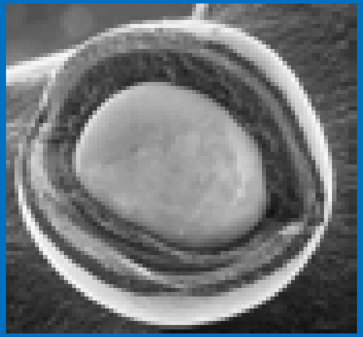
TRISO FUELS



Dr. Madeline Feltus
Department of Energy, USA
18 December 2019

Meet the presenter

Dr. Madeline Feltus has led the DOE Office of Nuclear Energy's Advanced Gas Reactor TRISO Fuels Qualification and Development Program since 2003. She provides technical support for DOE's advanced nuclear fuel research and development (R&D), light water reactor accident tolerant fuel R&D, and reactor development projects where she focuses on improving reactor fuels and materials irradiation performance for current and advanced fuel designs to have safe, accident-tolerant, robust, and reliable reactor fuel that can be used in existing and future advanced light water, gas-cooled, and sodium cooled reactors. She has been involved in writing and providing input for OECD NEA Experts Committee reports, IAEA technical documents, and reviewing manuscripts for technical journals. She is responsible for providing technical support and managing various university grant projects, vendor/industrial projects and small business R&D efforts.

Prior to joining DOE in 1999, Dr. Feltus was an assistant professor of nuclear engineering at the Pennsylvania State University (1991-1999). Madeline received her B.S. in Nuclear Engineering from Columbia University in 1977. While working full-time as a nuclear engineer at Burns and Roe, Public Service Electric and Gas (N.J.) and the New York Power Authority, she continued her graduate studies at Columbia and earned her M.S. in Nuclear Engineering (Reactor Physics, 1980), her M. Phil. in Mechanical Engineering (Thermal-Hydraulics, 1989) and her Ph.D. in Nuclear Engineering (1990) with her thesis on 3D time-dependent coupled kinetics-neutronics and thermal-hydraulics analyses.

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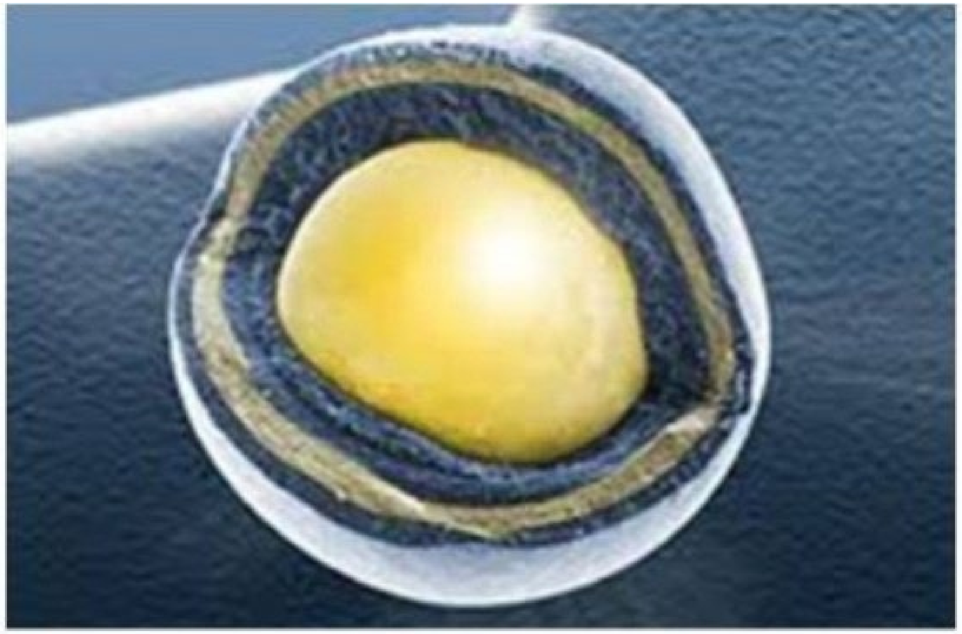
Presentation Outline

- **TRI-S**tructural **ISO**tropic(TRISO) Particle Fuel Fundamentals
- DOE's Advanced Gas Reactor (**AGR**) TRISO Fuel Program Overview, Timeline and Status
- AGR TRISO Fuel Program Element Details
- AGR TRISO Fuel Program Results
- Beyond the DOE AGR TRISO Fuel Program:
  - Commercial Fuel Fabrication, Qualification and Licensing
  - Future TRISO-Fueled Reactor Concepts
- References for Further Information



