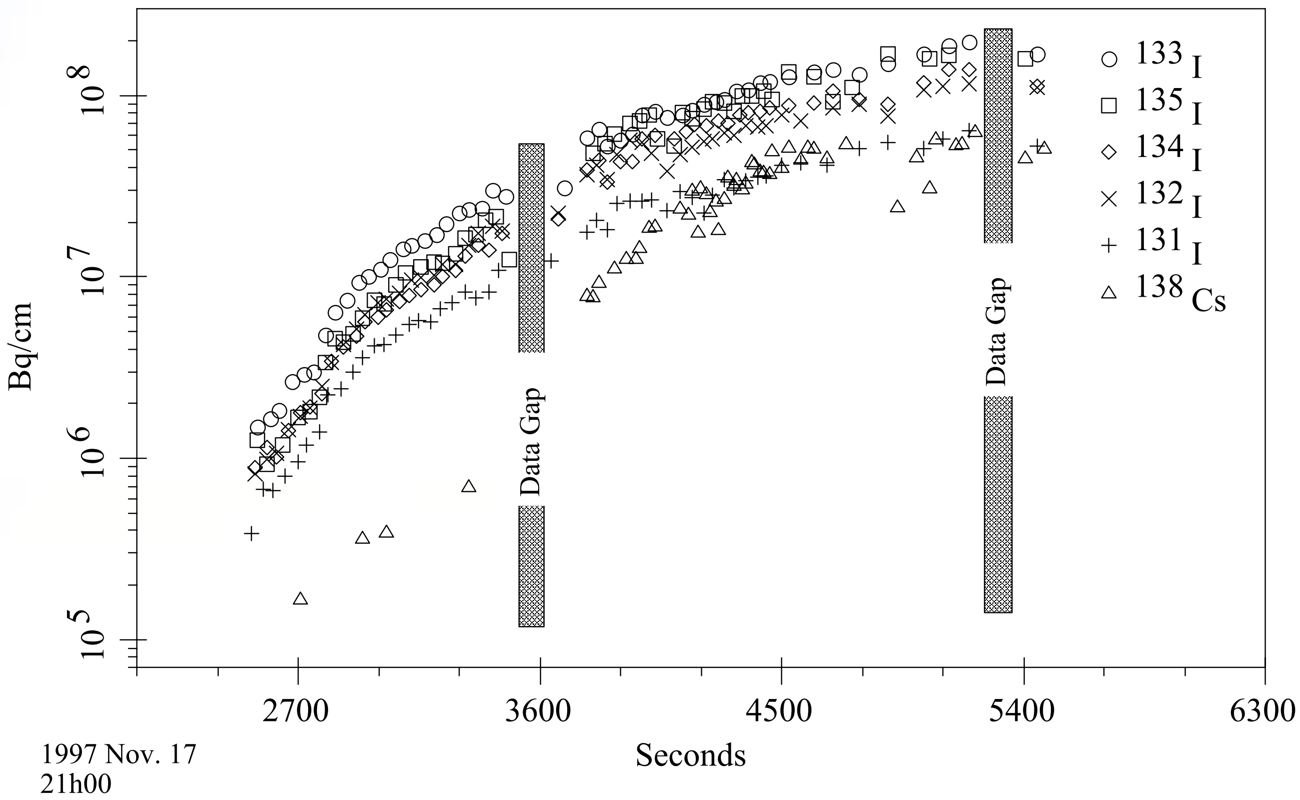
BTF-105B Objective

- Measure fission product release under high temperature conditions
  - fuel-averaged temperature target of 1800-2000°C
  - try to preserve element geometry to measure retained fission products and fuel performance
  - compromise resulted in a target fuel-averaged temperature about 1800°C for 15 minutes

