# Validation of Fuel Performance

## Presented to
## Nuclear Regulatory Commission Staff
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General Atomics


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# Outline
# Validation of Fuel Performance

- Fuel Performance Summary
- Fuel Performance Validation Program
- Fuel Materials Design Data Needs
- Fuel Performance Design Data Needs

# Summary of GT-MHR Fuel Requirements

| FUEL ATTRIBUTE | P $\geq$ 50% | P $\geq$ 95% |
|---|---|---|
| As-Manufactured Fuel Quality | | |
| Heavy metal contamination fraction | $\leq 1.0 \times 10^{-5}$ | $\leq 2.0 \times 10^{-5}$ |
| Missing buffer fraction | $\leq 1.0 \times 10^{-5}$ | $\leq 2.0 \times 10^{-5}$ |
| SiC coating defection fraction | $\leq 5.0 \times 10^{-5}$ | $\leq 1.0 \times 10^{-4}$ |
| **In-Service Performance** | | |
| **Failure fraction (normal operation)** | $\leq 5.0 \times 10^{-5}$ | $\leq 2.0 \times 10^{-4}$ |
| **Incremental failure during accident** | $\leq 1.5 \times 10^{-4}$ | $\leq 6.0 \times 10^{-4}$ |



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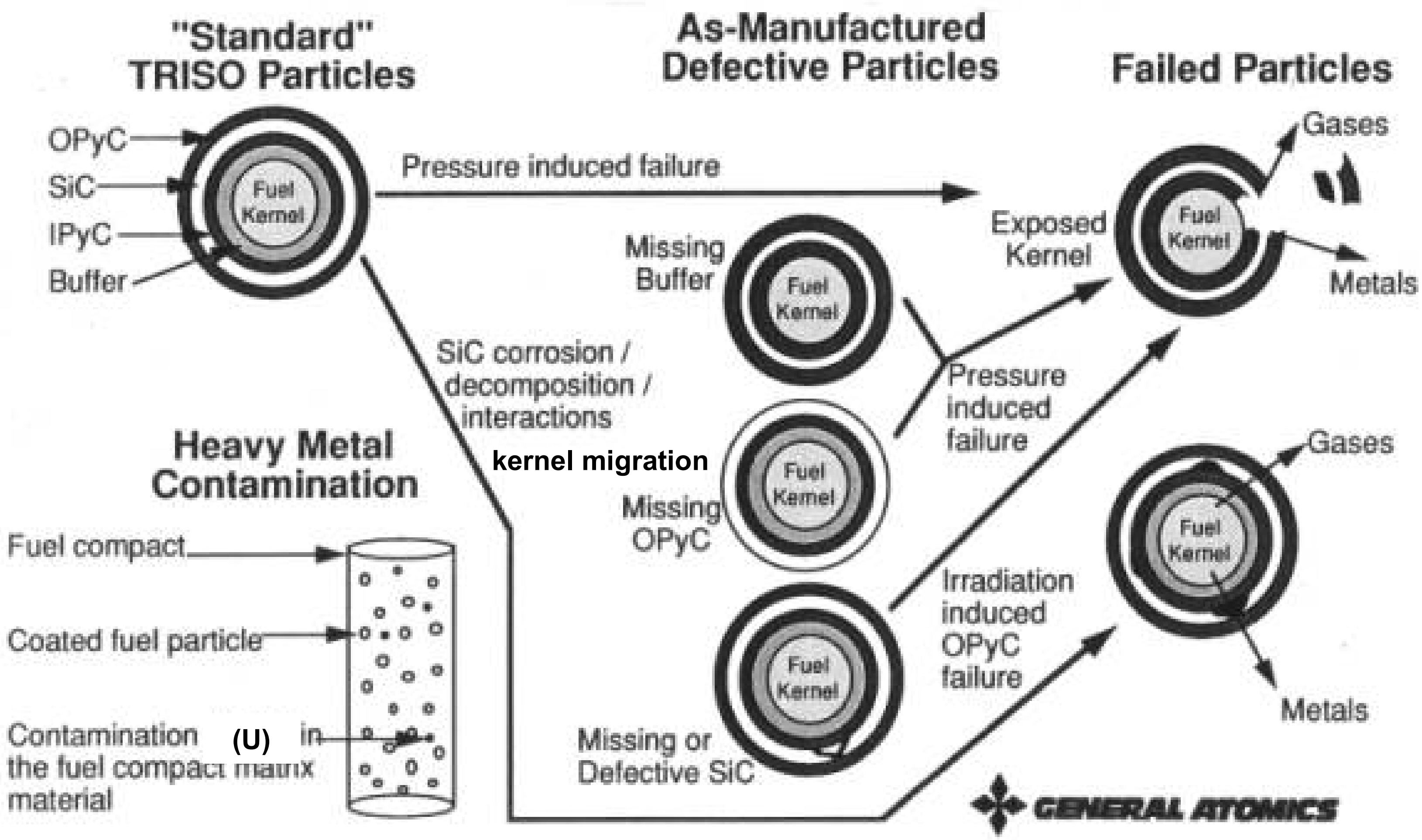
# Types of In-Service Failure

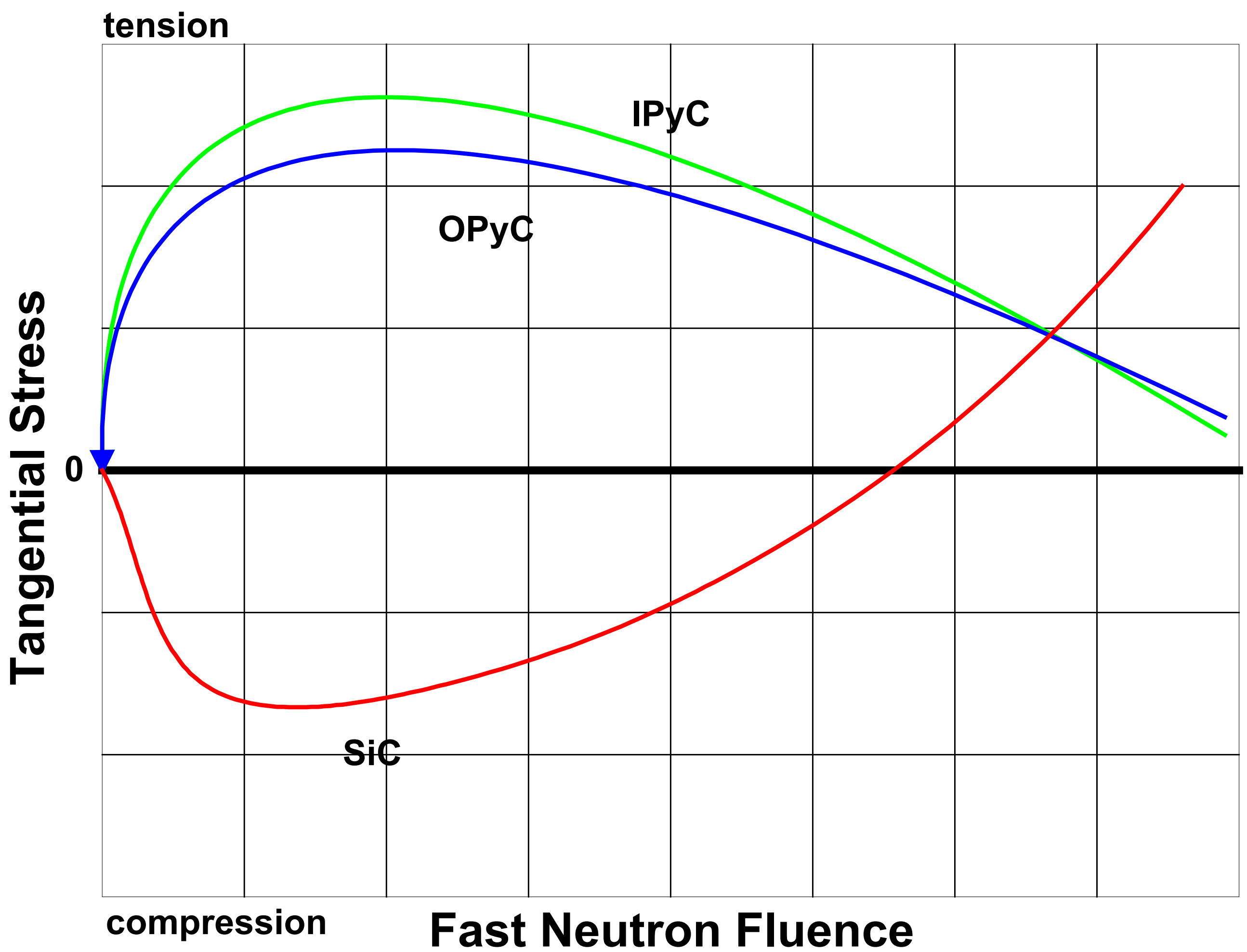
- Mechanical failure
  - Pressure vessel failure
    - Mainly from particles with as-manufactured defects
  - OPyC - compact matrix bonding