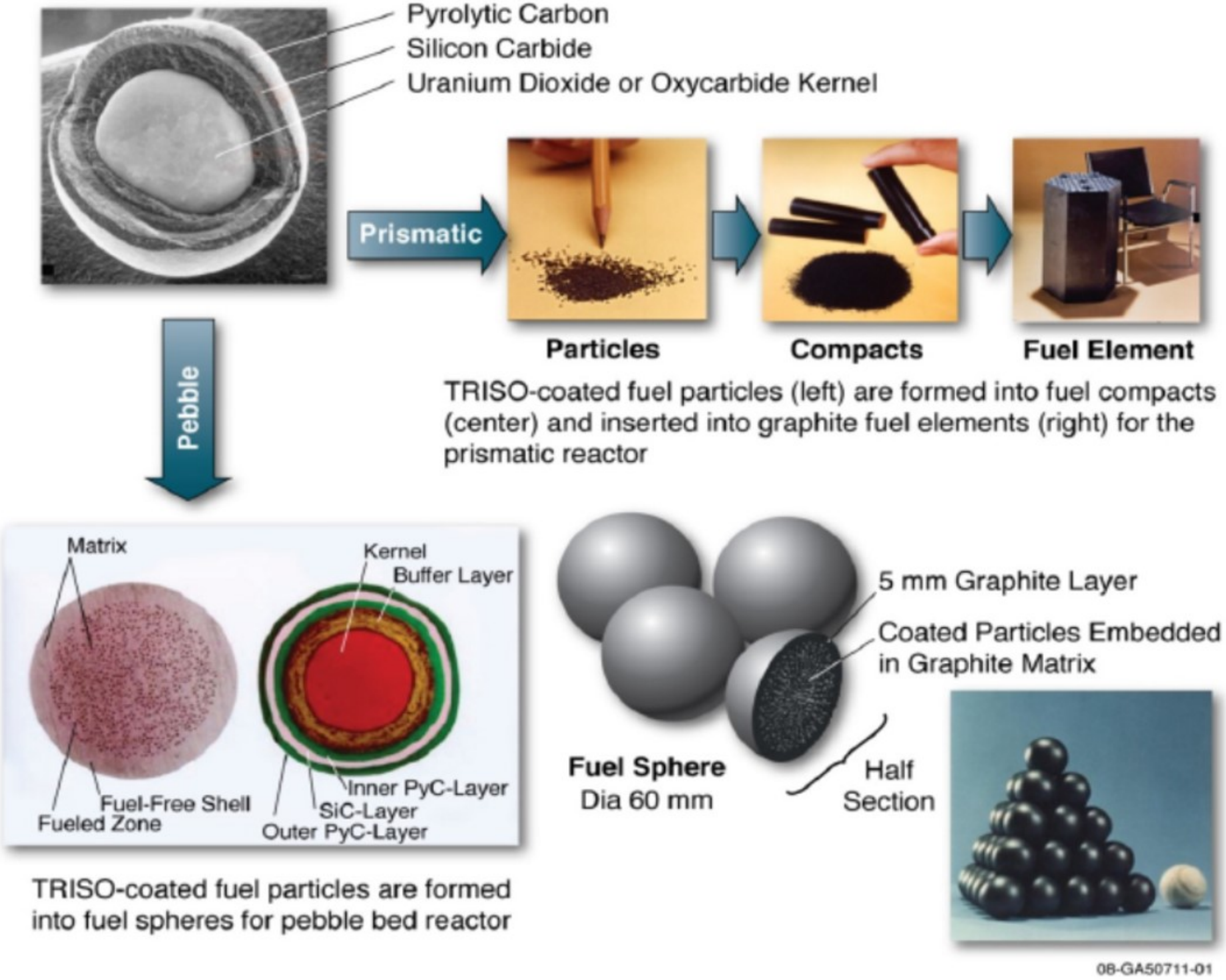
TRISO coated particle fuel

TRISO Particle Fuel

TRISO particles are embedded in graphitic matrix material

- Cylindrical compacts put hexagonal graphite blocks for prismatic reactor
- UCO fuel kernel for block or prismatic reactor with 12-19% U-235 enrichment
- Spheres for pebble bed reactor, flow through core
- UO_2 fuel kernel for pebble bed reactor with ~ 8 % enrichment (German)

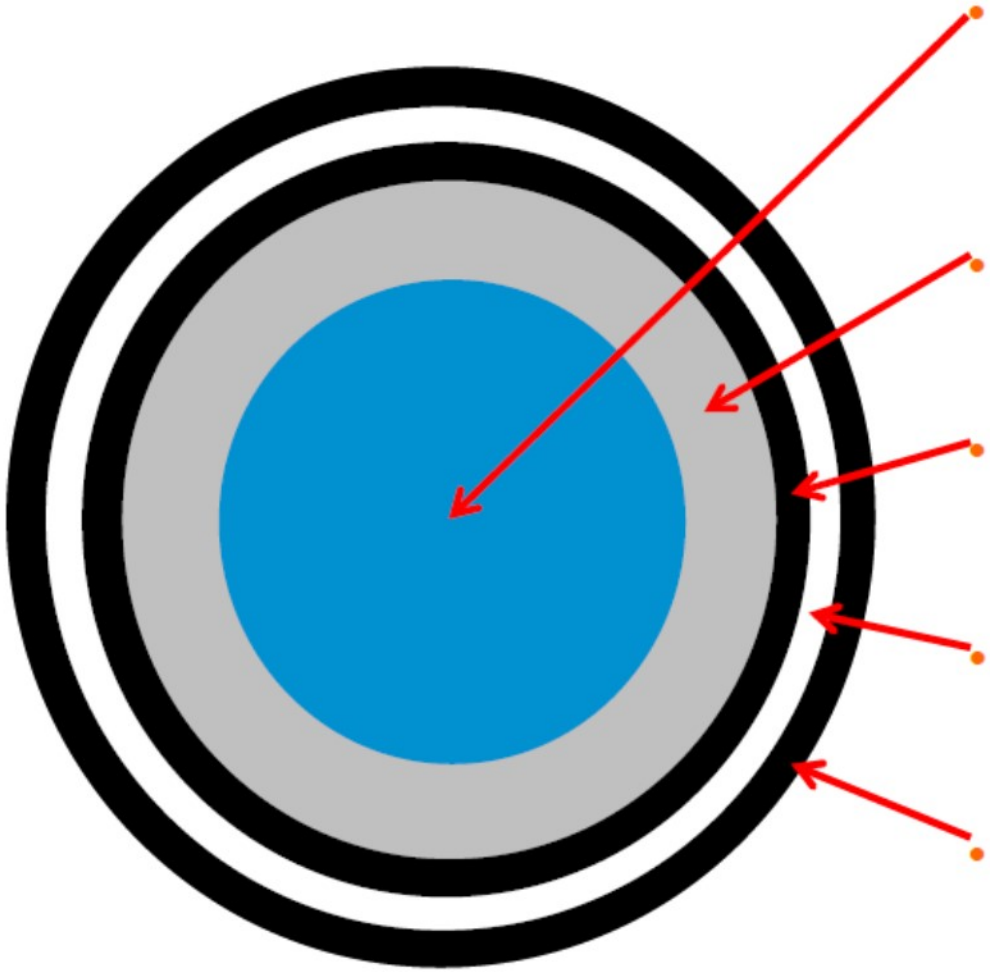
Prismatic and pebble bed TRISO particle use similar coating layer thicknesses, but the kernel enrichment and particle packing fractions are different