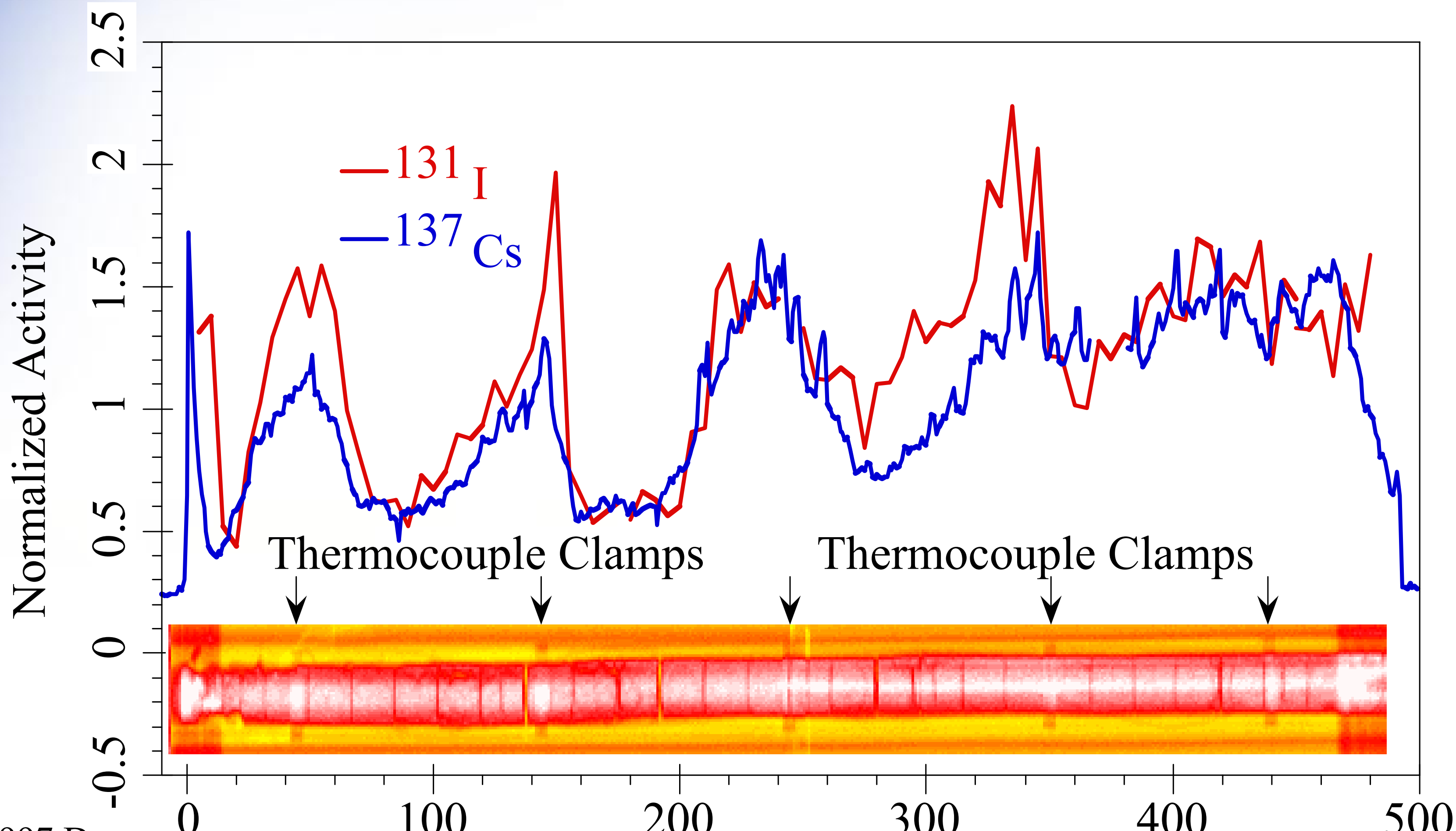
BTF-105B Noble Gas Release Kinetics



BTF-105B I and Cs Gamma Activities

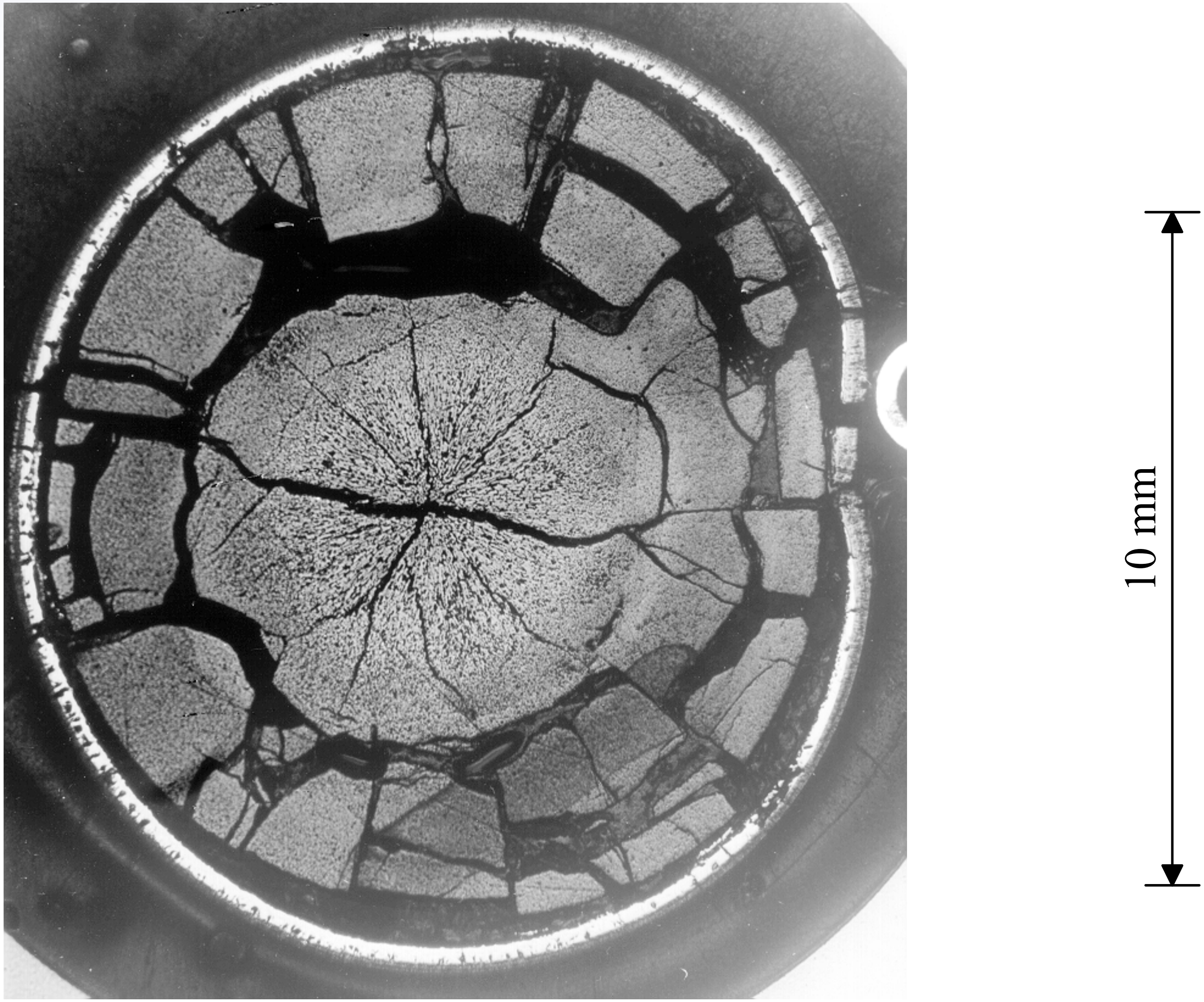


^{131}I, ^{137}Cs Along Fuel Element

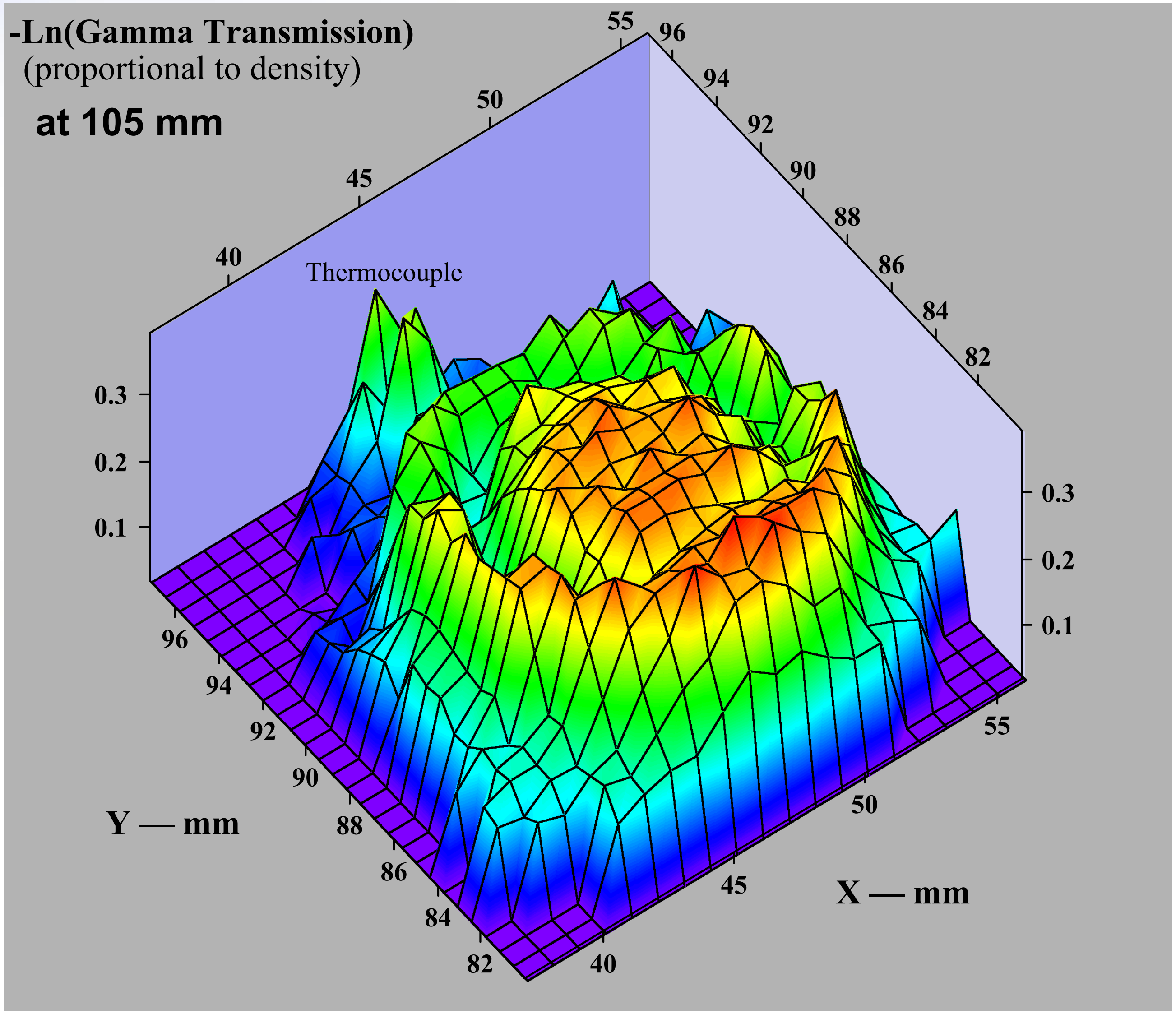


1997 Dec.,
1998 Jul. 10

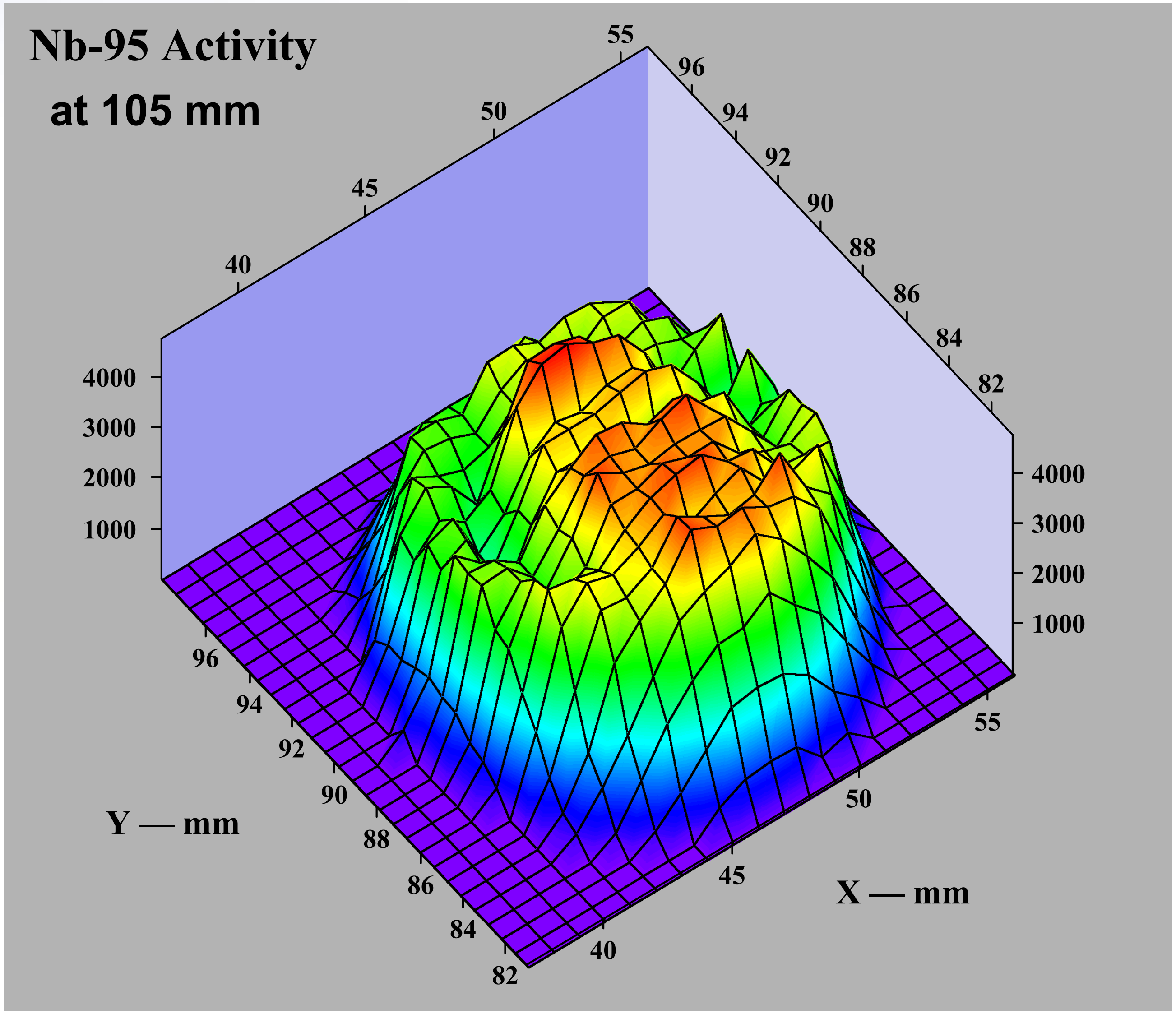
BTF-105B PIE, Elevation 105 mm



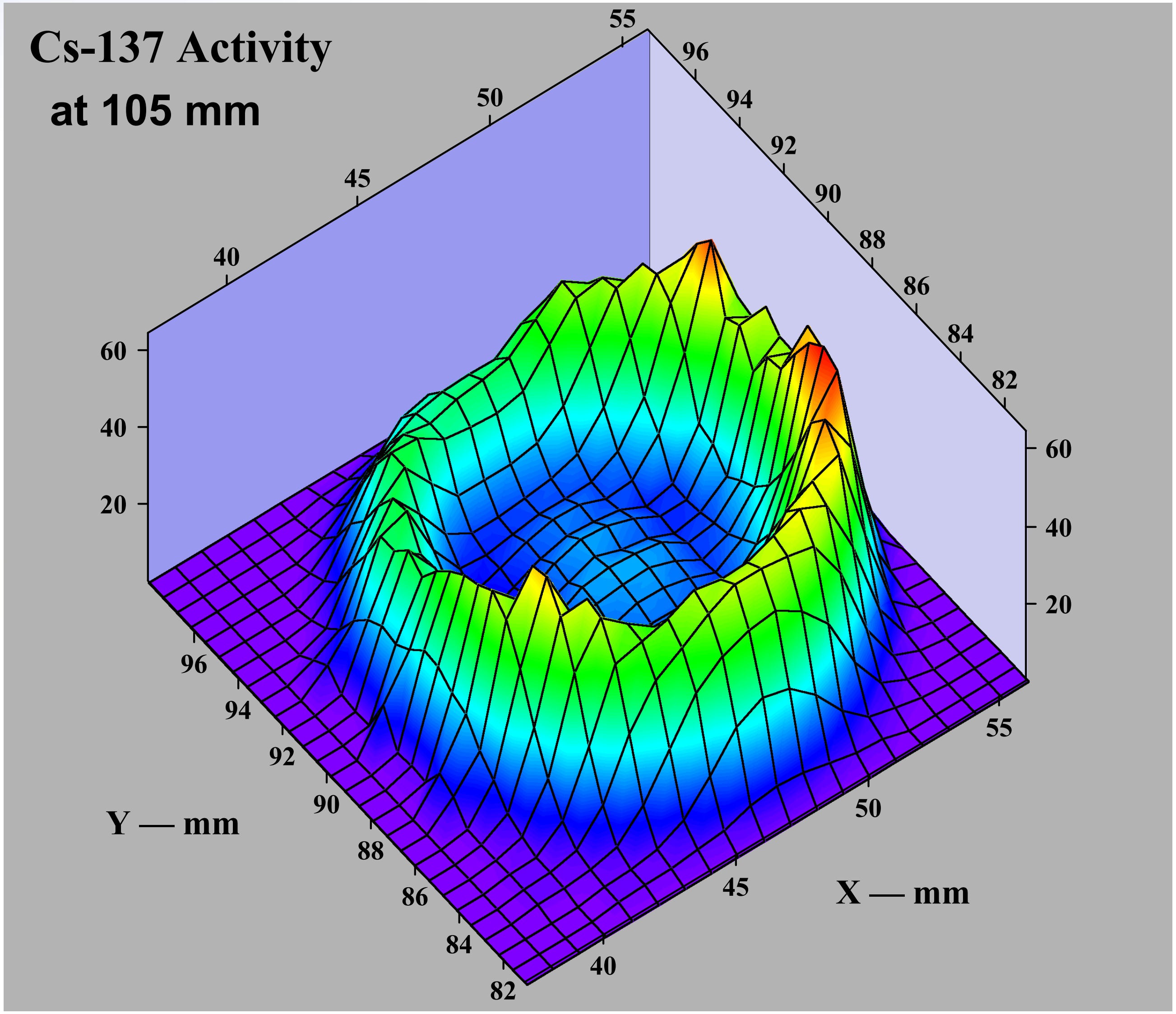
BTF-105B Elev. 105 mm Density Scan



BTF-105B Elev. 105 mm - ^{95}Nb Activity



BTF-105B Elev. 105 mm - ^{137}Cs Activity



