HTGR Technology Course for the Nuclear Regulatory Commission

May 24 – 27, 2010

Module 8

Fuel Performance

Outline

- Fuel operating experience in HTGRs
- Fuel irradiation and post-irradiation examination (PIE)
- Safety criteria and performance limits
- Fuel performance modeling
- Fuel cycle issues

Reactor Operation Experience for Fuel Has Been Good

- **Four experimental and three power reactors using coated particles**
  - UK, US, Germany, Japan, China
- **Commercial-scale production and reactor operation (and supporting R&D) have lead to**
  - Understanding of fabrication
  - Understanding of irradiation behavior and limits
  - Fuel quality and performance improvements

….coated particles w/~50,000 kg HM fabricated

Coated Particle Fuel Has Been Used Internationally In Seven Gas-Cooled Reactors

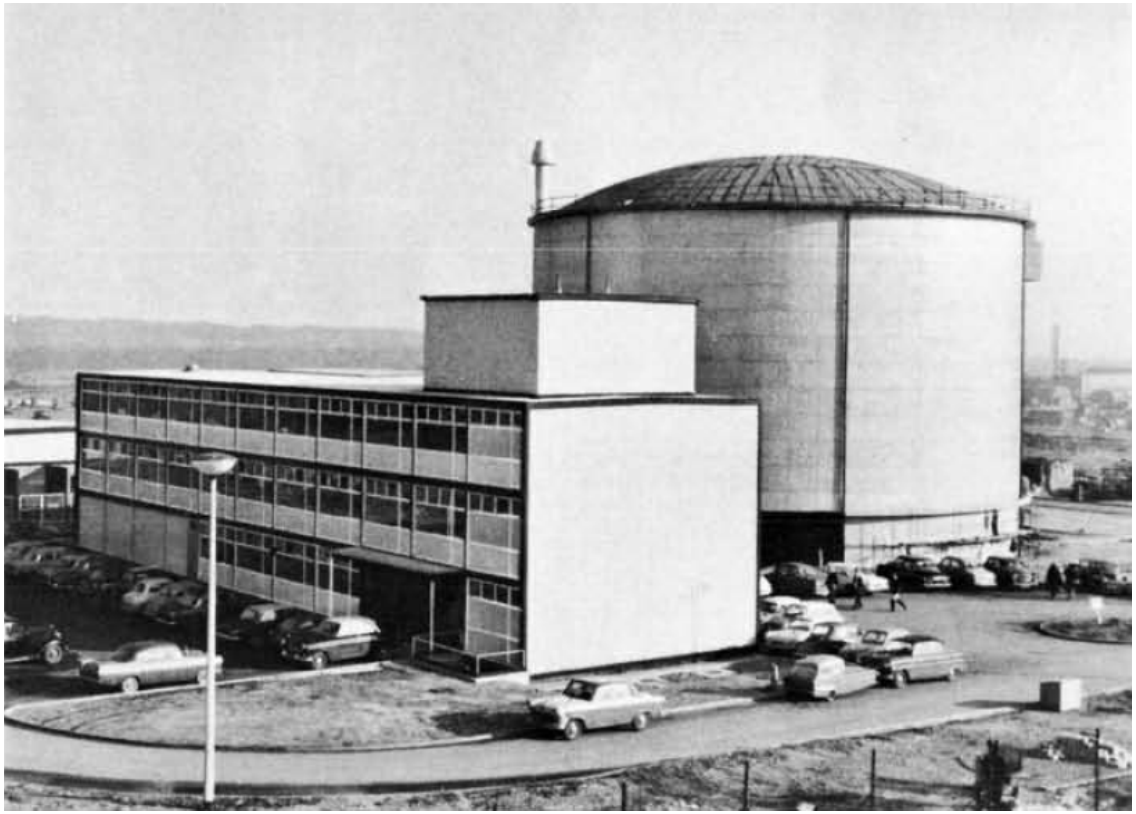
Reactor	Fuel	Fuel Enrichment (%)	Maximum Temp (°C)	Maximum Burnup (% fima)	Maximum Fast neutron fluence (10^{25} n/m^2)	Average Power Density (w/cc)*	Power/particle (milliwatt/part)	Packing Fraction (%)*
Typical Pebble Bed	TRISO (UO_2)	7.8	1048	8.75	2.4	10	55	7
Typical Prismatic	TRISO (UCO)	14 or 20	1250	26	4.5	31	40	23
Dragon	BISO/TRISO Various							
Peach Bottom I	BISO $(U/Th)C_2$	93	1400	28		28		
AVR	BISO/TRISO Various	93	1100->1280	16		7		40
THTR	BISO $(U/Th)O_2$	93	1100	10	4	17	40	40
Fort. St. Vrain	TRISO $(U/Th)C_2$, ThC_2	93	1200	16	4	29		60
HTTR	TRISO UO_2	3 to 10 (6 ave)	1490	~1	<1	24	35	28
HTR-10	TRISO UO_2	17	1200	~1	<1	6		35

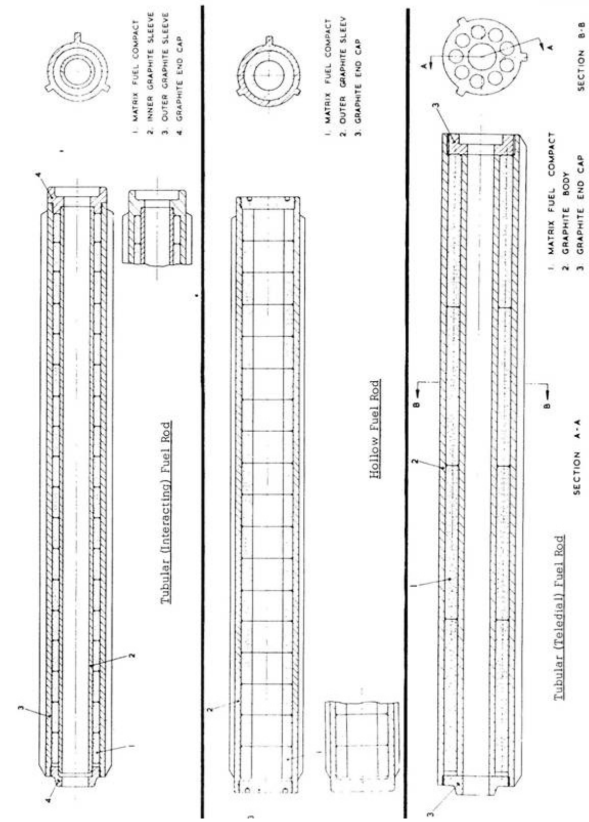
* Power density in volume where there are coated particles (compact and fueled region of pebble)

Idaho National Laboratory

GENERAL ATOMICS

Dragon, Winfrith, Dorset, UK

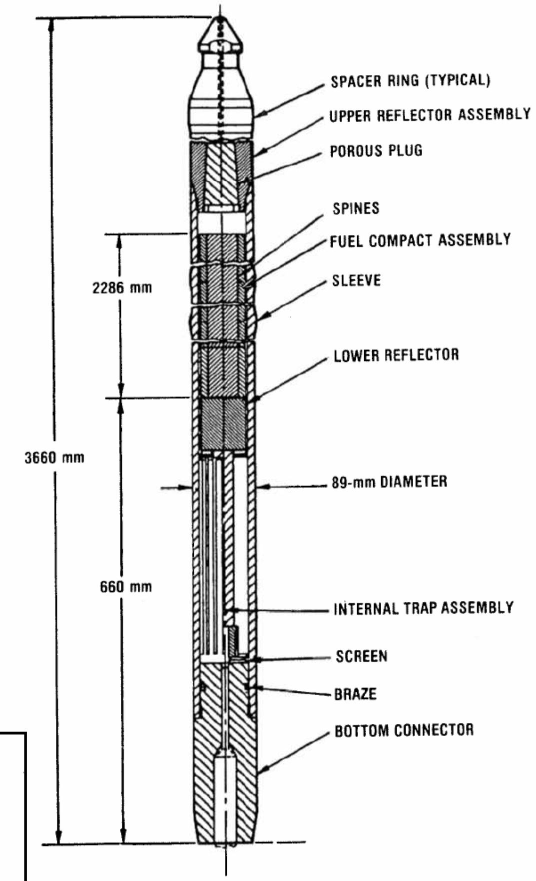




Operated 1965 to 1976 developing many new fuel designs – Tested BISO and TRISO with many fuel forms including Pu fuels – important early fuel developments were almost all made at Dragon

Fuel element – cylinders with outer sleeve, annular compacts, inner graphite filler, some elements internal purge sweeps fission products to monitoring and trapping system

Peach Bottom I (40 MWe), Delta, Pennsylvania

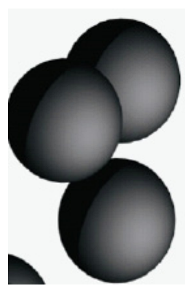


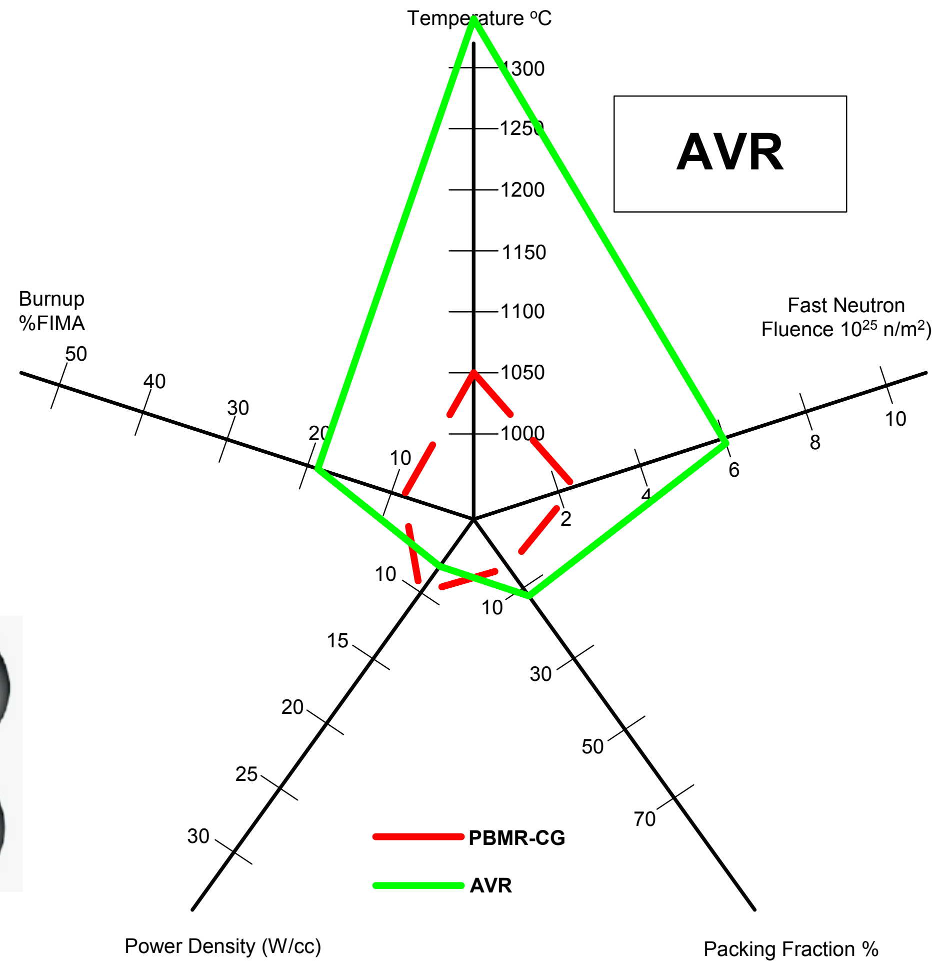
- Used BISO $(U/Th)C_2$ fuel particles no longer proposed for use in HTGRs
- First core experienced failures
- Corrected in the second core

Fuel element – cylinders with outer sleeve, annular compacts, inner graphite filler, internal purged sweeps fission products to trapping system

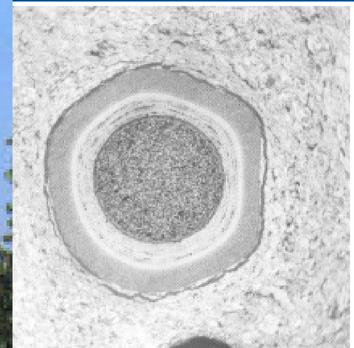
AVR (Arbeitsgemeinshaft Versuchsreactor), Hanau, Germany