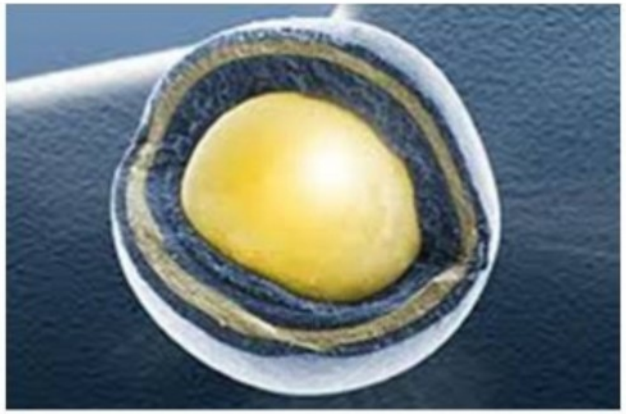
TRISO-coated fuel particles (left) are formed into fuel compacts (center) and inserted into graphite fuel elements (right) for the prismatic reactor

TRISO-coated fuel particles are formed into fuel spheres for pebble bed reactor

TRISO Particle Fuel Design



- **Fuel Kernel**
  - High density
  - Low enrichment (8-20%)
  - UO_2 or UCO
- **Buffer**
  - Low density (~50% theoretical density [TD]) isotropic pyrocarbc
- **Inner Pyrocarbon** (IPyC)
  - High density (~85% TD) isotropic pyrocarbon
- **Silicon Carbide** (SiC)
  - High density (~99% TD)
  - Fine grain
- **Outer Pyrocarbon** (OPyC)
  - High density (~85% TD) isotropic pyrocarbon



TRISO coated particle fuel

TRISO Particle Coatings Retain Fission Products

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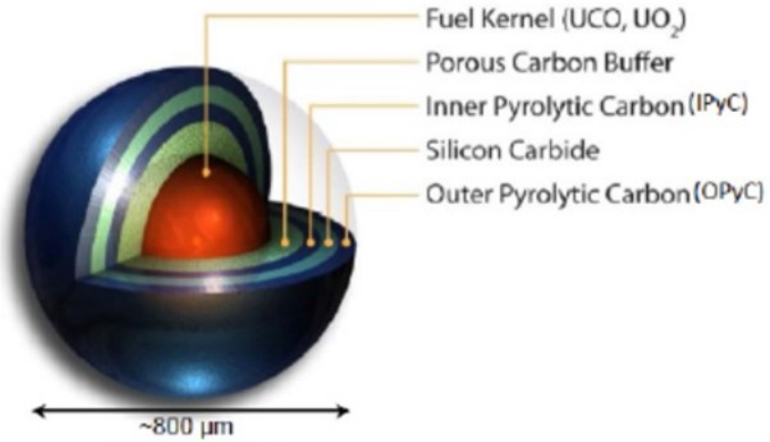
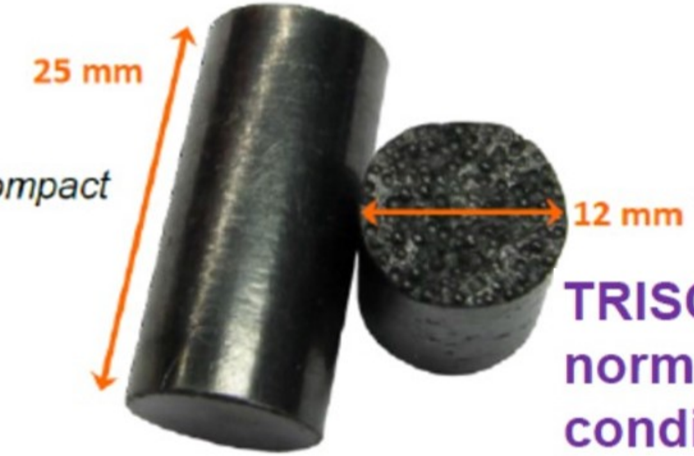
Tristructural isotropic (TRISO) Fuel



TRISO particle



AGR fuel compact

- TRISO fuel is at the heart of the safety case for modular high temperature gas-cooled reactors
- Key component of the "functional containment" licensing strategy
  - Radionuclides are retained within multiple barriers, with emphasis on retention at their source in the fuel

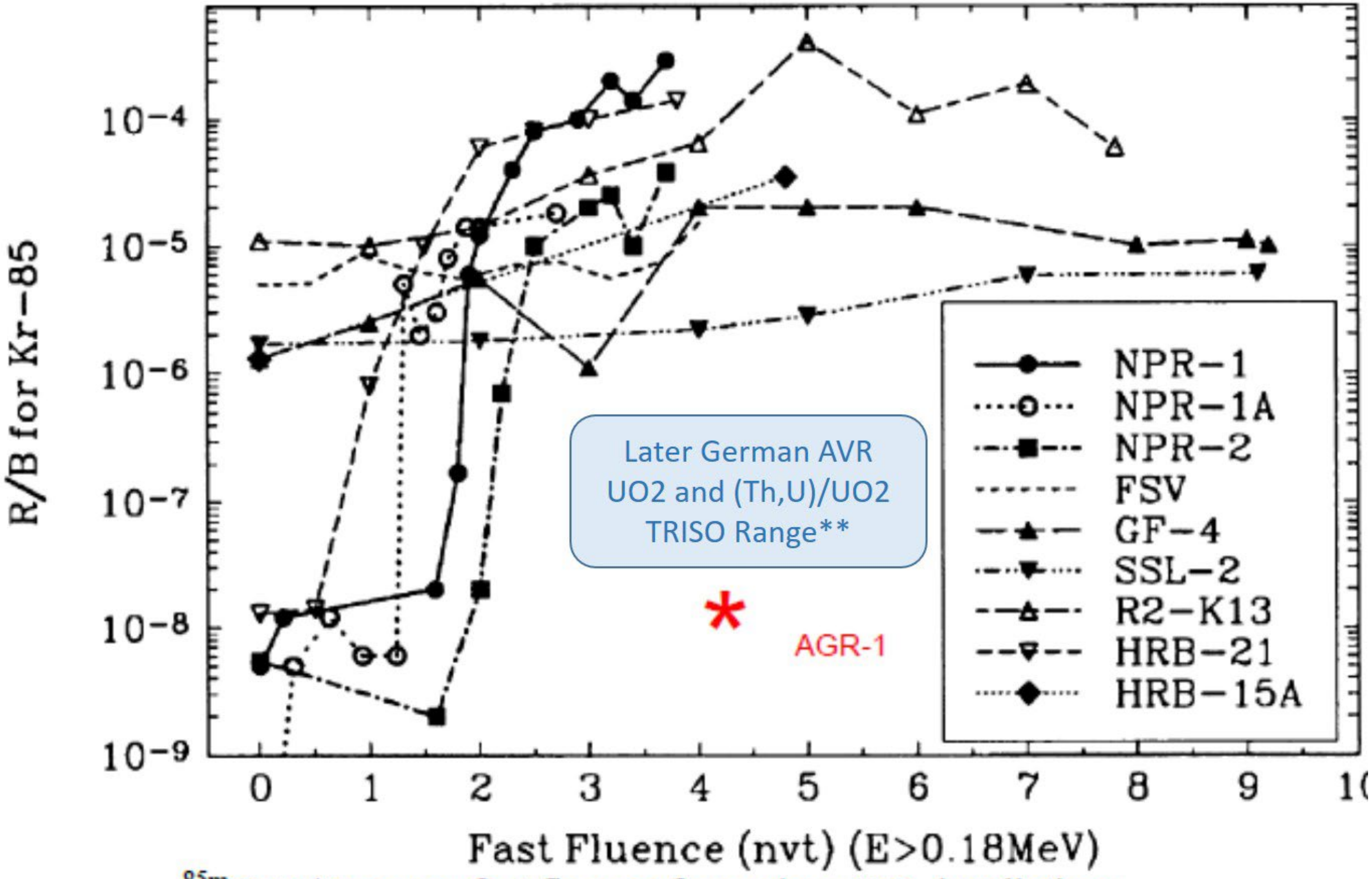
High-quality, low-defect fuel fabrication