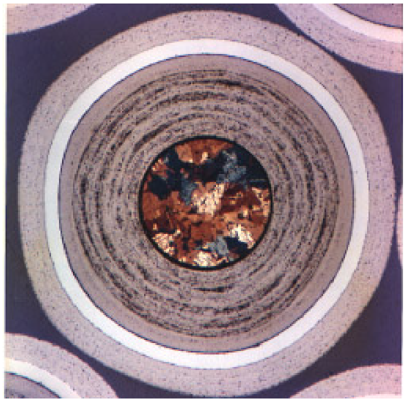
- Thermochemical failures
  - Kernel migration
  - Fission product reactions with SiC
  - Thermal decomposition of SiC

# Coating Failure Mechanisms



# Pyrocarbons Keep SiC in Compression





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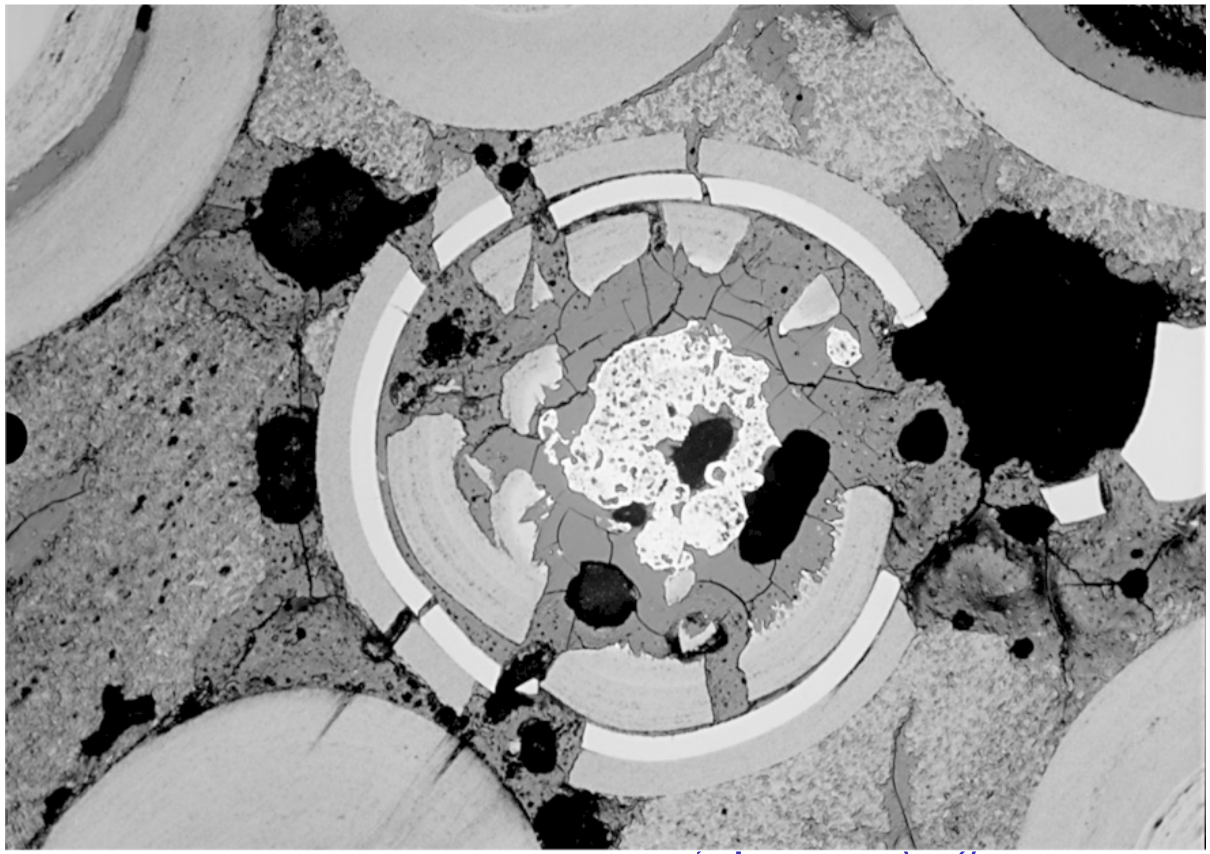
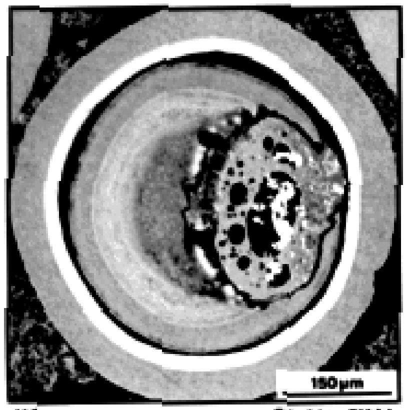
# Pressure Vessel Failure Seen During PIE
## (1976)

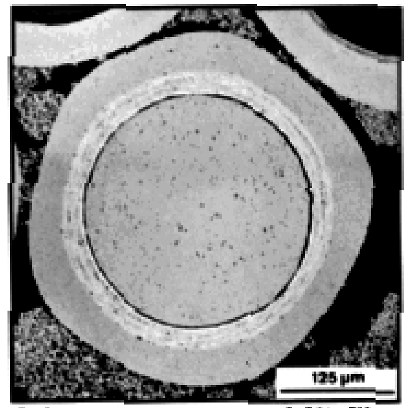


# PIE Used to Quantify Kernel Migration

**Relative Thermal stability of HTGR Candidate Recycle Oxide Fuel Kernels Irradiated in HRB-7. Time-average temperature, 1200-1220°C; thermal gradient, 1000-1030°C/cm; fast fluence, 6 x $10^{21}$ n/cm$^2$.**