Summary of BTF Test Conditions

Parameter	BTF-107 Test	BTF-104 Test	BTF-105A Test	BTF-105B Test
Fuel elements	1 pre-irradiated, 2 fresh	1 pre-irradiated	1 fresh	1 pre-irradiated
Pre-transient cooling	Pressurized water	Saturated steam	Saturated steam	Saturated steam
Maximum fuel temperature (K)	$\geq$ 2770 (peak)	~ 2100 (volume-average)	~ 2100 (volume-average)	~ 2100 (volume-average)
Transient duration (s)	~ 70	~ 2100	~ 2900	~ 4200
Time at high temperature after fuel failure (s)	~ 20	~ 1500	< 60	~ 2400

Integral % FPR in the BTF Experiments

Isotope	BTF-107	BTF-104	BTF-105A	BTF-105B
^{85m}Kr	37 ± 3	10 ± 4	2 ± 1	25 ± 6
^{85}Kr	-	47 ± 6	-	24 ± 7
^{88}Kr	37 ± 2	7 ± 2	3 ± 2	11 ± 3
^{131}I	56 ± 2	33 ± 5	< 2.0	21 ± 7
^{133}I	68 ± 34	20 ± 5	< 2.0	21 ± 8
^{137}Cs	56 ± 3	59 ± 5	-	34 ± 7
^{132}Te	20.8 ± 1.3	2.5 ± 0.7	-	1.1 ± 0.3

BTF Program Conclusions

- Data obtained for validation of CANDU fission-product behavior codes under severe-fuel-damage accident conditions
- Post-test simulations performed using CANDU safety analysis computer codes (CATHENA, ELOCA, SOURCE and SOPHAEROS)
- No new phenomena or phenomena interactions identified

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SOURCE IST 2.0

- **SOURCE IST 2.0 is the Canadian Industry Standard Toolset (IST) code for calculating fission-product release from fuel**
- **SOURCE IST 2.0 simulates all of the primary phenomena affecting FP release from CANDU fuel under accident conditions**
- **Release fraction is the key output of SOURCE**