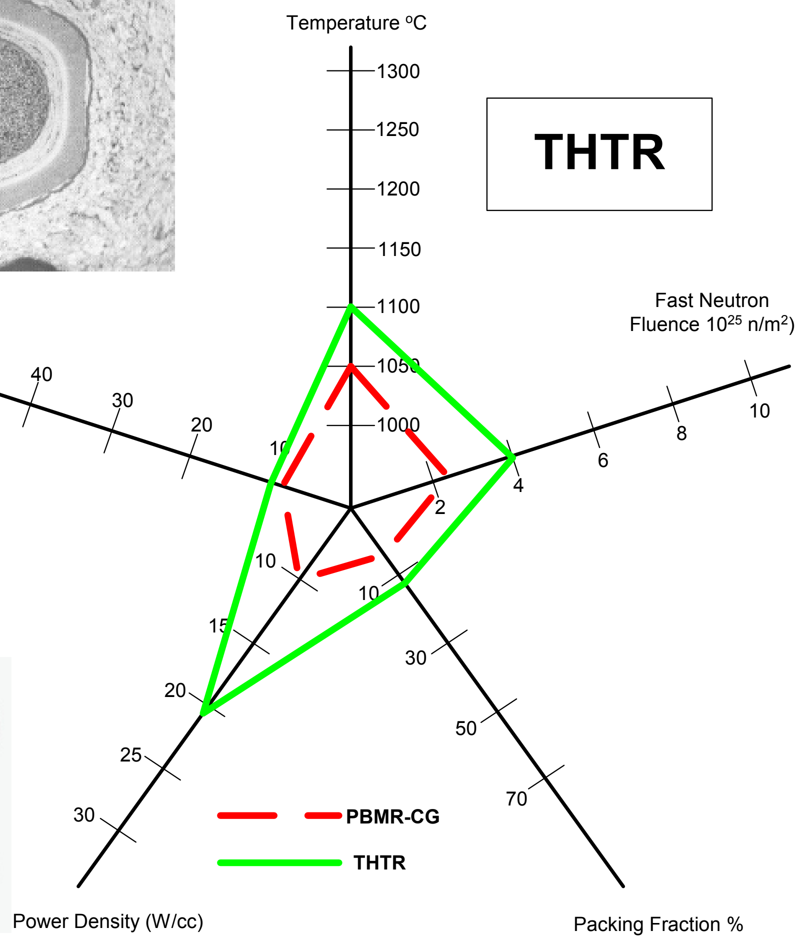
BISO and TRISO pebble fuels of various qualities tested over 21 years – total of 2 million pebbles
Operated with hot helium temperature up to 950 ^{o}C

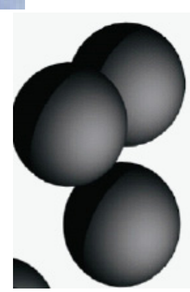




THTR (Thorium High Temperature Reactor), Hamm-Uentrop, Germany



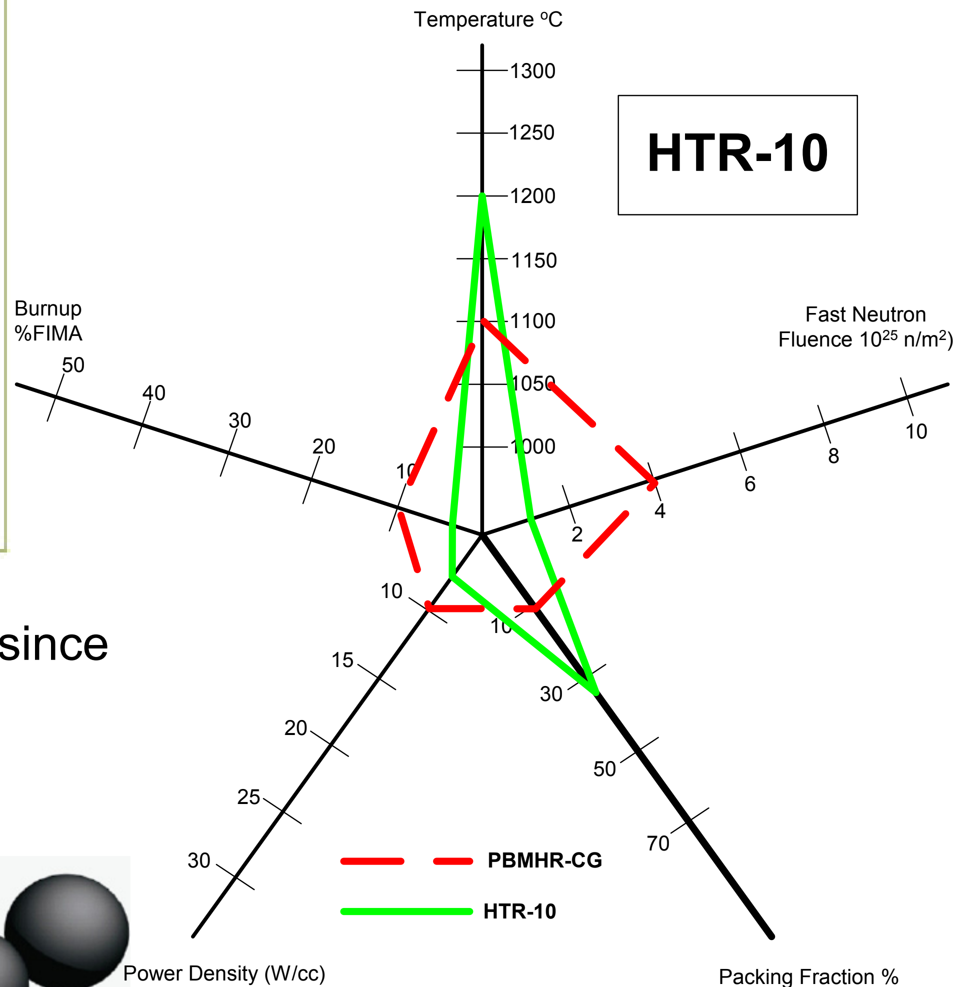




BISO $(U/Th)O_2$ fuels tested during 5 (1983 – 1988) year operation

Power reactor operated on the power grid – steam cycle with 750 °C hot helium - ~1million spheres

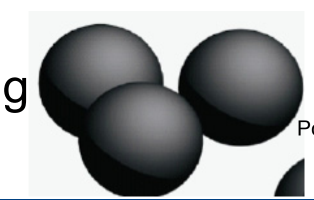
HTR-10, Beijing, China



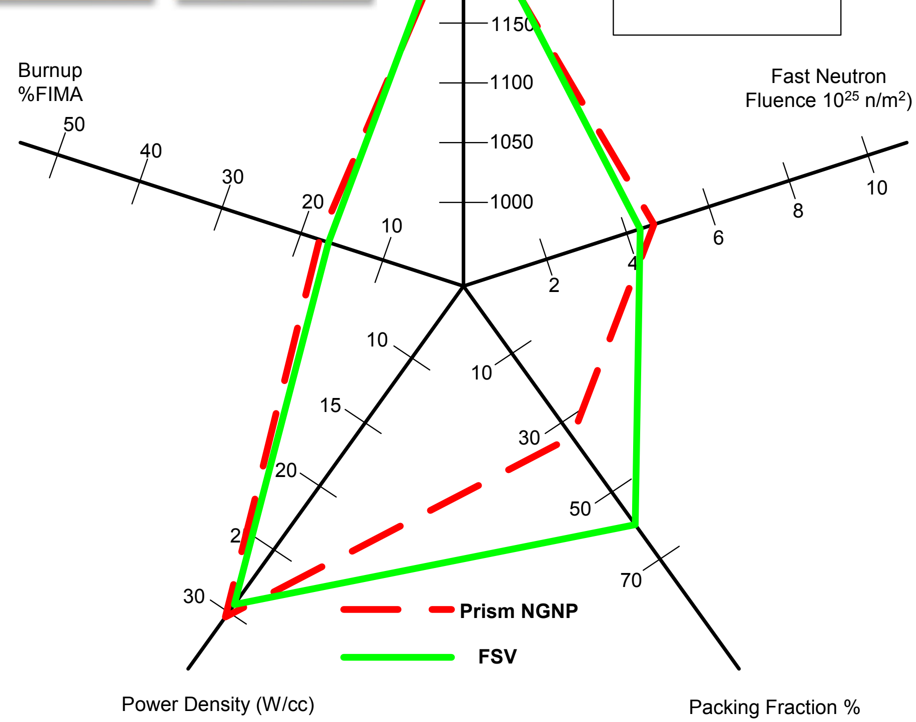
Operating with TRISO UO_2 pebble fuel since 2003

27,000 spheres

Small experimental reactor bring technology to China



Fort St. Vrain, Platteville, Colorado



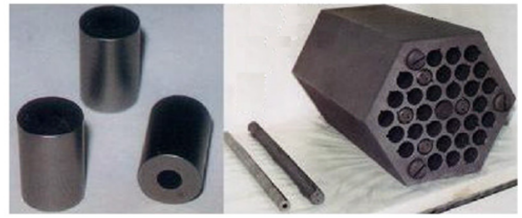
Operated on power grid for ~13 years (1976-1989) –reduced power

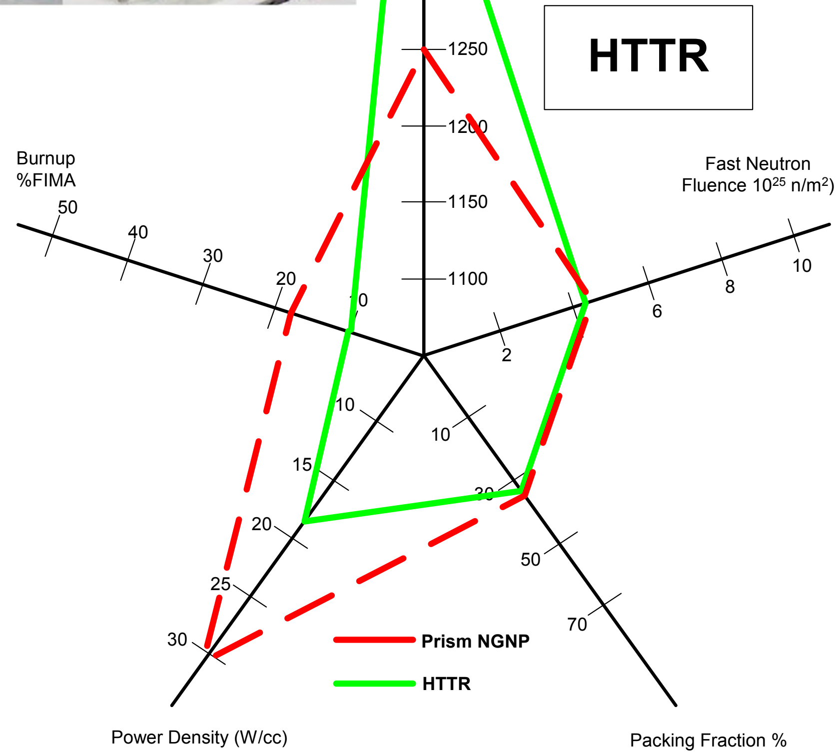
TRISO (U/Th)C_2 fissile and ThC_2 fertile fuel