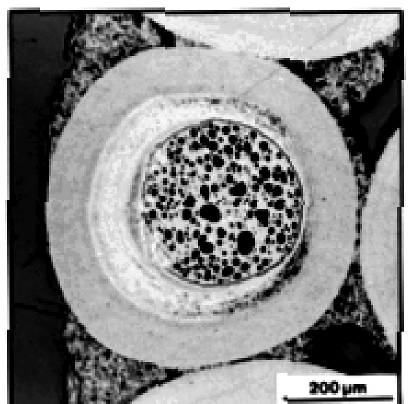



$UO_2$ 79.8% FIMA

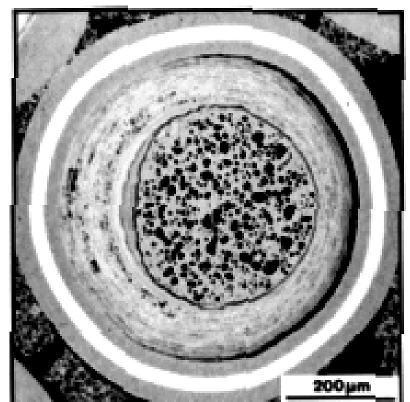



$ThO_2$ 8.3% FIMA

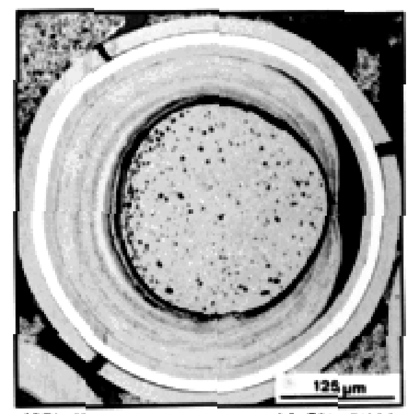

$(Th,U)O_2$ 43.9% FIMA




$(2Th,U)O_2$ 32.0% FIMA

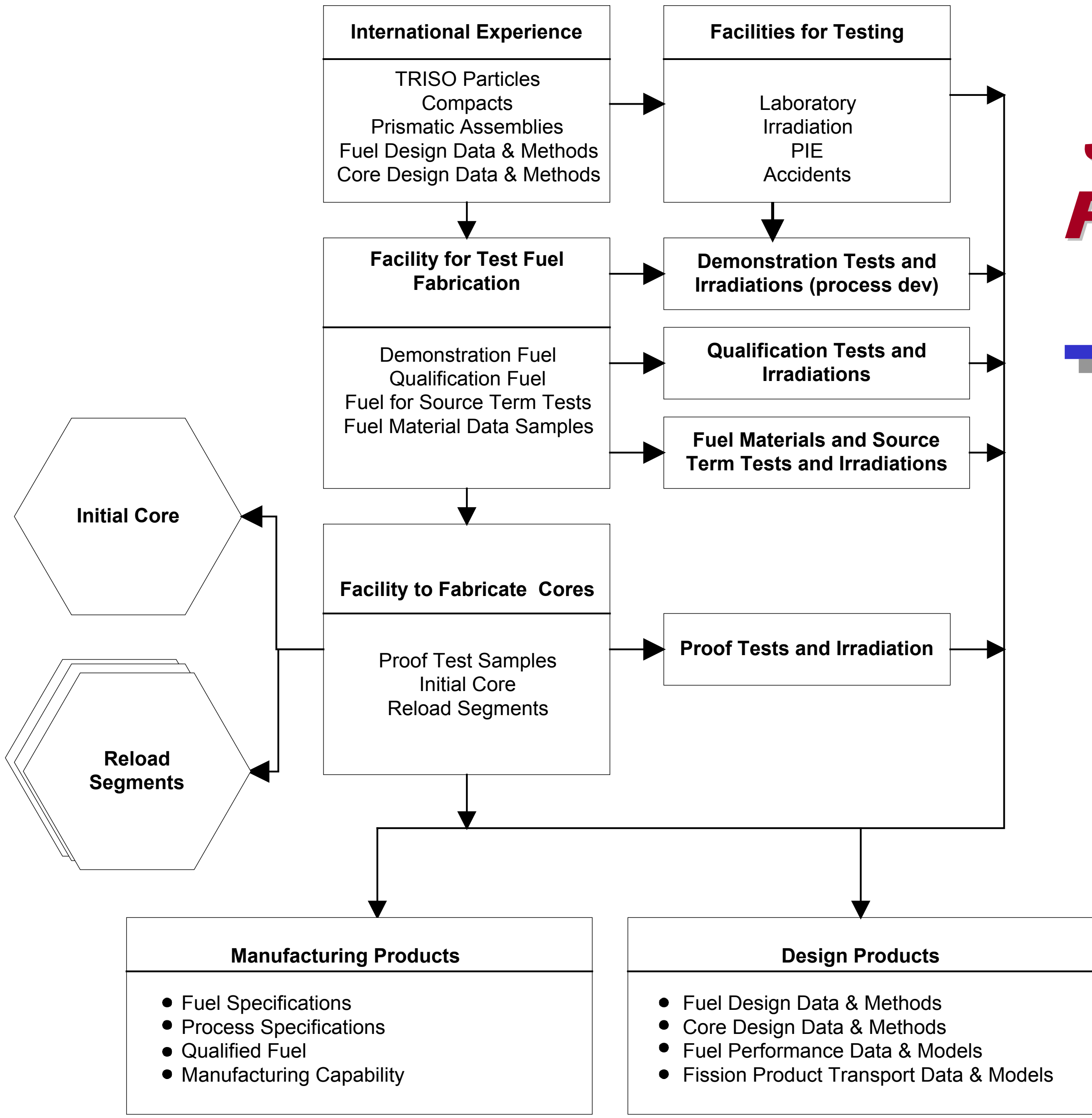



$(4Th,U)O_2$ 22.5% FIMA




$(8Th,U)O_2$ 16.5% FIMA

# Program to Satisfy Fuel Performance DDNs



# Two Groups of Fuel Technology Design Data Needs

## MATERIAL PROPERTIES

- C.07.02.01 Coating material property data
- C.07.02.03 Thermochemical performance data for fuel
- C.07.02.04 Fuel compact thermophysical properties

## FUEL PERFORMANCE VALIDATION TESTING

- C.07.02.05 Normal operation fuel performance validation data
- C.07.02.02 Defective particle performance data
- C.07.02.06 Accident fuel performance validation data
- C.07.02.07 Fuel proof test

# Fuel Materials DDNs

## MATERIAL PROPERTIES

- **C.07.02.01 Coating material property data**
- **C.07.02.03 Thermochemical performance data for fuel**
- **C.07.02.04 Fuel compact thermophysical properties**

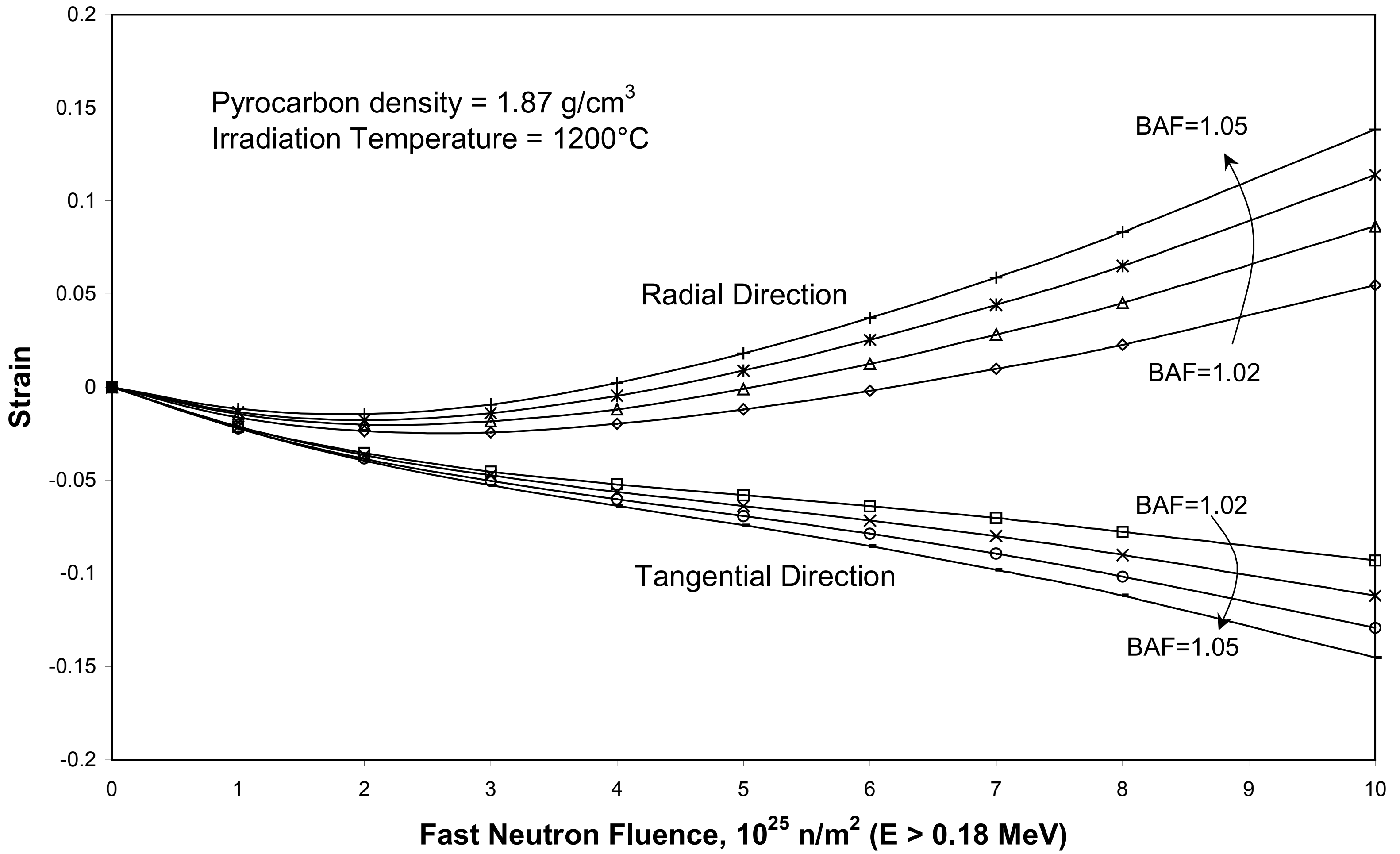
# C.07.02.01 Coating material property data