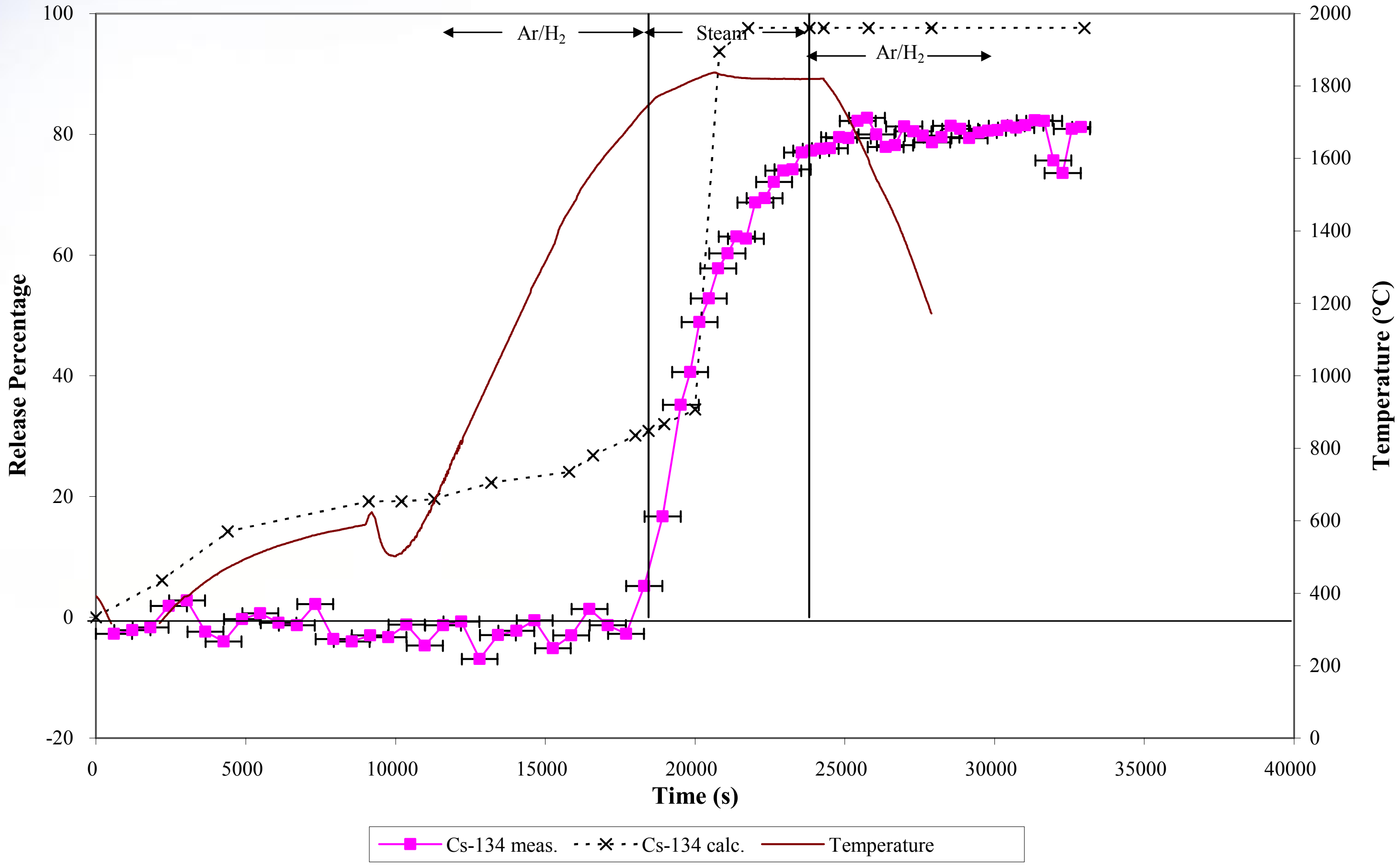
SOURCE IST 2.0

- **Basis Unit: A geometric subdivision of a fuel bundle. The smallest unit that the user has chosen to model. It could be a fuel element, an axial segment, or an annulus within a fuel element or axial segment. In the case of fragment tests, it could be the entire fragment.**
- **Bins (inventory partitions) (subdivisions of a basis unit):**
  - **Grain Matrix**
  - **Grain Boundary**
  - **Fuel Surface**
  - **Gap**
  - **Released**

SOURCE IST 2.0

- **Validation in progress:**
  - **Canadian hot-cell FP release tests**
    - **Steam: UCE12 TF01, HCE2 BM5, HCE2 BM4, HCE4 J03, HCE3 H03 & MCE2 TM19**
    - **Air: GBI3 DL5, HCE3 H02 & MCE1 T4**
    - **Inert (Ar/H_2): UCE12 TU09, HCE1 M12 & MCE2 TM03**
  - **International hot-cell FP release tests**
    - **Vercors 04, Vercors 05 & ORNL VI-5**
  - **Integral in-reactor tests**
    - **BTF-104, BTF-105B & PHEBUS FPT1**

SOURCE IST 2.0 Validation



Comparison of Measured and Calculated Cesium Release (10 Annulus Base Case) as Functions of Time for HCE3 Test H03 (Steam, 1840°C).