2450 fuel assemblies, 7.5 million compacts, 33,000 kg HM in fuel

Fuel performed well

HTTR (High Temperature Engineering Test Reactor), Oarai, Japan



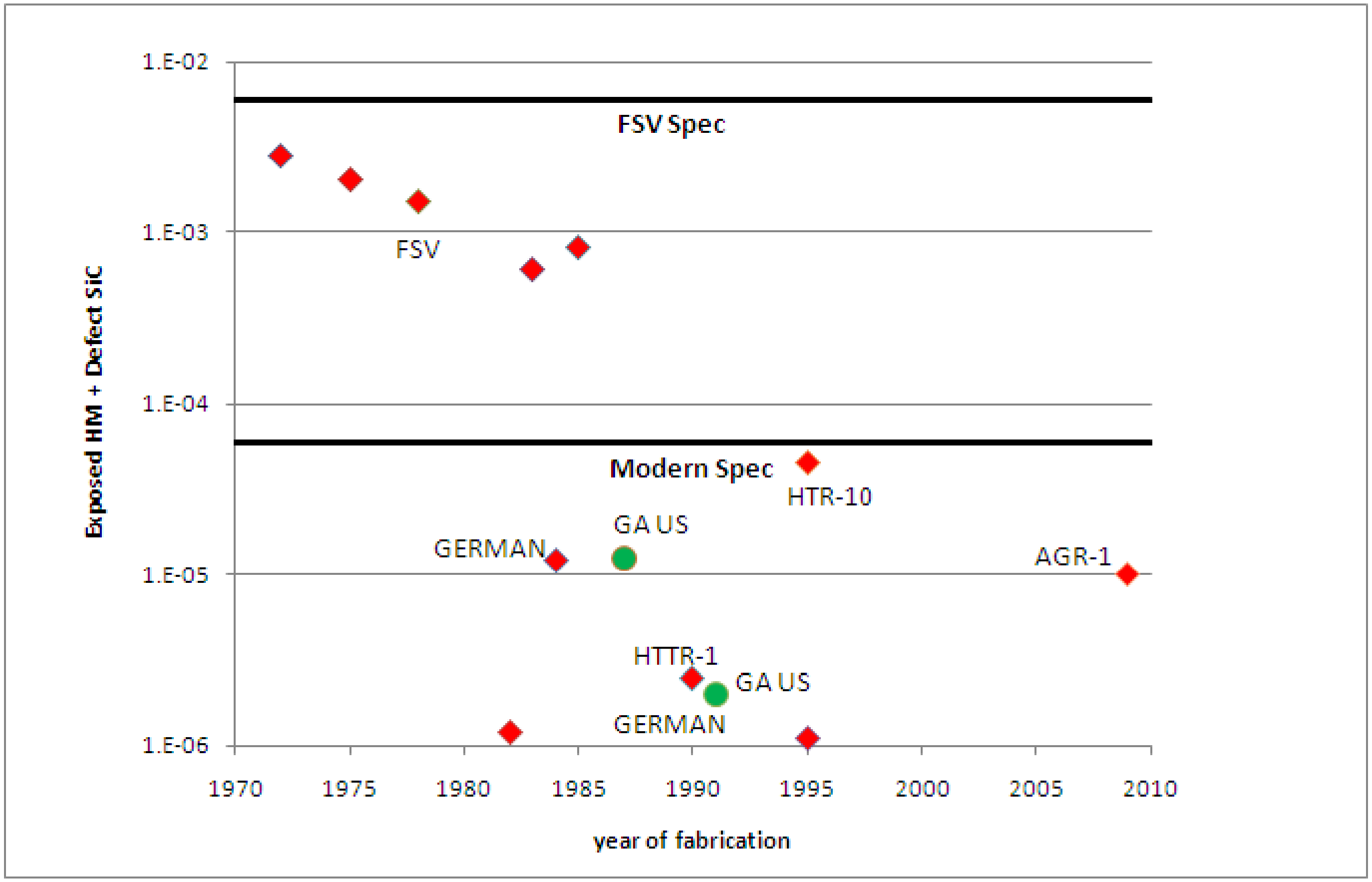


Currently operating with first core TRISO UO_2 fuel to 2014

Operating with 950°C helium temperature

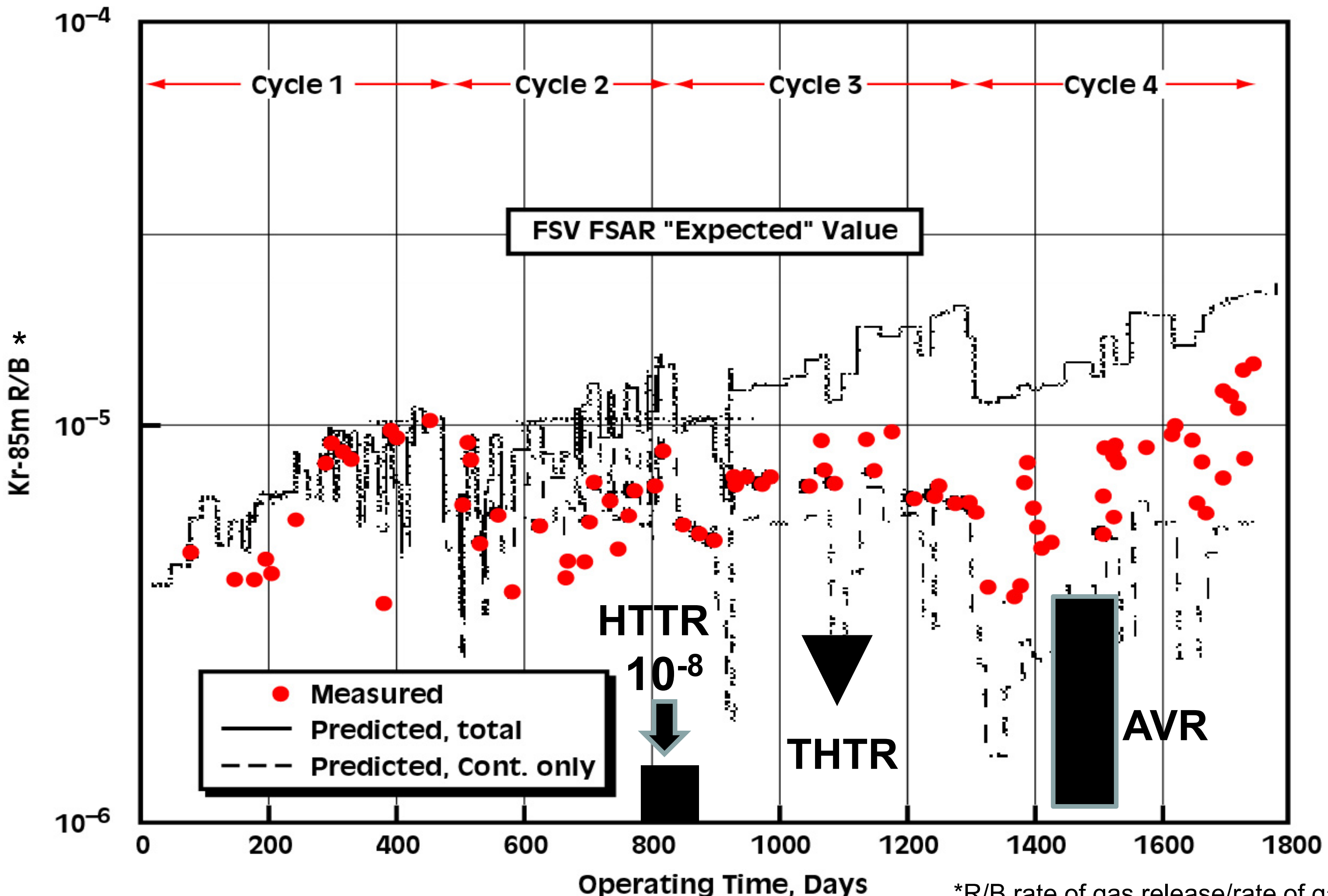
Excellent fuel performance – low measured fission gas release

Improved Equipment and Fabrication Procedures Provided Substantial as-Manufactured Quality Improvement



But some fuel has not performed well under irradiation

In-Pile ^{85m}Kr Release Measurements in FSV Indicate Good Coated Particle Fuel Performance



*R/B rate of gas release/rate of gas creation

Outline

- Fuel operating experience in HTGRs
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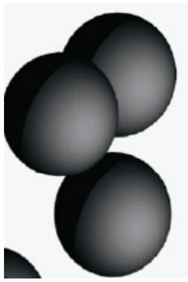
CP Irradiation & PIE Procedures and Equipment are Well-Developed Tools for Understanding CP Fuel

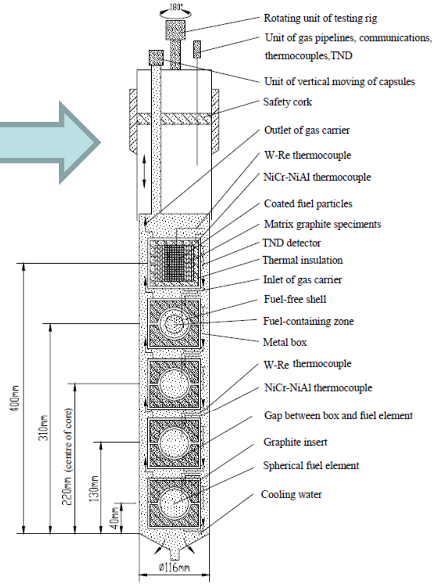


- **Fuel irradiations**
  - Test units – compacts, pebbles, particles
  - Test reactors and test equipment
  - Irradiations are conducted to
    - Determine fission product barrier failure mechanisms, rates, limitations, and margins
    - Design information on irradiated fuel materials
    - Demonstrate performance of evolving fuel developments
    - Validate fuel performance and fission product transport methods
  - Irradiation test measurements
    - Temperatures, neutron spectra and fluence, fission gas release
- **Post-irradiation examinations (PIE)**
  - PIE facilities and equipment extract quantitative data
  - Results contribute to understanding and quantification of fuel performance