Robust performance during irradiation and during high-temperature reactor transients

Low fission product release

TRISO fuel is engineered to retain fission products during normal operating (1000-1400 C) and Design Basis accident conditions including a Depressurized Cooldown Event (~1600 C)

U.S. and German Historical TRISO Fuel Experience



^{85m}Kr R/B versus fast fluence for various U.S. irradiations.

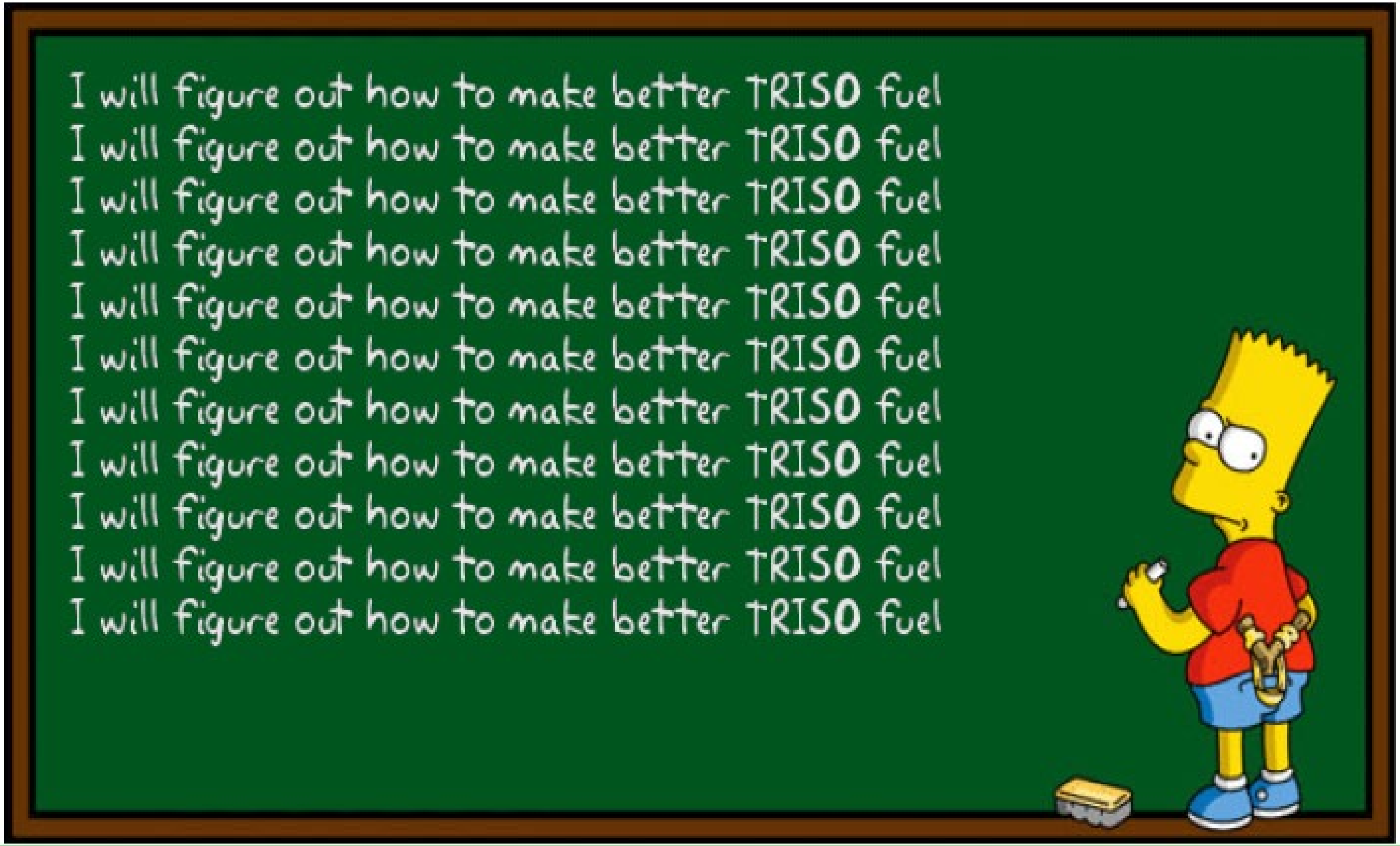
Historically, German TRISO fuel has ~1,000 times better performance than early U.S. fuel (before 1990's)