SOPHAEROS-IST 2.0

- SOPHAEROS initially developed by IRSN (France) to simulate fission-product transport and retention in the RCS under LWR severe accident conditions
- SOPHAEROS-IST 2.0 adopted as Canadian Industry Standard Toolset code for calculating fission-product transport and retention in the RCS
- When development is complete, SOPHAEROS will simulate all of the primary phenomena affecting FP transport and retention in CANDU RCS under accident conditions
- Fractional retention is the key output of SOPHAEROS

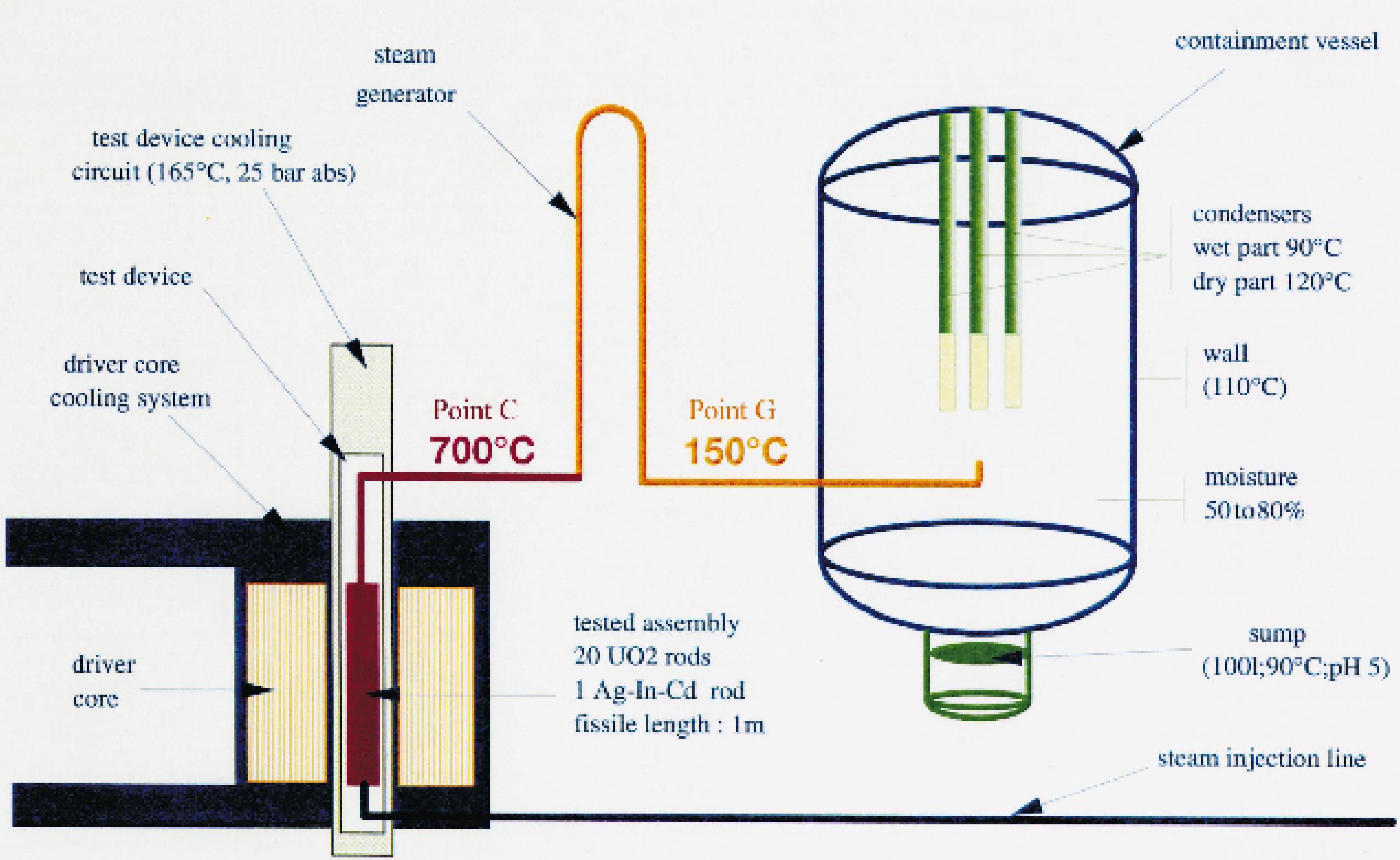
SOPHAEROS-IST 2.0

- Validation in progress:
  - Canadian laboratory FP transport tests
    - Mulpuru, End-fitting aerosol retention
  - Canadian hot-cell FP release and transport tests
    - HCE3 H01 & H03, HCE4 J01 & J03
  - International FP transport tests
    - LACE LA3B, Falcon ISP1 & ISP2, Marviken 2b & 7, DEVAP 23, 25 & 26, STORM ISP, TUBA-D
  - International hot-cell FP release and transport tests
    - VERCORS 04 & HT1, ORNL VI-2 & VI-5
  - Integral in-reactor tests
    - BTF-104, BTF-105B, PHEBUS FPT0 & FPT1