Irradiation Facilities at INL – ORNL & Worldwide

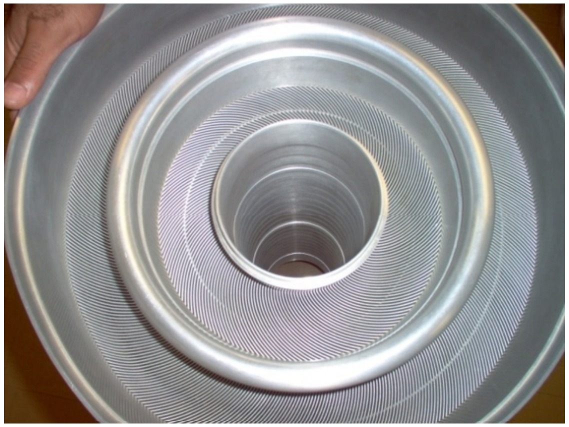
Advanced Test Reactor INL

Russia: IVV-2M Pebbles SM-3/RBT-6 Compacts



High Flux Isotope Reactor - ORNL

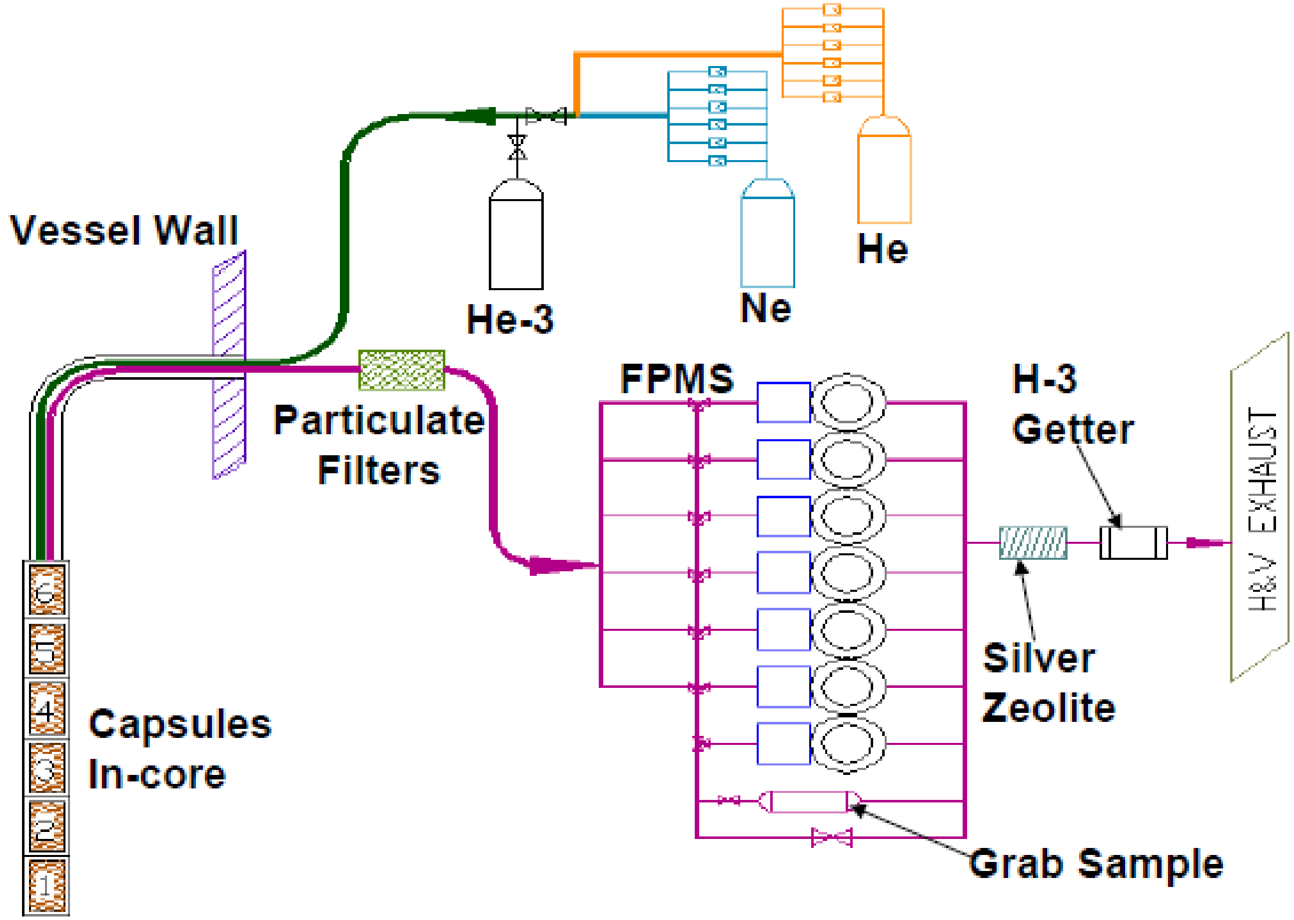
High Flux Reactor Petten, Netherlands



Many other reactors have been used for Coated Particle Irradiations

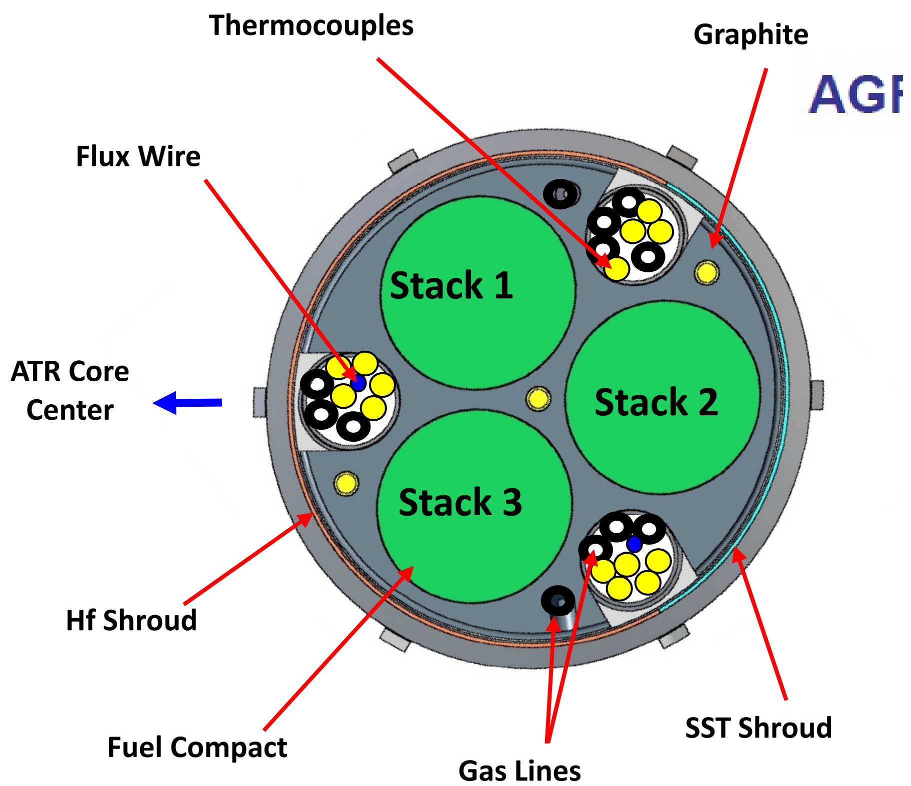
Irradiation Facilities Measure Irradiation Conditions and Coating Integrity via in-Reactor Fission Gas Release

AGR-1 Experiment Block Diagram



Six (6)-Capsule Test Train Design for AGR-1

Individual Cell Features



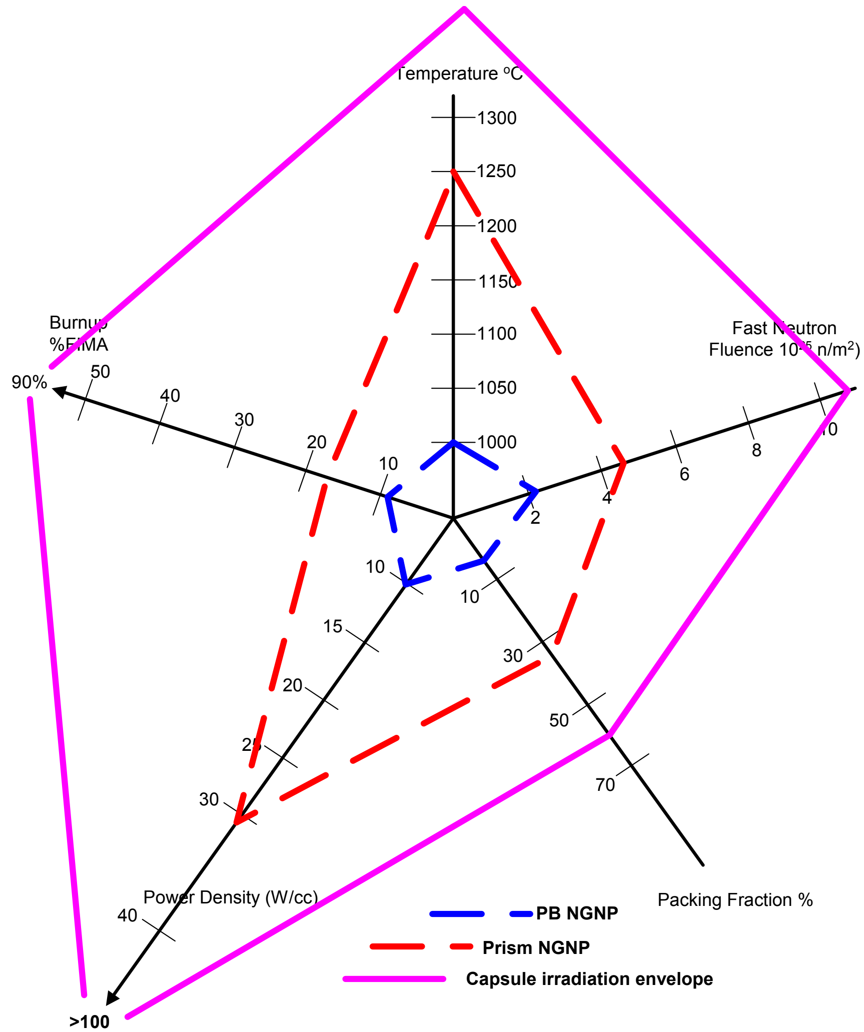
AGR-1 test train assembly
6-individual instrumented capsules

Twelve, 0.5" diam, 1" long compacts/cell

Capsule Irradiations Envelope Far Exceeded NGNP Operating Envelopes

All Coated Particle Irradiations

- **Earlier irradiations most Coatings survived**
- **But performance did not meet modern standards in all cases**
    - **1400°C**
    - **12 x 10^{25} n/m^2**
    - **60% PF**
    - **100 w/cc (fuel region)**
    - **~90% FIMA**

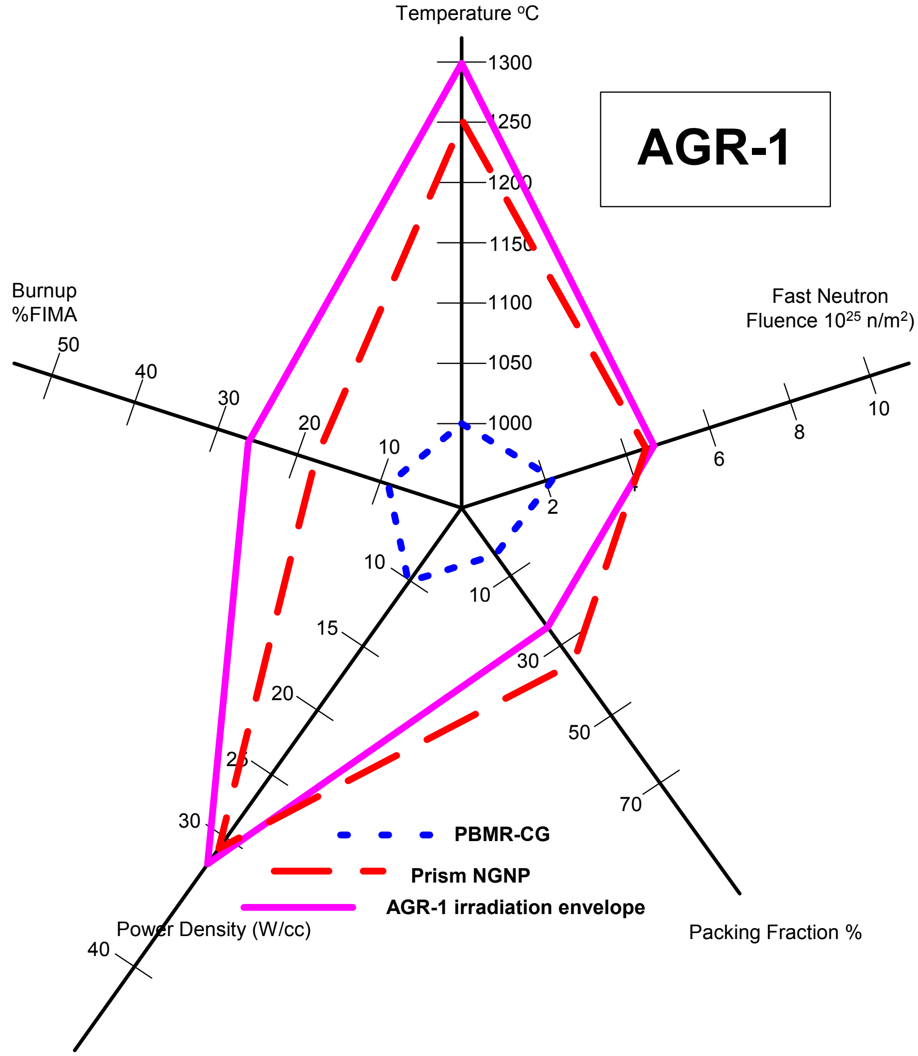


AGR-1 Irradiation Conditions Closely Match Expected Prismatic NGNP Service Conditions

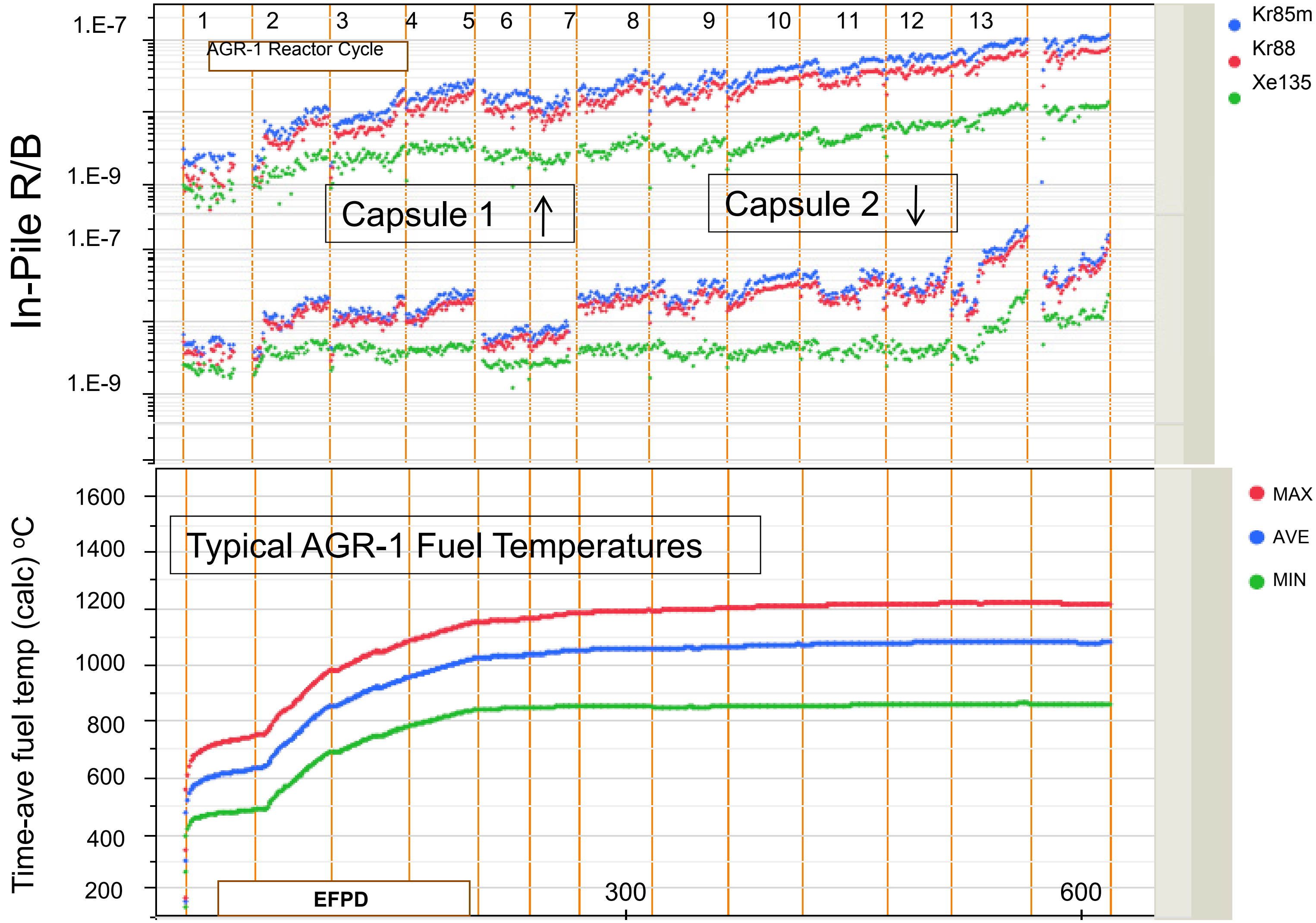
And satisfied performance requirements

(based on in-pile fission gas release measurements)