- **OBJECTIVE**
  - Obtain pyrocarbon and silicon carbide thermal and mechanical property data needed for fuel design and fuel performance models for various temperatures and irradiation states
- **EXISTING DATA**
  - Coating thermal data compiled in "Fuel Design Data Manual"
  - Coating mechanical data compiled in "Material Models of Pyrocarbon and Pyrolitic Silicon Carbide"
  - Uncertainties in mechanical properties high

# C.07.02.01 Coating material property data (cont'd)

- ADDITIONAL DATA NEEDED
  - Thermal and mechanical data for irradiated coatings on GT-MHR fuel at core temperatures
    - CTE, irradiation-induced dimensional change, thermal and irradiation induced creep, coating strength, poisson's ratio, etc.
    - thermal conductivity and heat capacity
  - Specific GT-MHR materials - reduce uncertainties
- PLANNED TECHNOLOGY PROGRAMS
  - Plan experiments to measure thermal and mechanical coating properties and prepare samples for test
  - Irradiate samples and make measurements
  - Update design manuals and performance models

# Pyrocarbon Irradiation-Induced Dimensional Change



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# C.07.02.03 Thermochemical performance data for fuel

- **OBJECTIVE**
  - Obtain data on thermochemical behavior models applicable for GT-MHR fuel and core design under normal operation and accident conditions
- **EXISTING DATA**
  - Oxidation potential calculated  for UCO as a function of burnup and temperature
  - Coating failure models based on existing data for the thermochemical processes are in the “Fuel Design Data Manual:
    - kernel migration
    - fission product attack on SiC coatings
    - thermal decomposition rates of SiC

# C.07.02.03 Thermochemical performance data for fuel *(cont'd)*

- **ADDITIONAL DATA NEEDED**
  – **Thermochemical data for GT-MHR fuel materials supplementing existing data base**

- **PLANNED TECHNOLOGY PROGRAMS**
  – **Irradiate special samples of fissile and fertile particles**
  – **Measure:**
    - **quantity and composition of gas in particles as function of irradiation conditions and temperature**
    - **measure rates of thermochemical coating failure mechanisms from irradiations and from special tests on irradiated fuels**

# Fuel Performance Design Data Needs

## FUEL PERFORMANCE VALIDATION TESTING

- C.07.02.05 Normal operation fuel performance validation data
- C.07.02.02 Defective particle performance data
- C.07.02.06 Accident fuel performance validation data
- C.07.02.07 Fuel proof test

# C.07.02.05 Normal operation fuel performance

- OBJECTIVE
  - Demonstrate fuel meets performance requirements under normal operating conditions
  - Validate performance models for normal operation

- EXISTING DATA BASE
  - Experience with over 100 coated particle fuel capsules in US and other countries testing a variety of fuel designs including TRISO-coated dense UCO
  - Data from FSV ($(U/Th)C_2$ & $ThC_2$) and other reactors

# C.07.02.05 Normal operation fuel performance *(cont'd)*

- **ADDITIONAL DATA NEEDED**
  - Demonstrate that the TRISO-coated dense UCO (LEU) fissile and the TRISO-coated dense UCO (natural U) fertile particles in GT-MHR compacts satisfy coating integrity and fission product retention requirements
  - Obtain an independent data base validating that the design methods used to predict fuel failure during normal operation are accurate to a factor of 4.
- **PLANNED TECHNOLOGY PROGRAMS**
  - Irradiate multicell fuel capsules in the temperature range up to maximum burnup and fast neutron fluence
  - Post-irradiation examination of each capsule to determine fuel condition and fission product distrubution and extract quantitative data

# Examples of Irradiation & PIE Testing Facilities with Experienced Staff Available

- 40 years experience in coated particle testing
  - HFIR at ORNL and ATR at INEEL can irradiate test fuel
  - ORNL has hot cells and equipment to perform Post-Irradiation Examination, and Accident Condition Testing

HFIR

Irradiated Fuels Examination Lab



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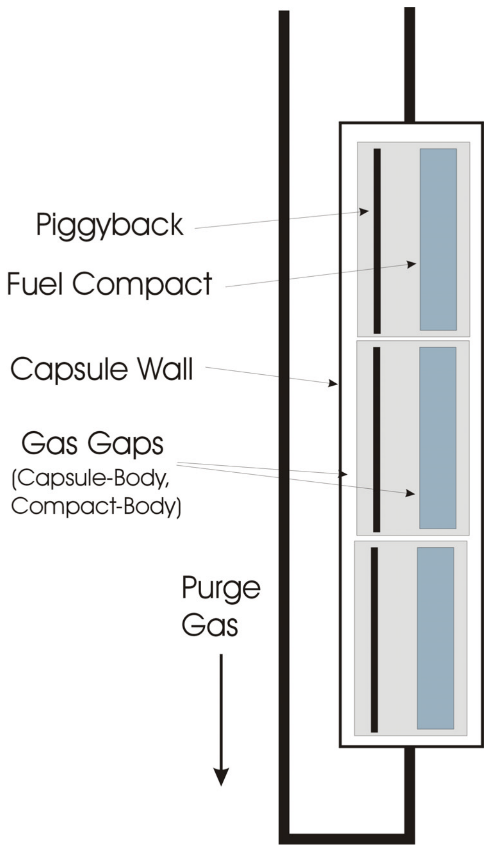
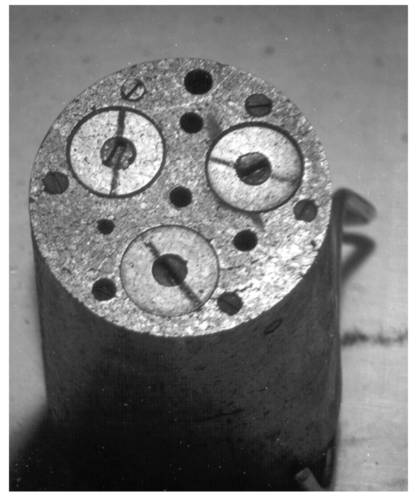
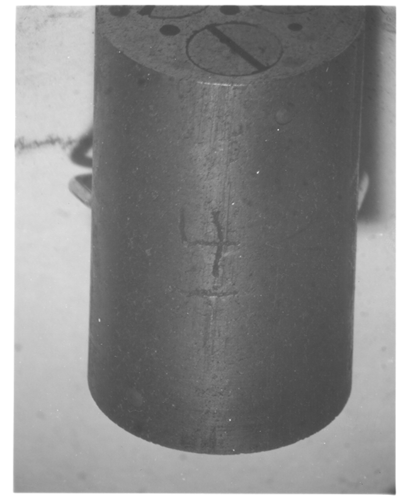
# GT-MHR CORE SERVICE CONDITIONS

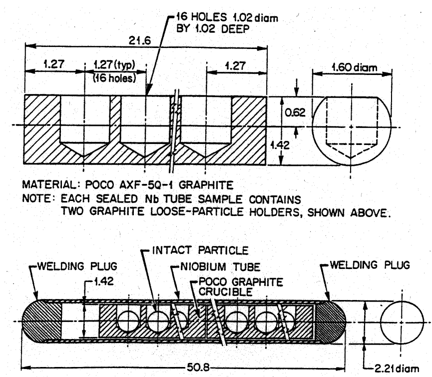
| | |
|---|---|
| **Fuel:** | **LEU (19.9%) TRISO/Natural UCO TRISO** |
| **Fuel Cycle:** | **Once-through, graded cycle one-half core replaced at each reload** |
| **Refueling Frequency:** | **417 EFPD's (1.5 calendar yrs. @ 90% CF)** |
| **Core Residence Time:** | **834 EFPD's (3.0 calendar yrs. @ 90% CF)** |
| **Maximum Equilibrium Burnup:** | |
| **Fissile Particle** | **≤ 26% FIMA** |
| **Fertile Particle** | **≤ 7% FIMA** |
| **Maximum Fast Fluence (E > 0.18 Mev)** | **≤ $5 \times 10^{25}$ n/m$^2$** |
| **Peak Fuel Temperature** | **≤ 1250°C** |