** All German Kr-85 R/B experience ranges 1.0 E-5 to 4.0 E-8 but at lower burnup and temperatures

TRISO Particle Fuel Performance Improvement

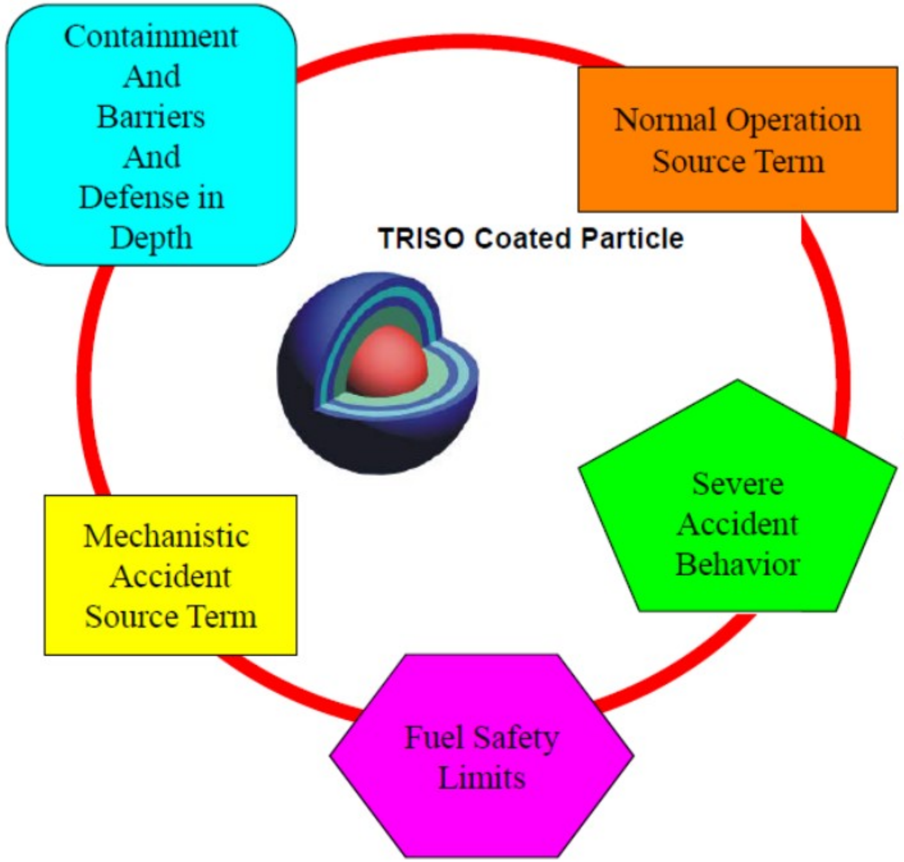
Excellent TRISO fuel fabrication and performance is needed for high temperature gas-cooled reactor (HTGR) deployment

- Understand the interplay between fuel fabrication specifications, production methods, and irradiation performance results
- Learn from past U.S. and German TRISO experience
- Use UCO vs. UO2 kernels to provide superior fuel performance at high burnup
- Innovation based on solid science, not by using a "recipe" trial method



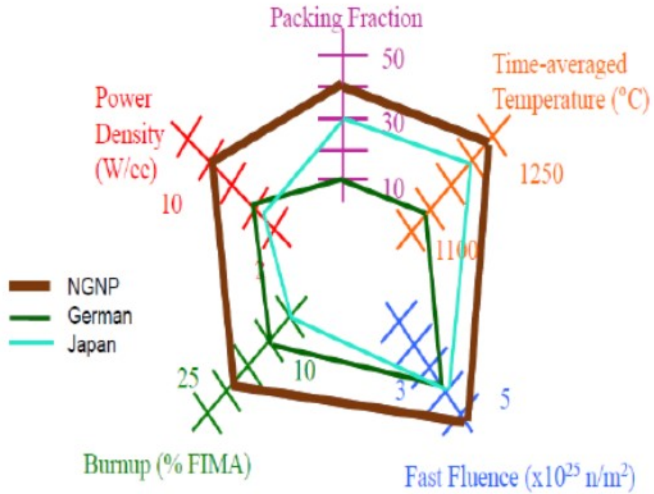
Adapted from http://www.addletters.com/bart-simpson-generator.htm#.XfcRqOhKiDk

TRISO Particles act as individual fission product "Containments" for Gas-Cooled Reactors



AGR Program Goal: Qualify TRISO UCO fuel in a performance envelope that is larger, more aggressive than previous German, Japanese fuel qualification experience

TRISO Fuel Service Conditions



TRISO coated particle fuel performance and fission product retention is the KEY FACTOR for making the HTGR/VHTR/NGNP Safety Case

Advanced Gas Reactor TRISO Fuel Qualification Program

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Objectives and motivation

- Provide data for fuel qualification in support of reactor licensing
- Establish a domestic commercial vendor for TRISO fuel