- 1300°C
- 4.5 x 10^{25} n/m²
- 28% PF
- 32 w/cc (fuel region)
- ~26% FIMA



Outstanding Coated-Particle Fuel Performance Observed in Most Recent US Irradiation

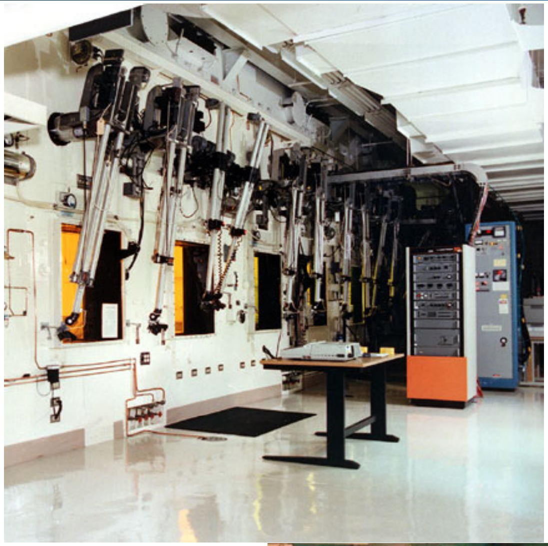


Summary – Fuel Irradiations

- **TRISO - extensive irradiation testing**
  - Exceeding NGNP operating envelope
  - German (pebble) and recent US (compact) irradiations demonstrate required performance

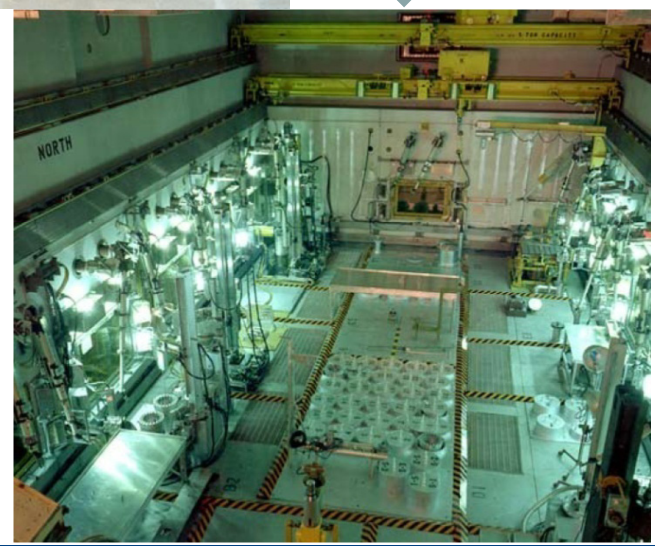
- **Additional testing needed**
  - Establish repeatability – statistical confidence
  - Fuel fabricated on production-scale equipment
  - Obtain additional design data, limitations, margins
  - Validate fuel and fission product design methods

Techniques for Coated Particle PIE are Well Developed



ORNL

INL



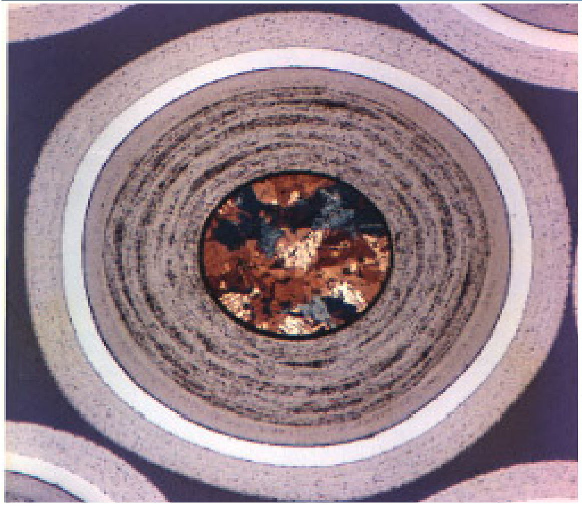
Coated particle post-irradiation examinations performed at well-equipped hot cells, TRIGA reactor, accident testing facilities at:

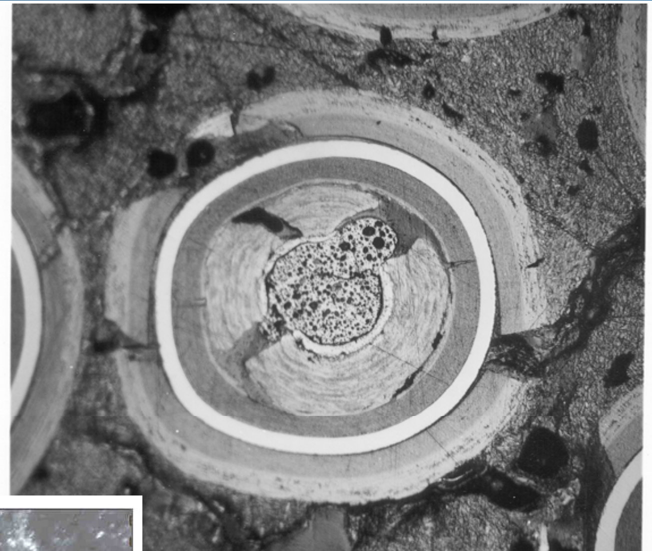
- Oak Ridge National Lab
- Idaho National Lab

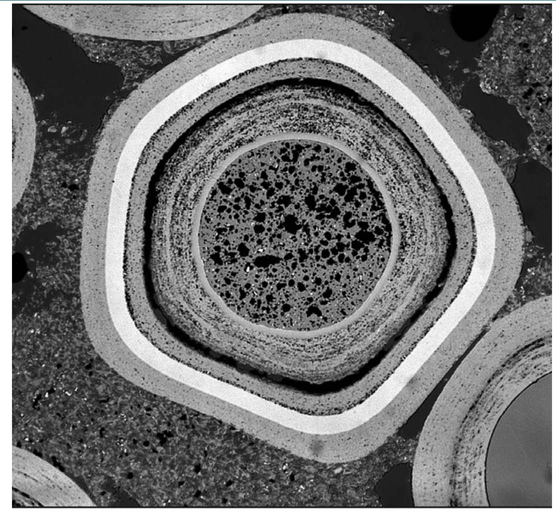
Specialized Methods Have Been Developed for Coated Particle Fuel Examination

- **Examine irradiated compacts and pebbles**
  - Dimensions, visual, metallographic, thermal/mechanical properties
  - Fission gas release (R/B) - reactivation
  - Solid fission product release
  - Accident behavior
- **Examine irradiated individual particles**
  - Compact & pebble deconsolidation
  - Individual microsphere gamma analyses (IMGA)
  - Exposed or uncoated heavy metal
  - Metallography
  - Scanning electron microscope/microprobe

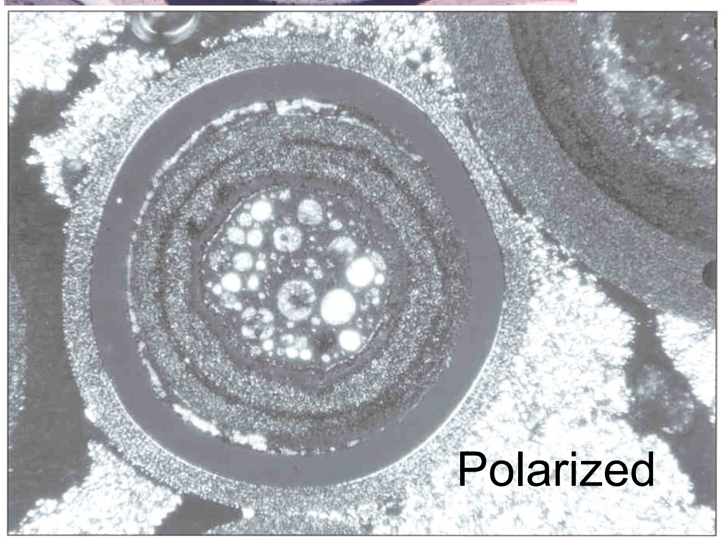
Metallography Reveals Condition of Particles w/SEM –Microprobe –Distribution of Elements (variety of irradiations)