# Typical Irradiation Capsule & Internals







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# Examples of TRISO-UCO Fuel Irradiations

| Irradiation | UCO/TRISO** enrichment | Irrad temp (°C) | Burnup (%) FIMA | Fission Gas Release @ 4 x $10^{25}$ n/m2 fast fluence |
|---|---|---|---|---|
| GT-MHR Requirement | LEU | 1250 | 26 | 1.6 x $10^{-6}$ |
| | Nat | | 7 | |
| HRB-17-18 | HEU | 775 | 78 | ---- |
| R2-K13 Cell 2 | LEU | 1190 | 22.5 | 8 x $10^{-5}$ |
| R2-K13 Cell 3 | LEU | 985 | 22.2 | 5 x $10^{-7}$ |
| FRJ2-P24 | LEU | 850-1300 | 18.6 - 22.2 | 2 x $10^{-7}$ * |

*max fluence 2.8 x $10^{25}$ n/$m^2$

** abbreviations

UCO - $UO_2$, $UC_2$ kernel mixture

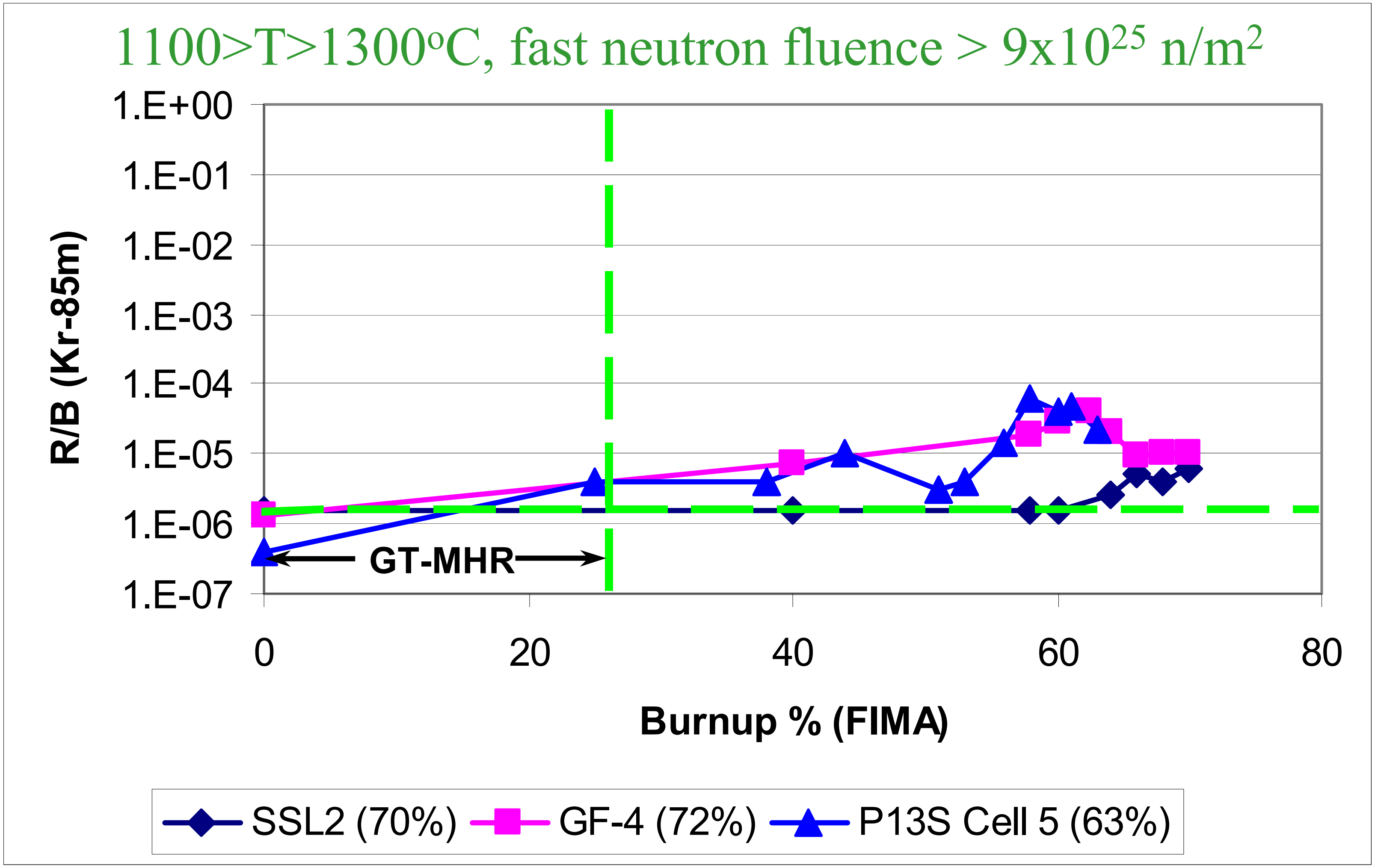
HEU - highly-enriched uranium

LEU - < 20% enriched uranium

Nat - natural uranium

T- TRISO coating

# Irradiations Indicate Good TRISO Coating Performance



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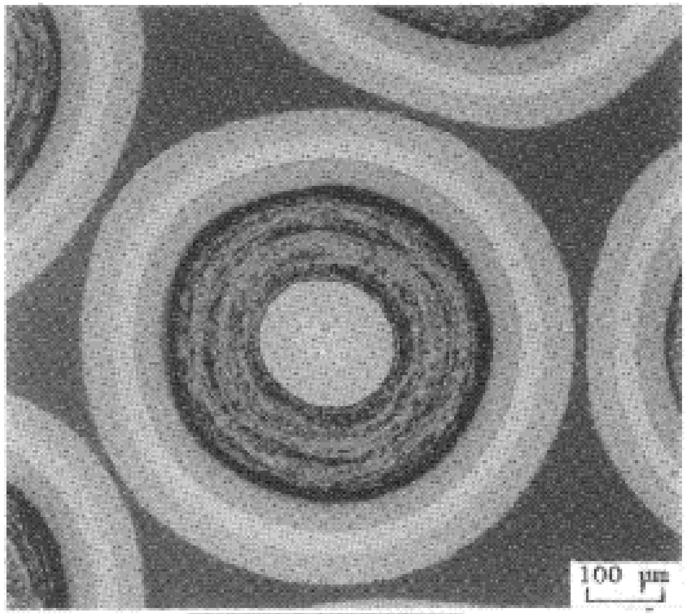
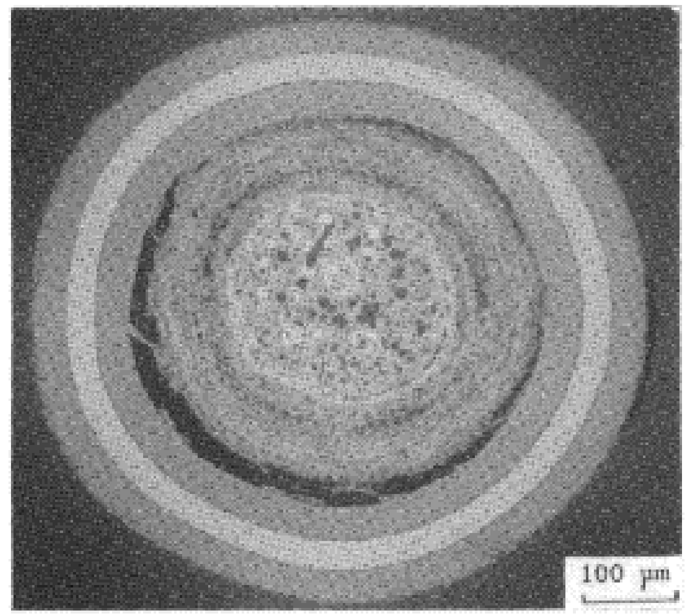
# UCO Kernels Perform Well Even at Burnup Levels Far Above Commercial Requirements