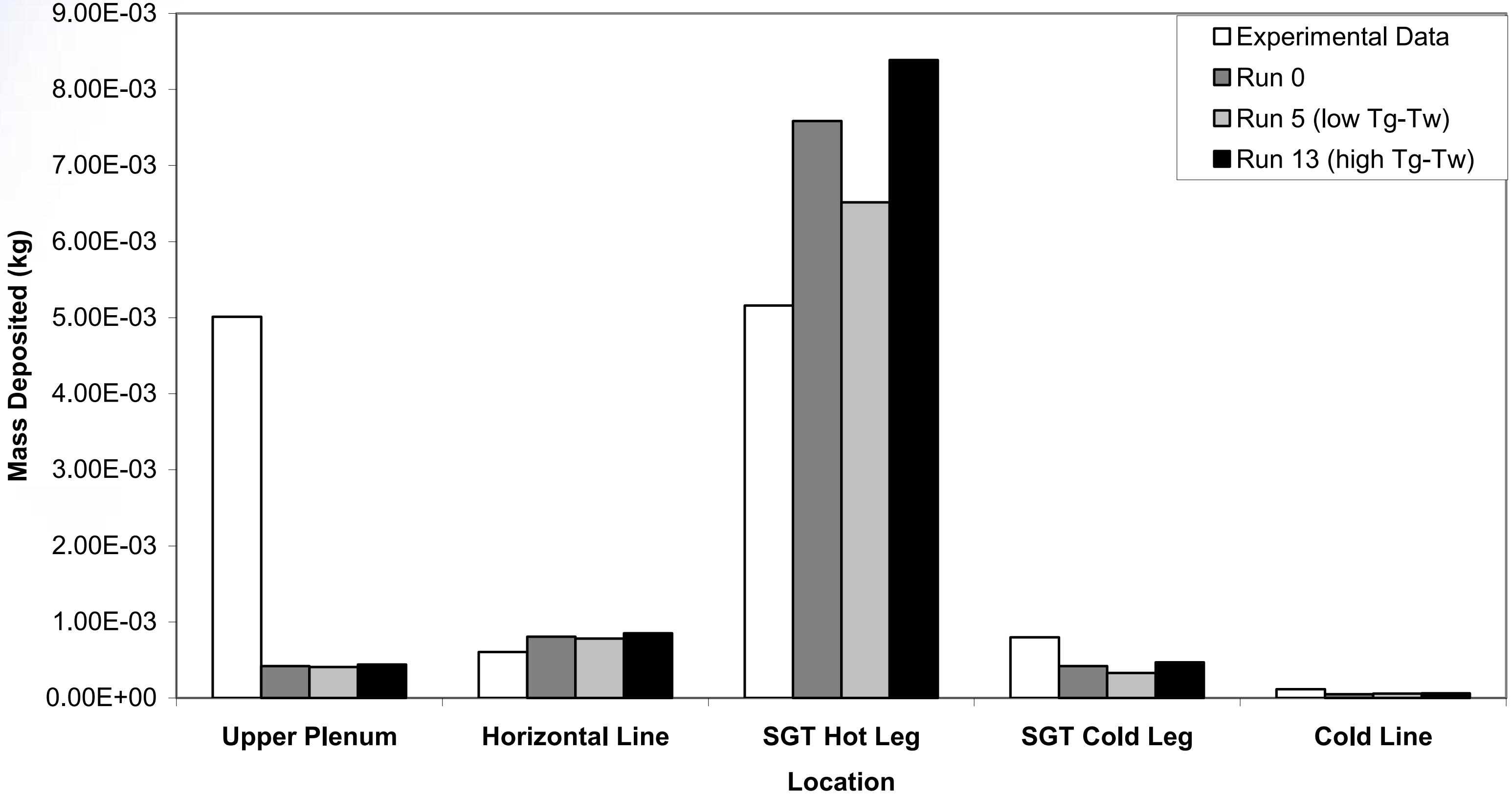
PHEBUS FP SOPHAEROS Validation Experiments

- PHEBUS FP in-reactor tests of fuel and FP behavior under LWR severe accident conditions
- Focusing on fuel relocation (molten pool formation), FP release, FP transport in RCS (including steam generator tube), and FP behavior in containment
- Two tests used for SOPHAEROS validation
  - FPT0 – bundle of 20 fresh fuel rods, one Ag/In/Cd control rod, retention in steam generator tube simulated
  - FPT1 – bundle of 18 previously irradiated fuel rods (23 MWd/kgU), 2 fresh fuel rods, one Ag/In/Cd control rod, retention in whole circuit simulated

PWR => Phebus scaling-down factor : ~5000



SOPHAEROS-IST 2.0 Validation



Deposition of Cs as a Function of Position in PHEBUS FPT1 Circuit

Summary

- Good technology base for understanding of fission-product release and transport behavior in CANDU reactor accidents
  - Phenomena
  - Experimental database
  - Computer codes
- Extension to ACR is straightforward

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