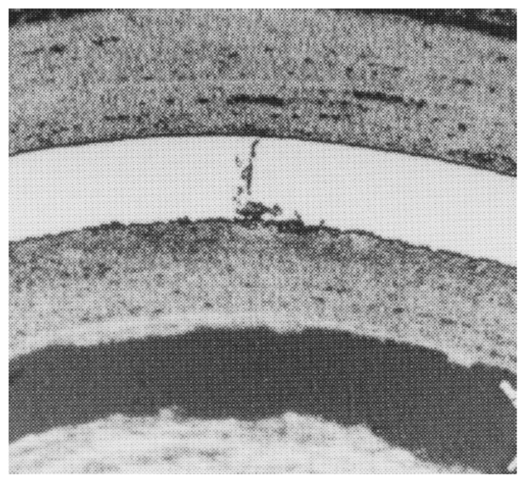


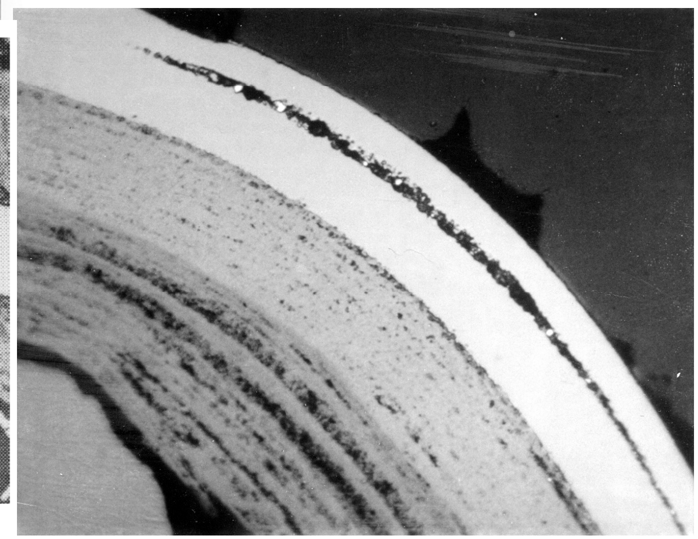


R71610 (C9900614-23) 200x



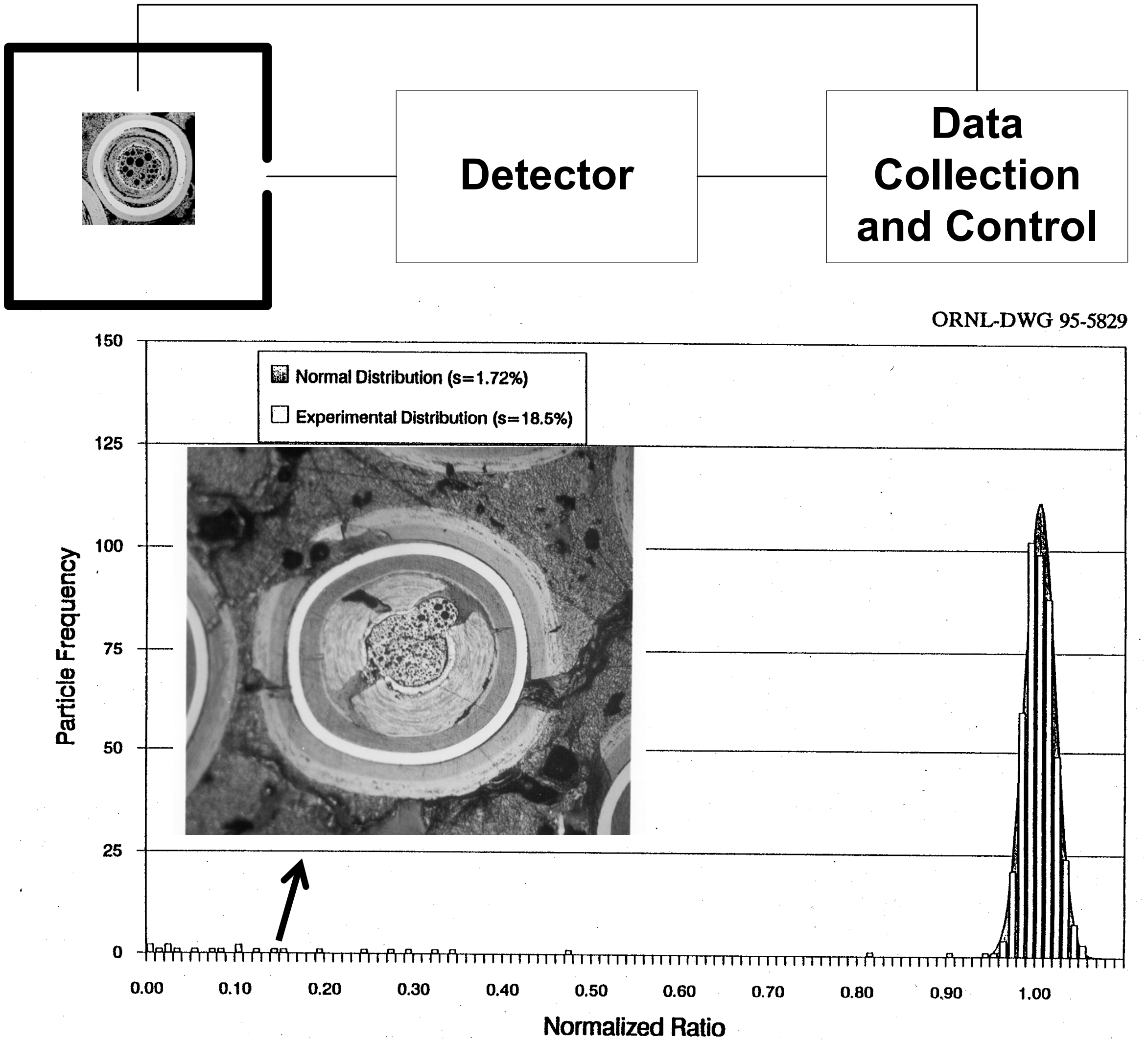
R71559 (C9900515-04) 200x — 20 μm





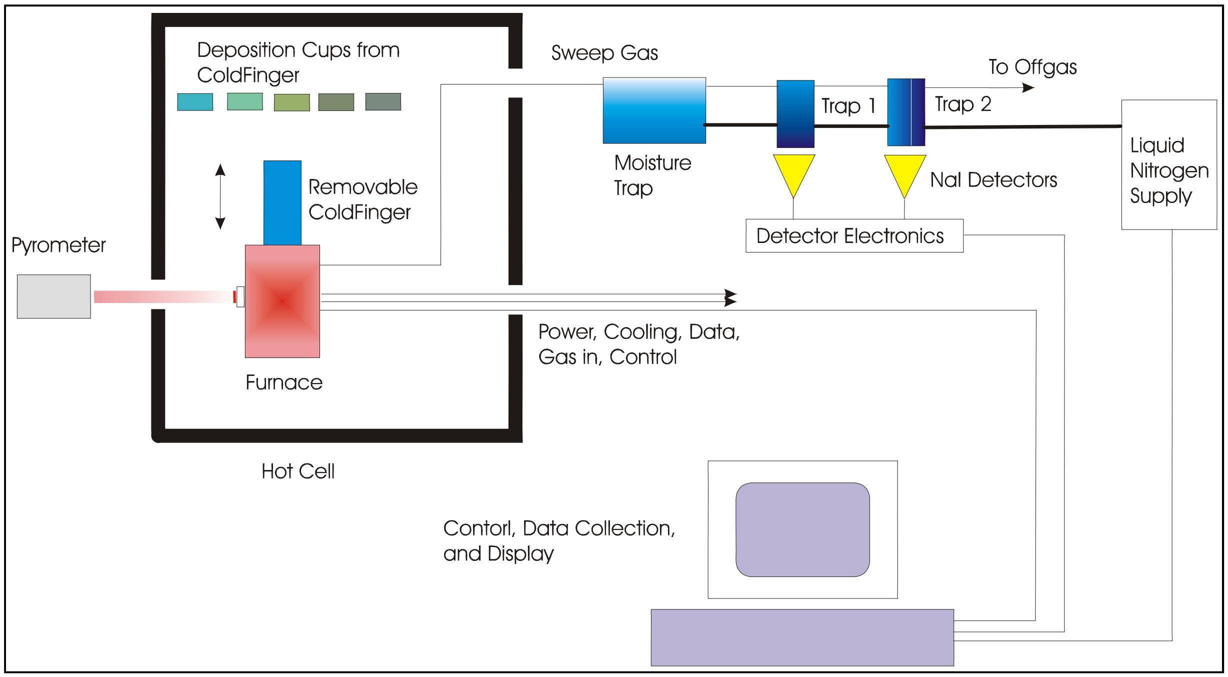
Individual Particles Can be Gamma-Counted and Isolated for Examination

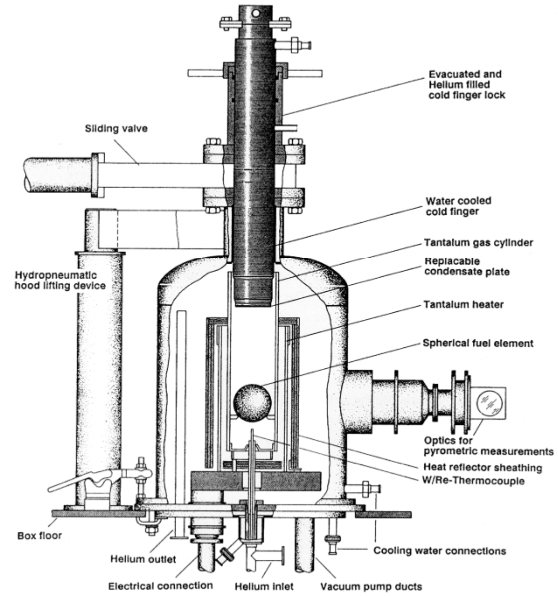
- IMGA gamma counts a large number of individual particles and tallies results
- Automated handling & counting
- Pick out problem particles for detailed examination



Accident Testing of Irradiated Fuel

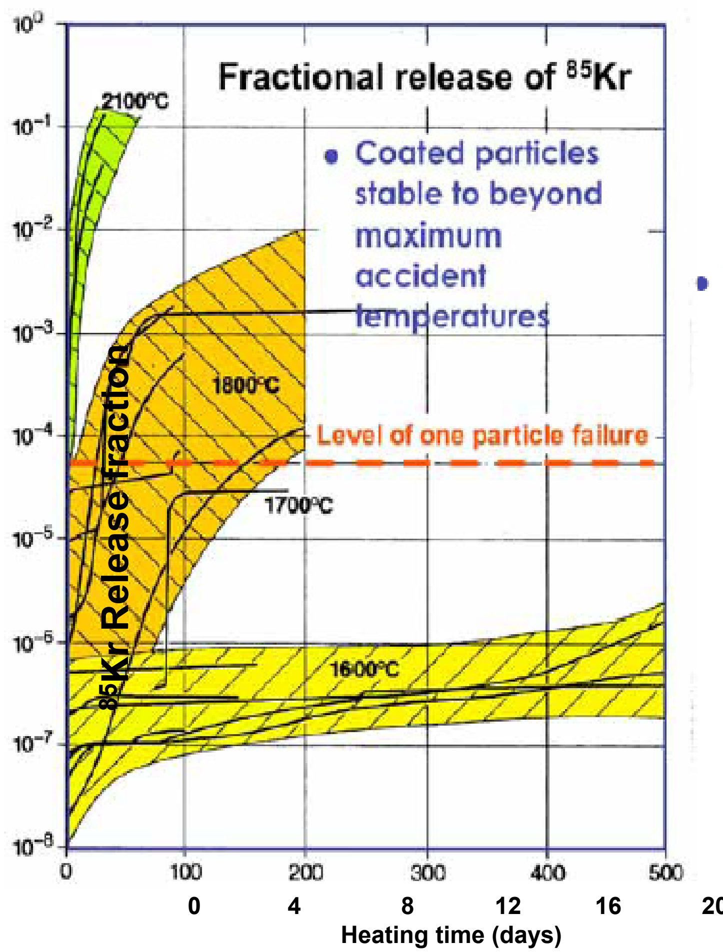
- **Furnace configuration**



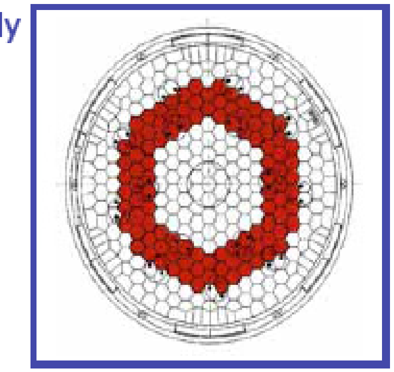


Test Compacts, Spheres, Particles (ORNL, INL, Worldwide)

FG Data Indicates Coating Failure Initiated above 1600 °C
Satisfying the Accident Criterion is Achieved by Reactor Design