AS MANUFACTURED




78% FIMA BURNUP
$4.2 \times 10^{25}$ n/M$^2$ (E>0.18 Mev)
755$^0$C TEMPERATURE
HRB-17 IRRAD CAPSULE

# Irradiation in Test Reactors Used to Generate Fuel Materials and Performance Data

- **Validation of fuel performance and fuel models for normal operation**
- **Procedure**
  - **Test conditions**
    - **representative fuel samples**
    - **conditions to envelope GT-MHR operation including uncertainties from core design estimates**
  - **Preparation**
    - **characterize the test fuel samples properties and distributions**
    - **predict fuel behavior prior to test**
      - irradiation conditions - quantify uncertainties (temperature, gradients, fluxes and fluences, burnup, etc.)
      - coating integrity accounting for various failure mechanisms
      - fission product transport
      - fission product retention of barriers



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# Irradiation in Test Reactors Used to Generate Fuel Materials and Performance Data (cont'd)

- **Procedures (cont'd)**
  - **Irradiation Test**
    - **control irradiation conditions**
      - test conditions envelope core conditions including uncertainties
      - in-pile measurements
        - test reactor conditions
        - thermocouple temperatures
        - gas flows and purity
        - noble gas fission product release
  - **Comprehensive post-irradiation examination**
    - **burnup and fast neutron fluence**
    - **coating integrity vs. irradiation conditions**
    - **fission product distribution**
    - **calculations of irradiation detailed time and spacial variations of irradiation conditions from measurements**

# *Irradiation in Test Reactors Used to Generate Fuel Materials and Performance Data (cont'd)*

- **Success Criteria**
  - **Meets objectives of the test**
  - **Final Qualification Test demonstrated that performance goals were satisfied**
    - **test conducted according to plan**
    - **required fission product retention achieved**
    - **required coating integrity achieved**

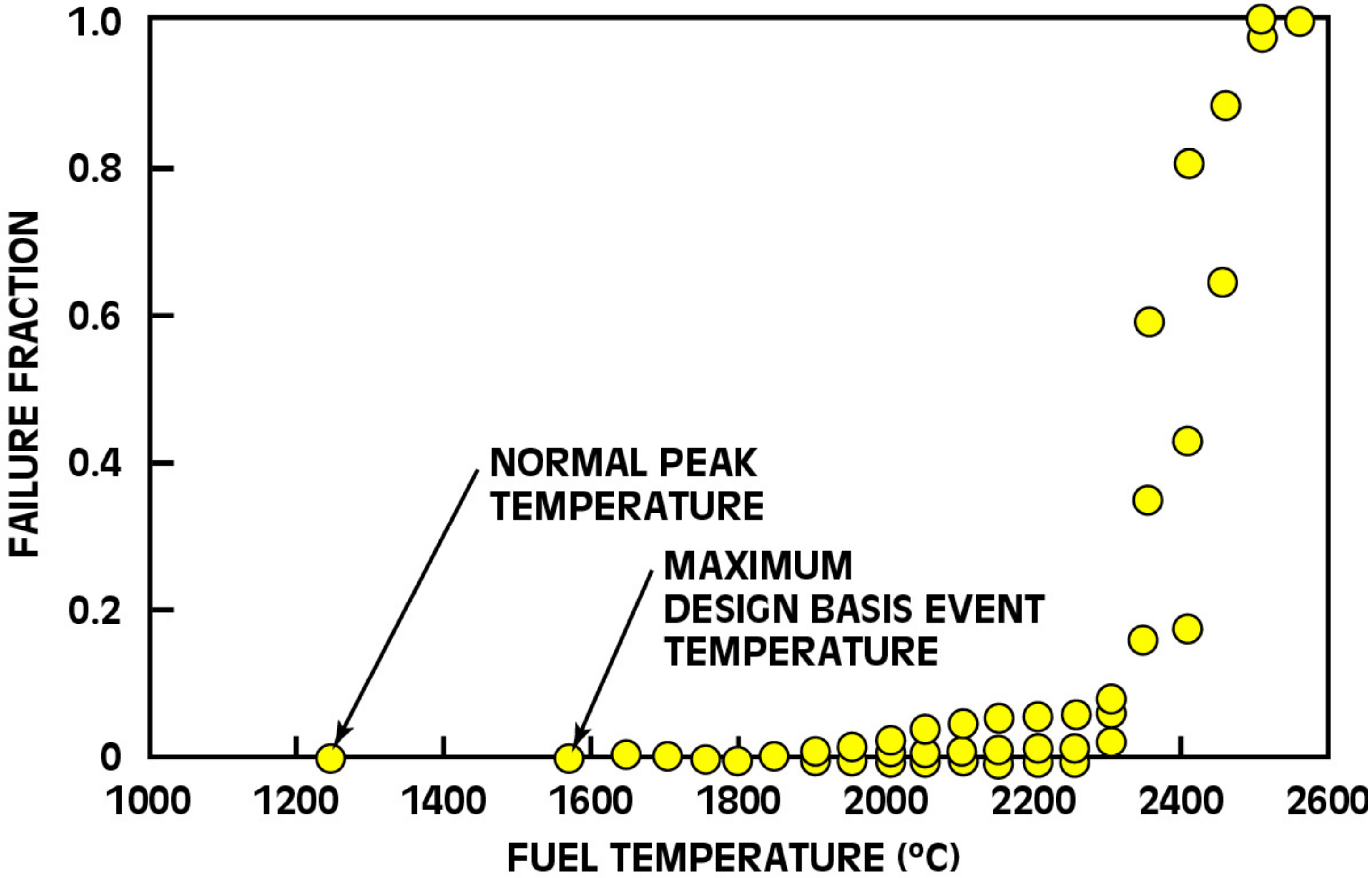
# Post-Irradiation Examination (PIE)

- Examine irradiated fuel
  - Tests (examples)
    - metallography
    - burn-leach for failed SiC
    - compact deconsolidation
    - individual particle gamma counting
    - scanning electron microscope images
  - Coating failure
    - mechanisms
    - quantification and dependence on in-service conditions
    - incipient coating failures and mechanisms
  - In-pile fission product release (mass balance and distribution in capsule components)

# C.07.02.06 Accident fuel performance validation data

- OBJECTIVE
  - Determine performance of fuel at various stages of irradiation during core conduction cooldown conditions
  - Validate performance models used for core conduction cooldown events
- EXISTING DATA BASE
  - Coating failure fractions from gaseous fission product release during rapid heatup of loose particles to temperatures 2500 $^{o}$C
  - Extensive US and international database for the constant temperature heating of oxide and carbide-based TRISO particles in spheres and compacts to 2000$^{o}$C including tests of UCO-TRISO