Reduce market entry risk

Approach

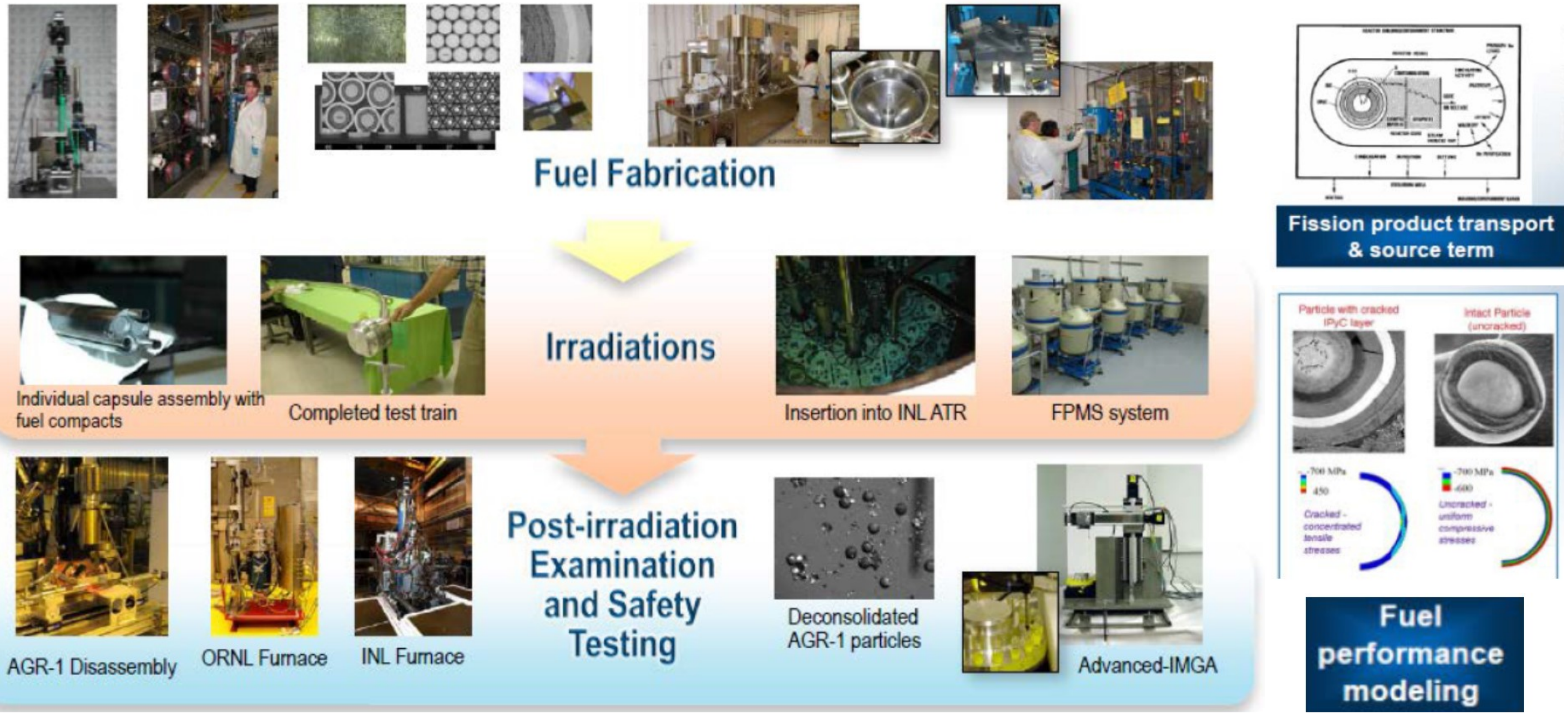
- Focus is on developing and testing **UCO** TRISO fuel
  - **Develop fuel fabrication and QC measurement methods**, first at lab scale and then at industrial scale
  - **Perform irradiation testing** over a range of conditions (burnup, temperature, fast neutron fluence)
  - **Perform post-irradiation examination and safety testing** to demonstrate and understand performance during irradiation and during accident conditions
  - **Develop fuel performance models** to better predict fuel behavior
  - **Perform fission product transport experiments** to improve understanding and refine models of fission product transport

Advanced Gas Reactor TRISO Fuel Qualification Program Approach (cont.)

Fuel Qualification

- Irradiation
  - Demonstrate we can meet in-service failure rate specification at 95% confidence (~ 1E-05)
    - Statistics dictate particle population (300,000-400,000)
    - Bound reactor service envelope (temperature, burnup, fluence)
    - Qualified data for key measurements with defensible uncertainties
    - Validate the fuel specification (proof test) in an integral sense
- Accident Safety
  - Demonstrate we can meet in-service failure rate specification at 95% confidence (e.g., ~1E-04 at 1600°C)
  - Statistics dictate particle population (4,000-20,000) at a given temperature. Focus on 1600°C but have good statistics at 1700 and 1800°C
  - Other issues
    - Moisture and Air Ingress Effects
    - Reactivity Insertion Event Testing if needed
    - Reactivation of short-lived dose-important isotopes, e.g., Iodine-133