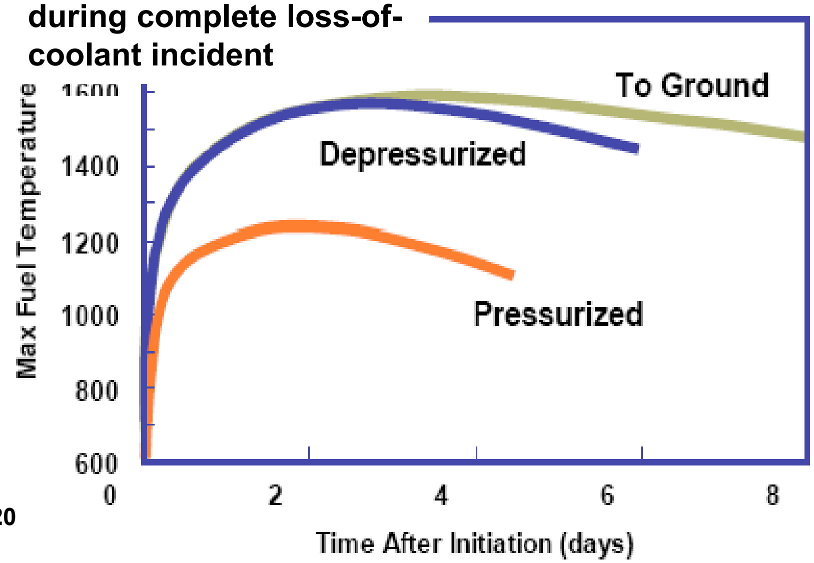


- Heat removed passively during loss-of-coolant events - annular core

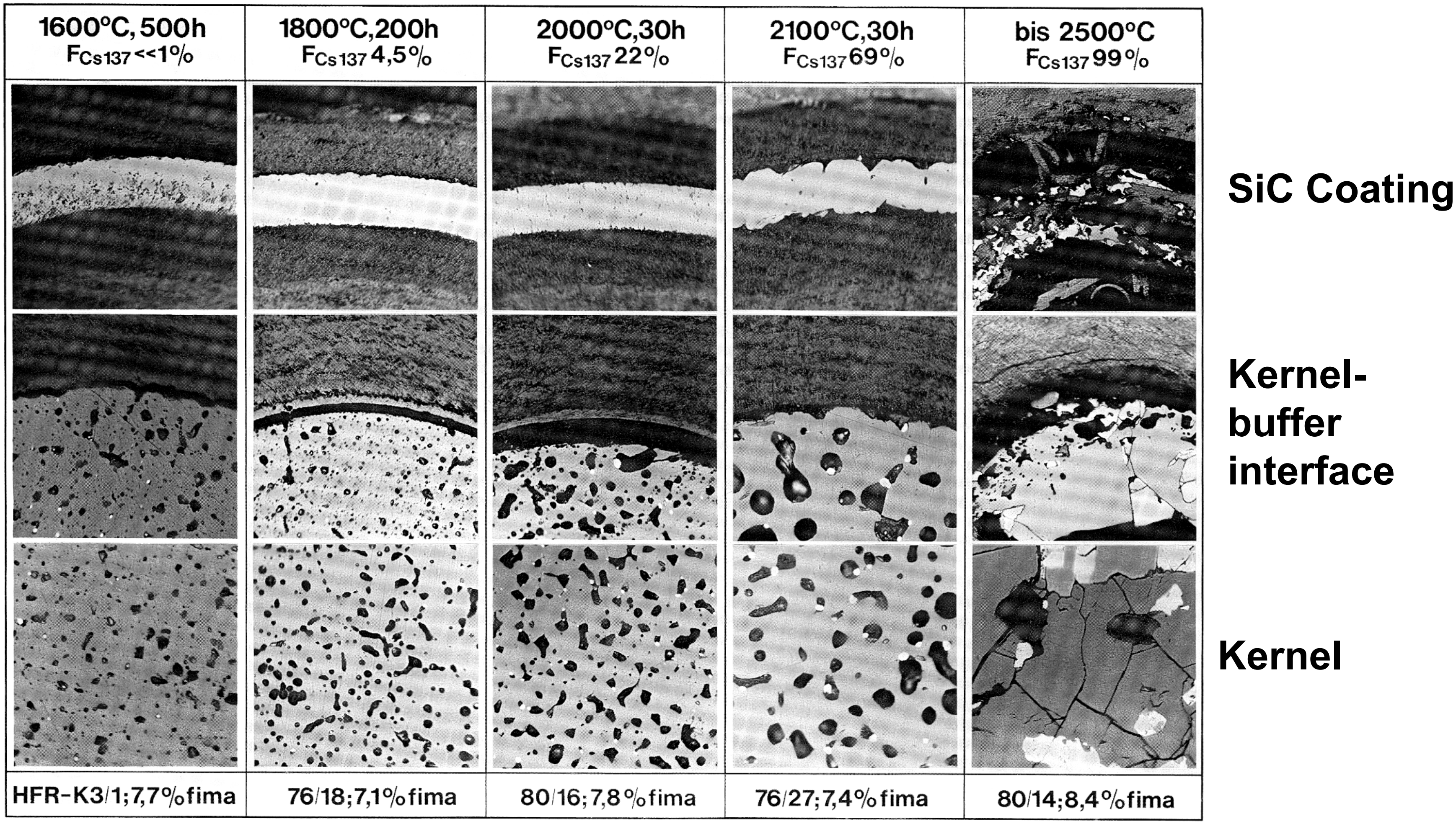


- Fuel temperature stays

Fuel temperature stays below the damage limits during complete loss-of-coolant incident



PIE Reveals Details of Coating Response to Accident Conditions – Determine Mechanisms & Rates



Ceramographic sections through UO_2 TRISO particles

Summary – Post Irradiation Examination

- Irradiation testing of CP fuels can realistically simulate reactor conditions
- Irradiation facilities can measure and control irradiation conditions and collect in-pile data
- Specialized PIE tools have been developed for coated particle fuel to obtain quantitative performance and design data
- Accident conditions can be simulated and data on fission product barriers and fission product release collected

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Fuel Safety Approach

- **Fuel safety criteria are related to the fuel fission product barriers – coatings**
- **Based on meeting plant top-level dose limits with margin**
- **Coating failure allowance allocated to as-manufactured and in-service performance**
- **Testing established service environment where performance requirements are achieved**
- **Coating integrity during operation is protected by Operational Technical Specifications**
  - Parameters are monitored and limited to meet safety criteria and stay within performance limits
  - Coating integrity monitored by primary coolant radioactivity
- **Coating failure limitation during accidents is achieved by reactor design – passive, conductive heat loss**

Estimated Maximum Service Conditions for Pebble & Prismatic NGNP Fuel (not Limits)

Parameter	Maximum Value* (PBMR-CG)	Maximum Value* (Prismatic NGNP)
Maximum fuel temperature–normal operation, °C	1048	1400
Maximum time averaged fuel temperature, °C	1048	1250
Fuel temperature (accident conditions), °C	1483	1600
Fuel burnup, % FIMA	8.75	17**
Fast neutron fluence, 10^{25} n/m^2 (E > 0.18 MeV)	4	5

*Anticipated max. temperatures are not design limits. These temperatures may be exceeded for a limited time (days or weeks) without resulting in fuel failure and can be exceeded by a small fraction of the fuel for longer periods without resulting in excessive fission product release.

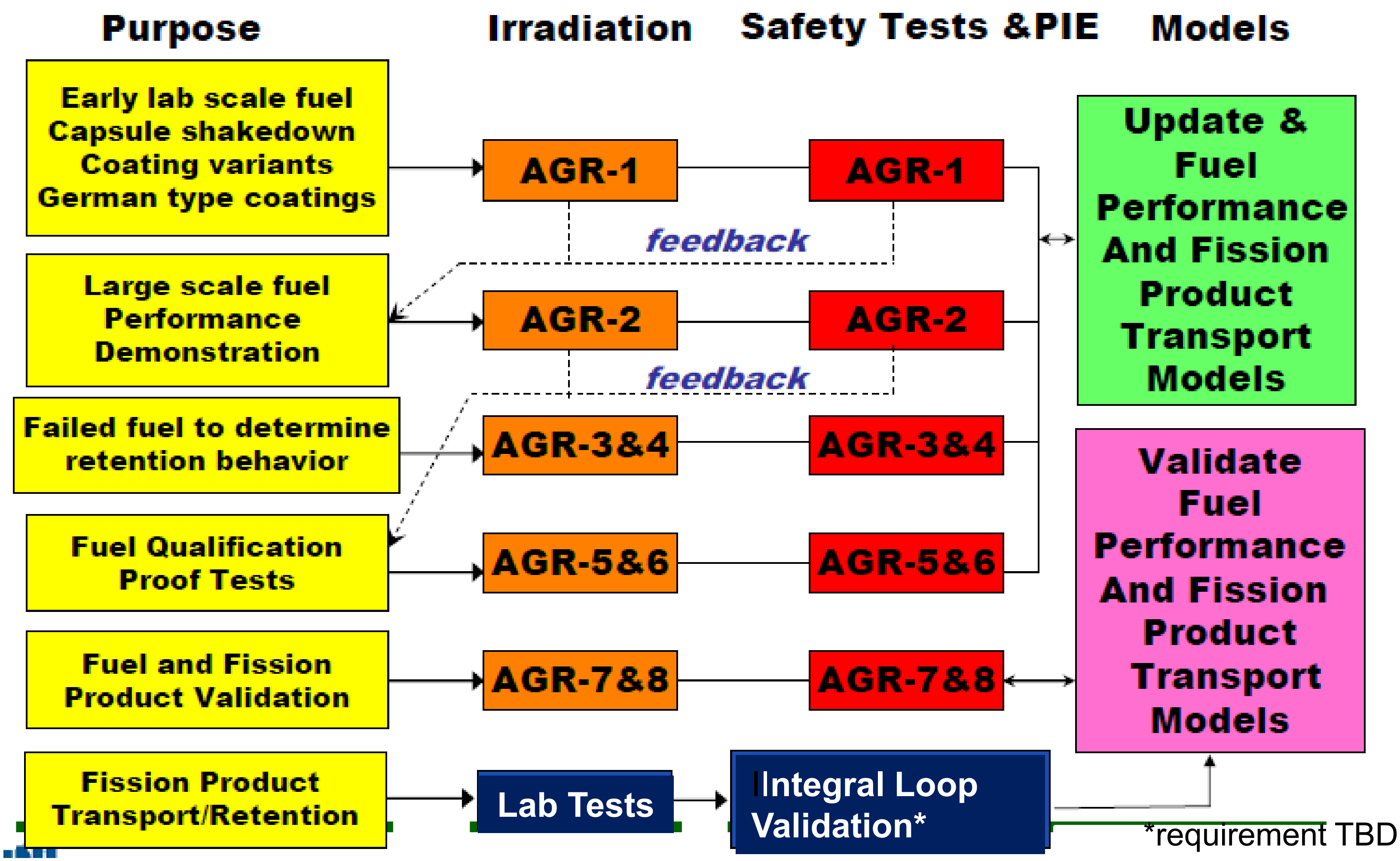
*These do not represent "cliffs" where if exceeded failure will result

**Estimated FIMA for 14% enriched reference fuel particle under development by NGNP/AGR Fuel Program

Comprehensive Fuel Qualification Program Being Conducted by NGNP/AGR Fuel Program

- Process development
- Test sample fabrication
- Irradiation testing & PIE
- Accident testing
- Validate fuel performance models
- Fuel product and process specifications
- Technology for commercial fuel fabrication
- Reduce market risk
- Qualify fuel for NGNP

NGNP/AGR Fuel Program Overview



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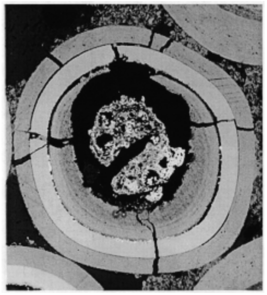
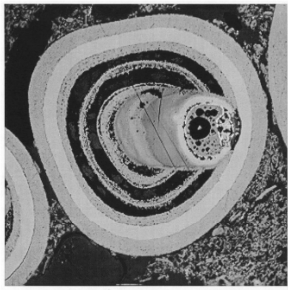
Role of Fuel Performance Modeling

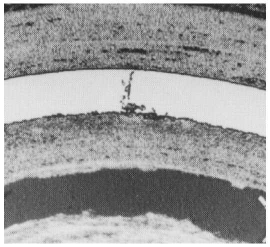
- Guide current and future particle designs
- Assist in irradiation and safety experiment planning
- Predict observed fuel failures
- Predict fission product transport through particles and matrix
- Interpolate fuel performance for core design assessments

……INL leading US model development - PARFUME

Coating Failure Mechanisms to be Modeled



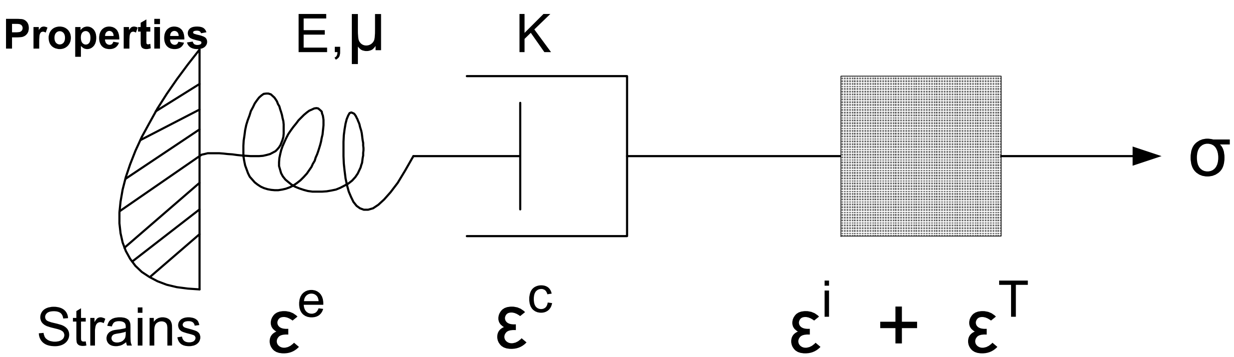


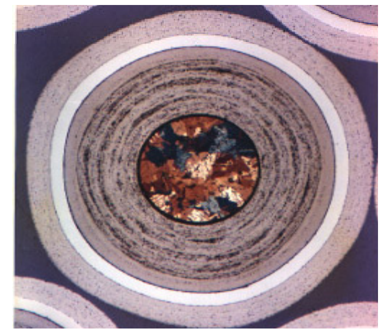


- Coating Stresses
  - Internal gas pressure
  - Irradiation induced dimensional changes
  - Interactions between coatings
- Fuel kernel thermo-chemistry
  - Oxygen management
  - Fission product compounds and phases
- Carbon Transport in temperature gradient
  - Kernel migration
- Chemical reactions with coating
  - CO/CO_2, palladium, lanthanides, impurities other fission products
  - SiC decomposition at high temperature
- Inter-relationships between failure mechanisms