# Short-Term Temperature Limit ~2200 °C where SiC Decomposes



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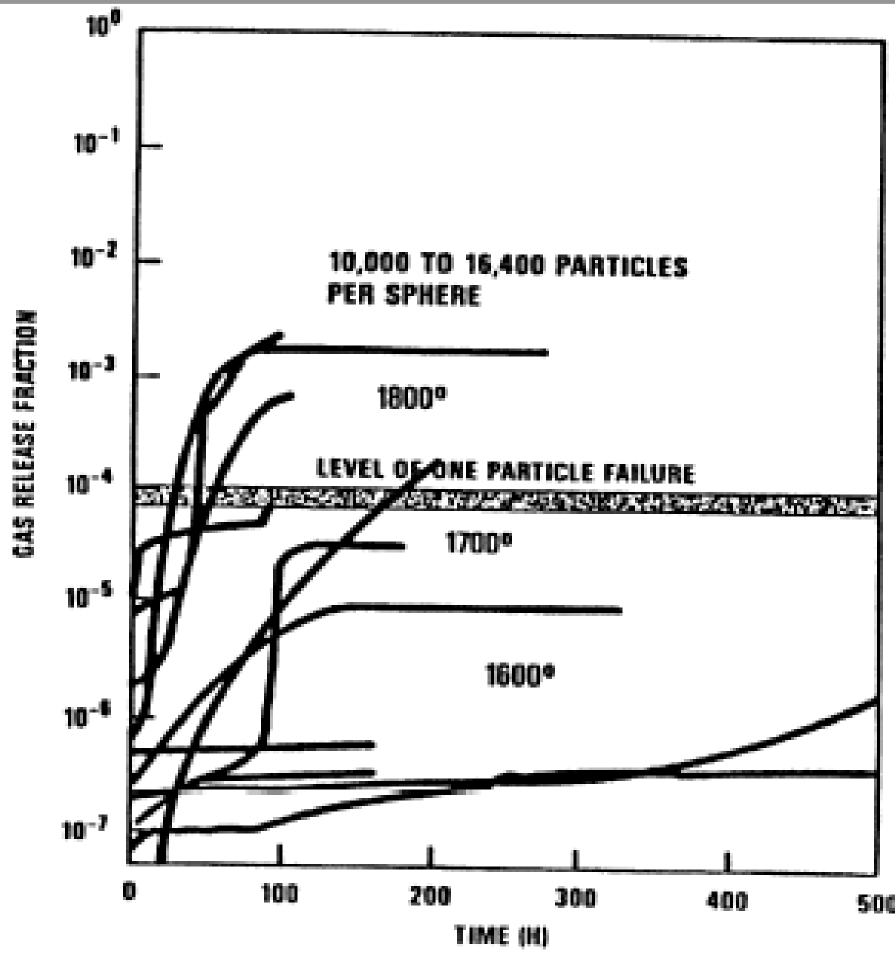
# COATING FAILURE IS NOT OBSERVED DURING TEMPERATURE EXCURSIONS UP TO 1600 °C FOR SEVERAL HUNDRED HOURS

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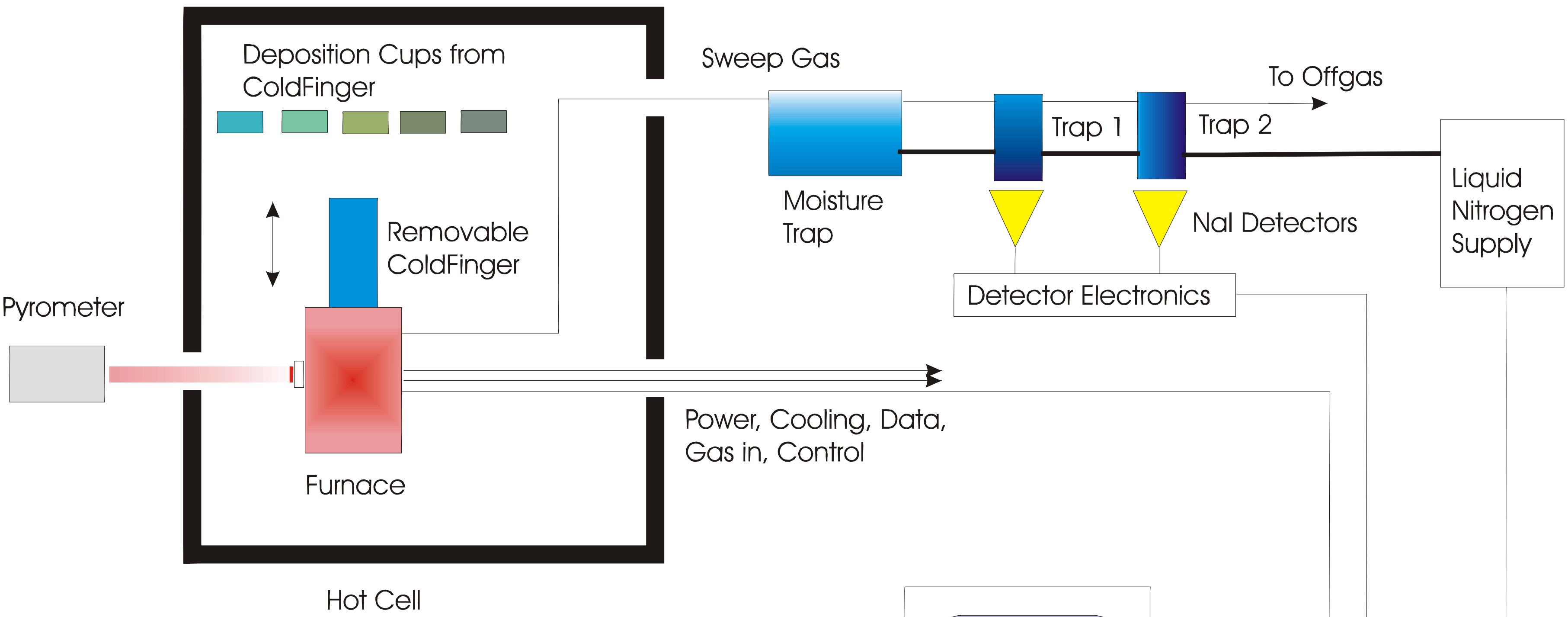
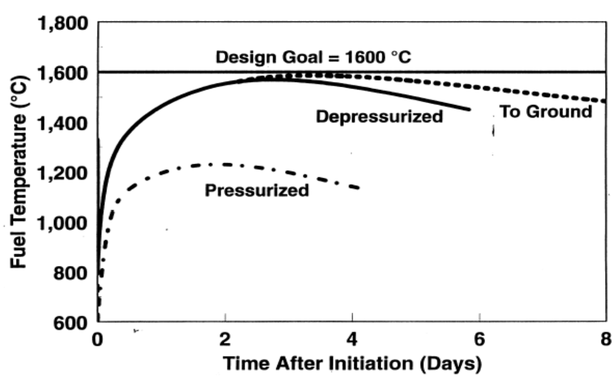
# C.07.02.06 Accident fuel performance validation data *(cont'd)*

- **ADDITIONAL DATA NEEDED**
  - Accident simulation data for irradiated GT-MHR fuel in compacts for temperatures up to 2000°C
  - Post-heating examination to assess fuel condition, identify failure mechanisms, and quantify rates
- **PLANNED TECHNOLOGY PROGRAMS**
  - Heat fuel compacts irradiated under various conditions
  - Collect solid and gaseous fission product release data as a function of test conditions and time
  - Examine heated fuel and identify and quantify coating failure

# Accident Testing



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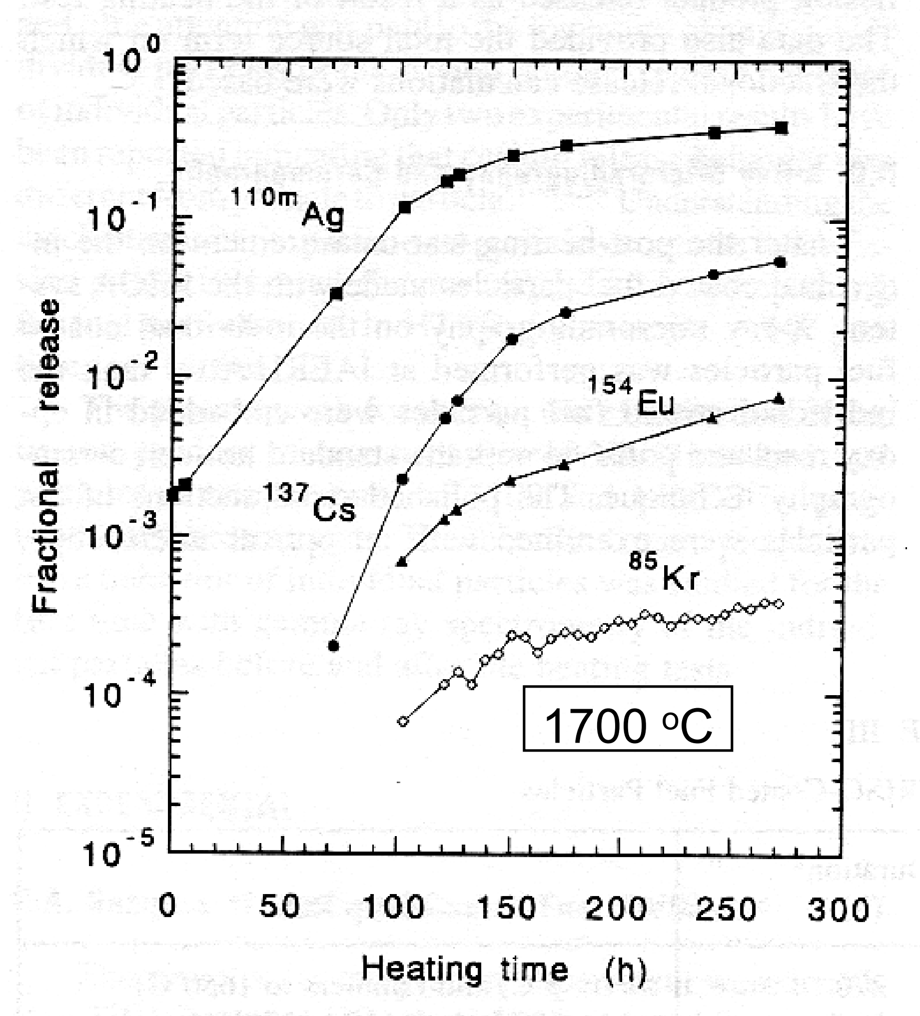
# Fission Product Release Data Collected During Accident Simulation Test