Advanced Gas Reactor TRISO Fuel Qualification Program



Advanced Gas Reactor TRISO Fuel Qualification Program

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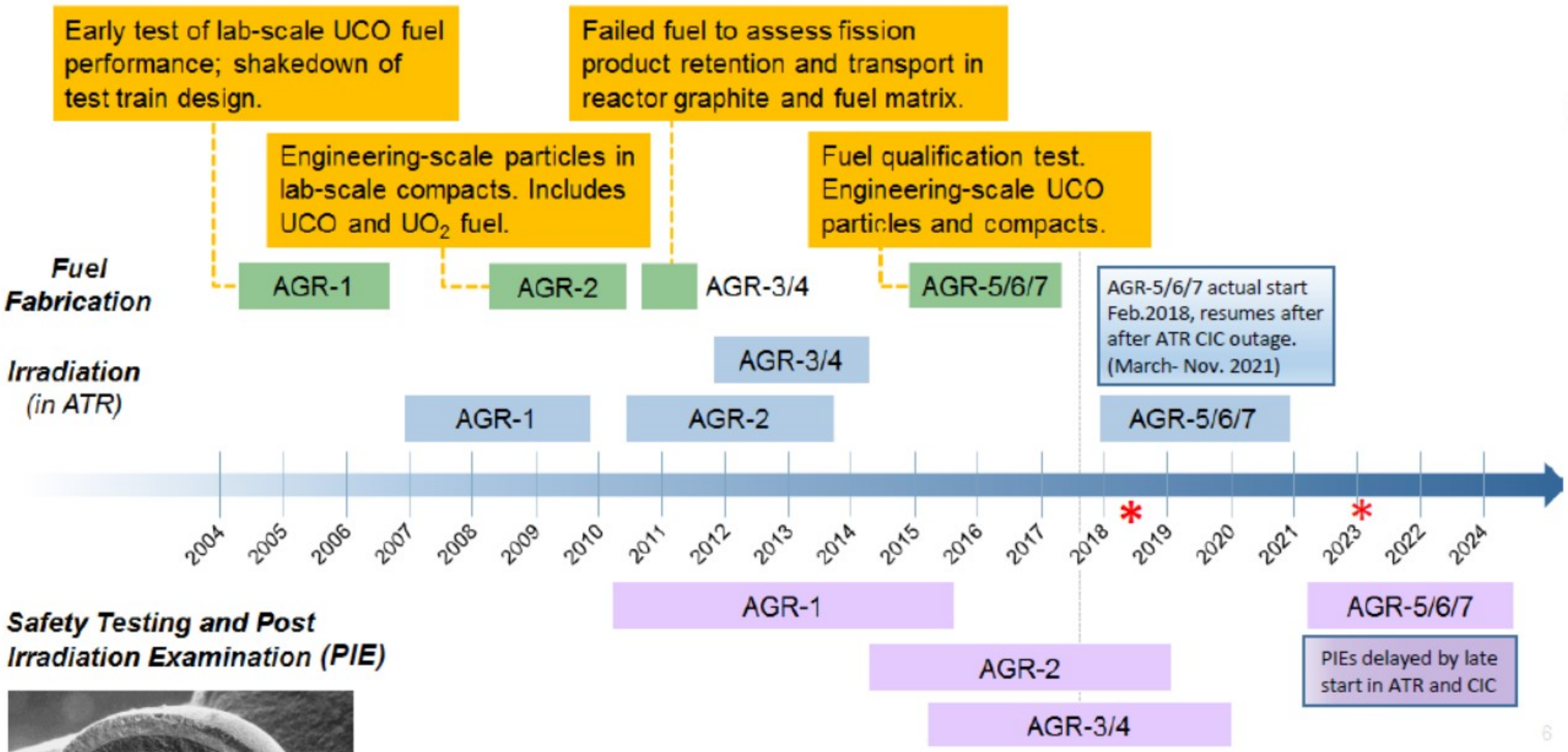
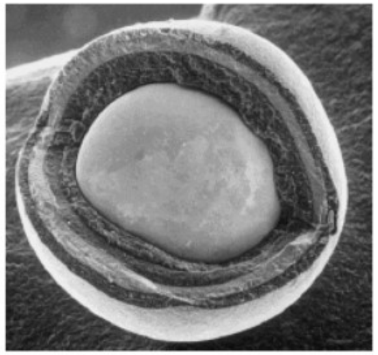




Goal: ***Re-establish U. S. TRISO fuel production capability***

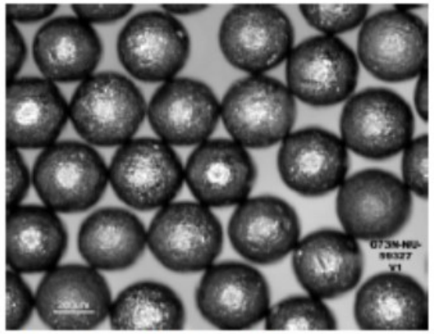
Oak Ridge National Laboratory — Lab Scale fabrication

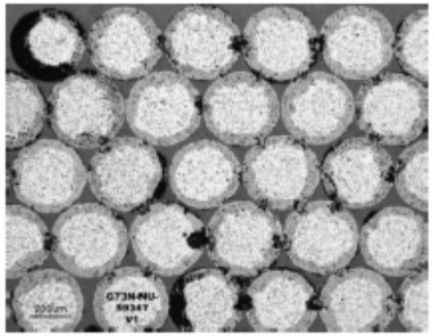
BWXT — Engineering Scale fabrication

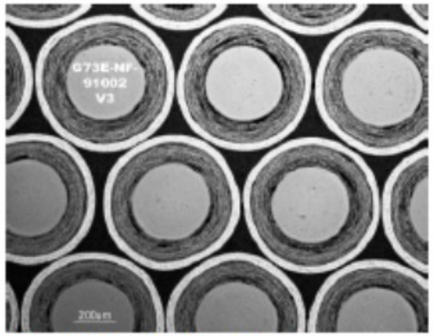
INL — Advanced Test Reactor Tests

Oak Ridge National Laboratory, INL — Both labs perform PIEs, Safety Heat Up Testing

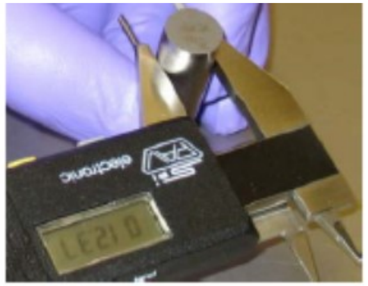
AGR TRISO Particle Fuel Fabrication Development