Coating Stress Modeling Requires Large Quantities of Detailed Data

- **Linear Viscoelastic Constitutive Equation for Coatings**





Failure by Brittle Material Statistical Model - Weibull

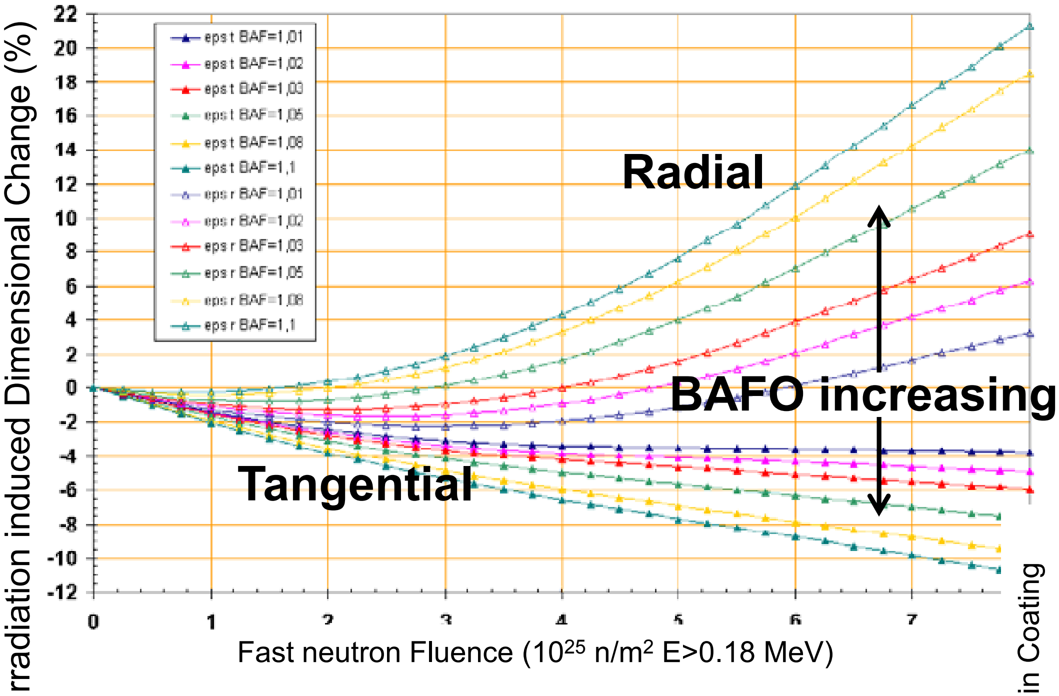
$$P_f = 1 - exp(\int_V \left(\frac{\sigma}{\sigma_o}\right)^m dV)$$

Coating properties depend strongly on:

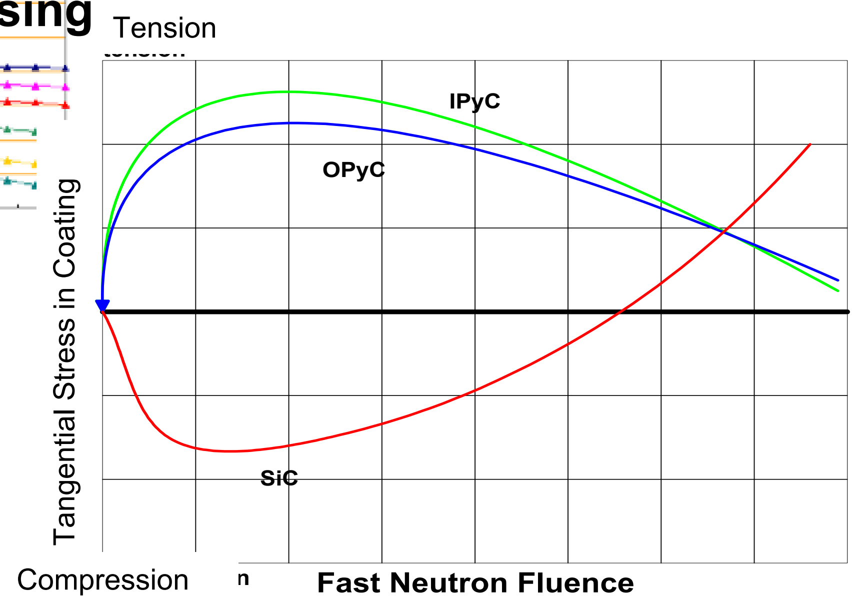
- Fabrication process that affects coating structure
- Exposure to fast neutrons
- Temperature
- Imposed stress

……the coating properties constitute the largest uncertainty in predictions of coated particle performance

TRISO Coatings Are Complex Structures with Complex Interactions Between Coating Layers



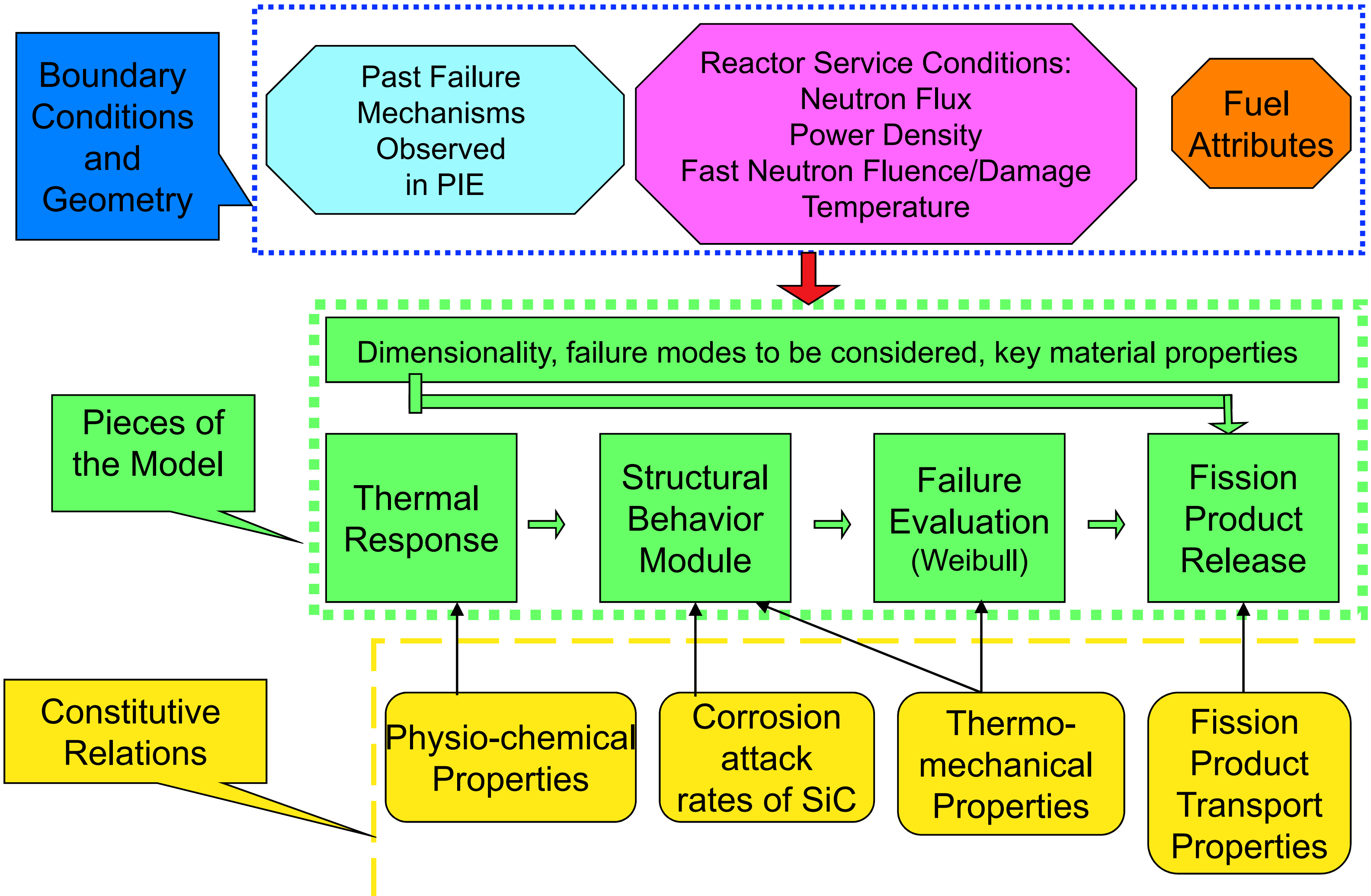
- Pyrocarbons shrink
- Keep SiC in Compression
- SiC does not fail



PyC shrinks under fast neutron irradiation

- PyC structure (**BAF$_O$**)
- Temperature

INL PARFUME – Integrating First-Principle Treatment of Failure Mechanisms for General Applications



Accident Modeling

- **Initial empirical separate effects treatments used in the past**
  - Pressure vessel, chemical attack, amoeba
  - Thermal decomposition depending on accident temperature and state of irradiation
- **1-D performance codes being upgraded and integrated for applications during accidents**
- **Covered in Module 15**

Summary – Fuel Performance Modeling

- **1-D fuel particle performance codes are being developed in many countries**
  - Codes have different levels of capability
  - Goal to integrate failure mechanisms
  - Most still under development moving toward a common goal of universal applicability
- **Uncertainties in performance predictions arise mainly from properties of irradiated coatings**
- **Multi-dimensional codes are used to predict non-spherical effects**

Outline

- Fuel operating experience in HTGRs
- Fuel irradiation and post-irradiation examination (PIE)
- Safety criteria and performance limits
- Fuel performance modeling
- Fuel cycle issues

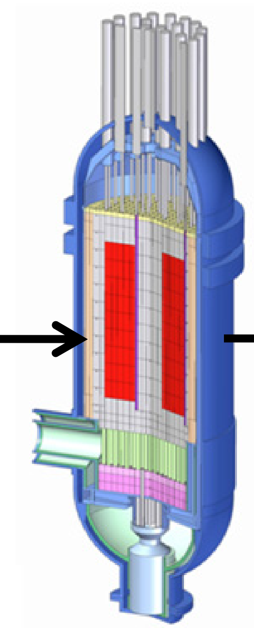
Fuel Cycle Issues

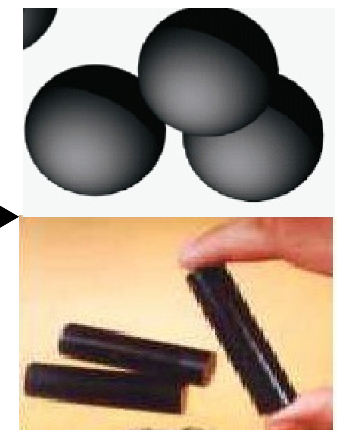
- **Sustainability**
  - Resource utilization
  - Enrichment
  - Thorium
- **Proliferation**
  - Reprocessing of coated particles
- **Fuel cycle economics**
- **Ultimate disposal of coated particle fuel**

Once-Through LEU Fuel Cycle being Considered for NGNP - Good Proliferation Resistance

10% enr. UO_2
15% enr UCO

NGNP





Ultimate Disposal

Many other cycles possible
Selection depending on economics and waste management policy

Fuel Cycle Parameters

Parameter	Units	PBMR-CG (LEU)	GT-MHR (LEU)	PWR
HM loading	MT/GW(th)	11.2	7.5	36
Ore utilization	U3O8/GW(e)-Yr	183	182	212
Conversion Ratio	new fissile/used fissile	0.46	0.4	0.5
Discharged Pu	kg/GW(e)-Yr	147	96	338
Heat load - discharge@ 10 years	kw(th)/GW(e)-Yr	25	24	26

Summary

- Coated particle fuel has been manufactured in commercial quantities and successfully used in power reactors
- Substantial experience with fuel irradiation, examination, and testing ➡ strong database on fuel performance
- Performance modeling is continuously improving – additional data and validation needed

Suggested Reading

- **Fuel Operating Experience in HTGRs**
  - A. Baxter, et al., "FSV Experience in Support of the GT-MHR Reactor Physical, Fuel Performance , and Graphite," IAEA Technical Committee Meeting on 'Proceedings of the Development Status of Modular High Temperature Reactors and Their Future Role," November 1994, ECN, Petten, Netherlands
  - Nuclear Technology, 35, No. 2 206-573 (1977) entire volume

- **Fuel Irradiation and PIE**
  - D. Petti, et al., "Technical program plan for the advanced gas reactor fuel development and qualification program," Idaho National Laboratory Report INL/EXT-05-00465, Rev. 2, July 2008
  - "Fuel performance and fission product behaviour in gas cooled reactors," IAEA-TECDOC-978 (1997)

Suggested Reading

- **Fuel Performance Modeling**
  - B. Boer, et al., "Stress analysis of coated particle fuel in graphite of high-temperature reactors," Nucl. Tech., 162, 276-292 (2008)
  - G. Miller, et al., "Current capabilities of the fuel performance modeling code PARFUME," 2nd International Topical Meeting on High Temperature Reactor Technology, Beijing, China, September 2004
  - G. Miller, et al., "Statistical approach and benchmarking for modeling of multi-dimensional behavior in TRISO-coated fuel particles," J. Nucl. Mater., 317, 69-82 (2002)
  - H. Nabielek, et al., "The performance of high-temperature reactor fuel particles at extreme temperatures, Nucl. Technol., 84, 62 (1989)

- **Fuel Cycle Issues**
  - C. Ellis, et al. "Modular helium reactor fuel cycle concepts and sustainability, Proceedings of the Conference on High Temperature Reactors, Beijing, China, September, 22-24, 2004
  - N. Zondi, "The Pebble Bed Modular Reactor and its alignment to the South African National Strategy for Sustainable Development, Paper G00000226, Proceedings of the Conference on High Temperature Reactors, Beijing, China, September, 22-24, 2004