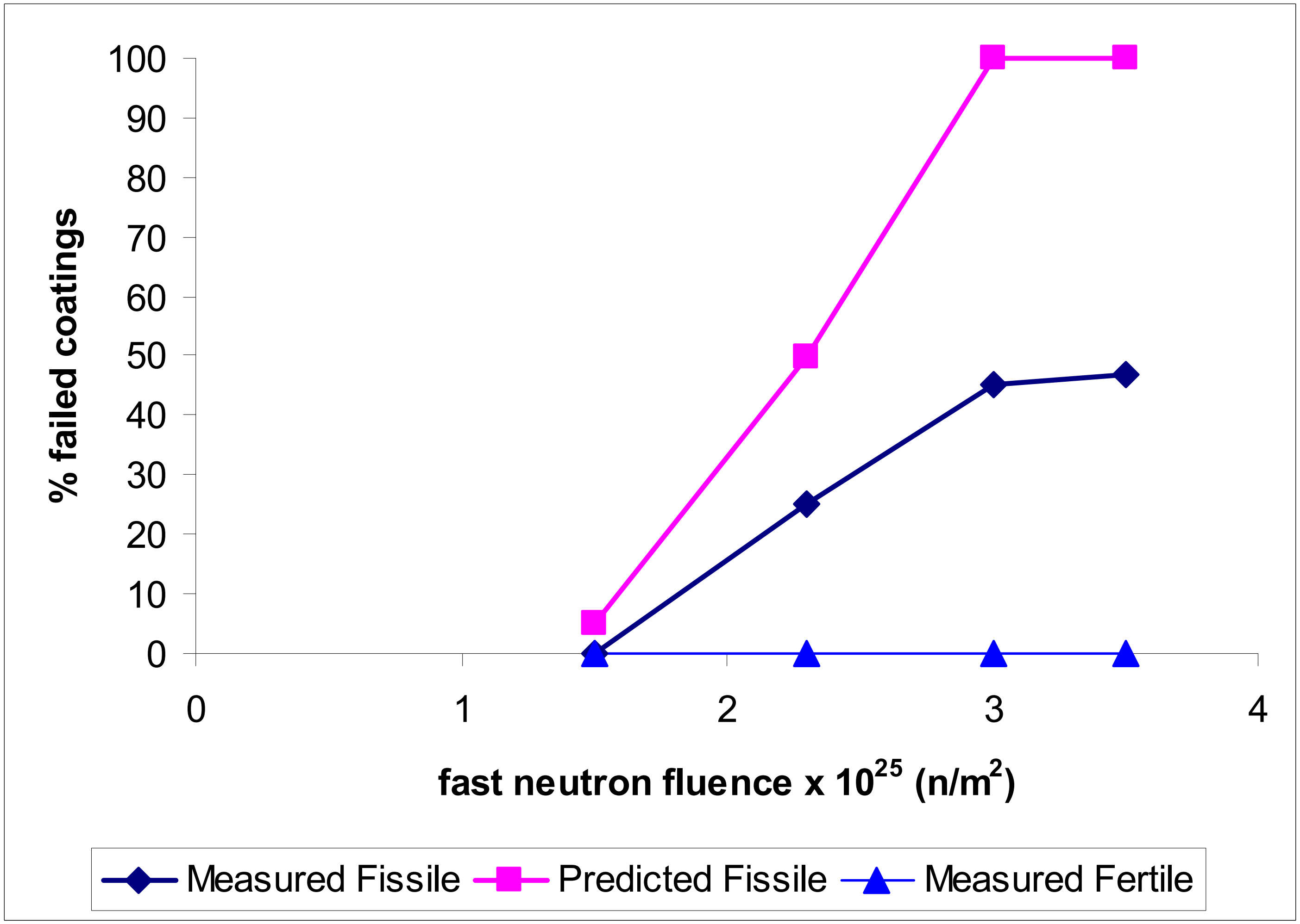
- HRB-22 $UO_2$ LEU fuel (Minato, et. al. Nucl. Tech 131, July 2000)
- Irradiated fuel compacts
- Solid and gaseous fission product release vs. Time



# C.07.02.02 Defective particle performrmance data

- **OBJECTIVE**
  - More precise performance models for particles with defective coatings, especially missing buffers and SiC defects
- **EXISTING DATA BASE**
  - Irradiated particles with:
    - missing buffers
    - missing OPyC
    - heavy metal dispersed in buffer

# Missing Buffer Failure Data/Predictions



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# C.07.02.02 Defective particle performrmance data *(cont'd)*

- **ADDITIONAL DATA NEEDS**
  - Improved performance models for particles with missing buffers as function of irradiation conditions & temperature
  - Improved performance models for particles with failed SiC and intact OPyC layers as a function of burnup, fluence, and temperature
- **PLANNED TECHNOLOGY PROGRAMS**
  - Irradiate batches of particles with missing buffers and particles with failed SiC but intact OPyC coatings followed by PIE to determine failure characteristics
  - Post-irradiation heating of these batches of defective particles to determine coating failure under accident conditions

# C.07.02.07 Fuel Proof Test

- OBJECTIVE
  - Demonstrate fuel produced for the initial GT-MHR core:
    - meets product specification
    - normal operation performance meets requirements
    - accident performance meets performance
    - consistent with fuel performance models
- EXISTING DATA BASE
  - Fuel Proof Tests for Peach Bottom I and FSV
  - Experience with over 100 coated particle fuel capsules

# C.07.02.07 Fuel Proof Test *(cont'd)*

- **ADDITIONAL DATA NEEDED**
  - Irradiation, PIE, accident testing of fuel from the initial core production line
  - Test under normal and accident conditions enveloping expected in-service conditions
  - Demonstration that production line fuel meets performance requirements
- **PLANNED TECHNOLOGY PROGRAMS**
  - Remove a random sample of fuel compacts from the production line
  - Irradiate under enveloping conditions
  - Perform PIE to confirm performance
  - Test irradiated fuel under accident
  - Perform examination to confirm performance

# Fuel Technology Program Summary

- The fuel technology program as described will:
  - Improve and scale-up fabrication facilities and and fabricate GT-MHR coated particle fuel for tests
  - Qualifying fuel by test
  - Obtaining fuel data for design and licensing
  - When commercially ready, establishing a GT-MHR fuel fabrication plant
  - Demonstrating fuel from fabrication plant meets the requirements of the GT-MHR

# The planned fuel technology program will accomplish the objectives:

- Finalize process and product specifications
- Scale-up and improve fuel fabrication equipment
- Provide a statistically significant demonstration of GT-MHR fuel
  - Fuel manufacturing processes and Quality Control methods ensure production of fuel meeting specification requirements
  - Fuel meets GT-MHR performance requirements under normal operation and accident conditions
  - Validated methods are available to accurately predict fuel performance

# Outcome Objectives

- NRC feedback on the approach being taken to finalize fuel process and product specifications
- NRC agreement or feedback on the adequacy of DDNs supporting validation of fuel performance