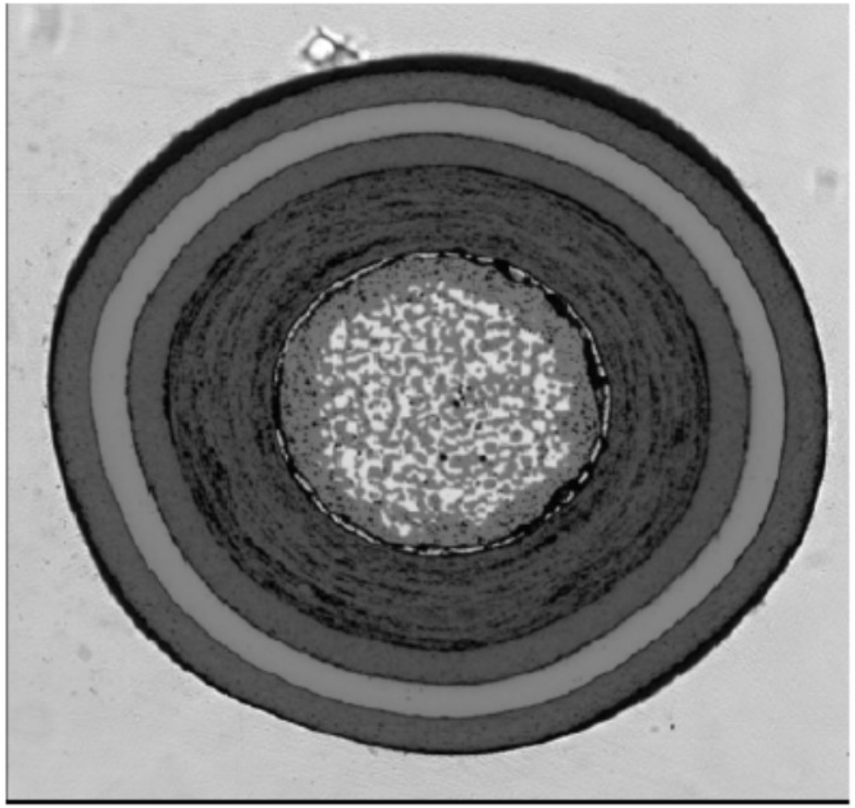

Loose kernels


Sintered kernels


Buffer/IPyC Particles

- **Lab Scale Fabrication (ORNL)**
  - Established baseline for UCO kernels, TRISO coating, and cold pressing compacts
- **Kernel Fabrication (B&W)**
  - Established baseline for UCO
  - Kernel chemistry improvement has been completed
- **Coating Development (B&W)**
  - Completed coater activities using surrogate and UCO kernels
- **Compacting Development (B&W)**
  - Automated over-coating of TRISO particles
  - Improved handling/process parameters
  - Automated compacting to produce excellent compacts





Advanced Gas Reactor TRISO Fuel Qualification Program

- B&W completed qualification studies for AGR TRISO fuel particle and compact manufacturing process in March 2012.
- B&W's completely automated compacting machine can make high packing fraction, very dense compacts ~5-10 per minute.
- B&W made AGR-5/6/7 fuel specimens during FY 2014-2016.

B&W's Industrial Scale Line for Kernel Production, TRISO Coating, Matrix Overcoating and Compacting Processes

Advanced Gas Reactor TRISO Fuel Qualification Program

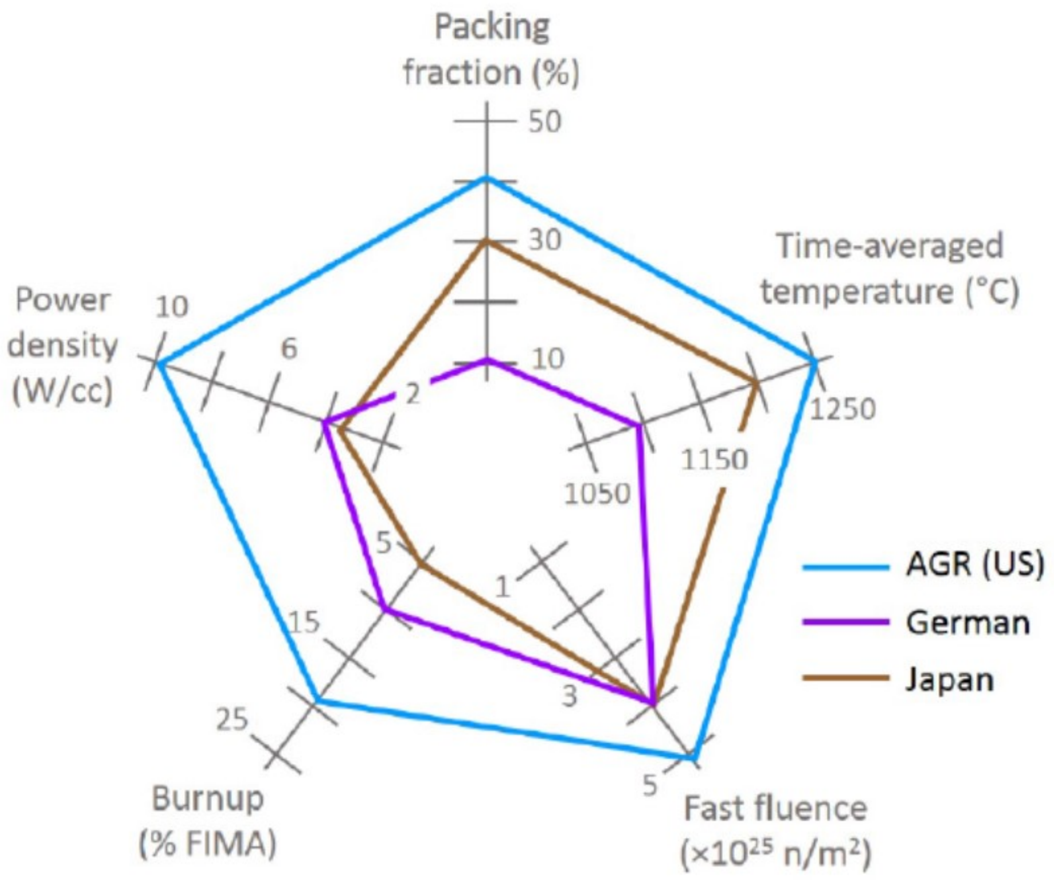
AGR-1: Shakedown capsule, ORNL lab-scale fuel, to show new process parameters could fix historical fuel fabrication problems
AGR-2: Demonstrate engineering scale UCO and UO2 TRISO particle performance, with lab-scale compacting, that fuel works at very high temperature gas cooled reactor (VHTR) service conditions.
AGR-3/4: Designed-to Fail particles (20) in center of compact with driver fuel in ORNL compacts.
AGR-5/6/7: Fuel produced in fuel vendor's pilot fuel fabrication line, is qualified for reactor operating envelope and safety margin conditions with 95%/95 confidence statistical quantities of fuel

AGR Fuel Fabrication and Experiments

Experiment	Purpose	Kernel Fabrication	TRISO Coating	Overcoating Compacting
AGR-1	Shakedown/ early fuel experiment	Engineering	Laboratory	Laboratory
AGR-2	Performance test fuel experiment	Engineering	Engineering	Laboratory
AGR-3/4	Fission product transport experiments	Engineering	Laboratory	Laboratory
AGR-5/6/7	Fuel qualification and fuel performance margin testing experiments	Engineering	Engineering	Engineering

Advanced Gas Reactor TRISO Fuel Qualification Program

Targeted Fuel Performance Envelope



- Program goal is to qualify fuel to a performance envelope that is more aggressive than previous German and Japanese qualification efforts

AGR TRISO Program Performance Envelope Parameter Values Exceed and Bound TRISO-fueled High Temperature Gas Reactor Designs

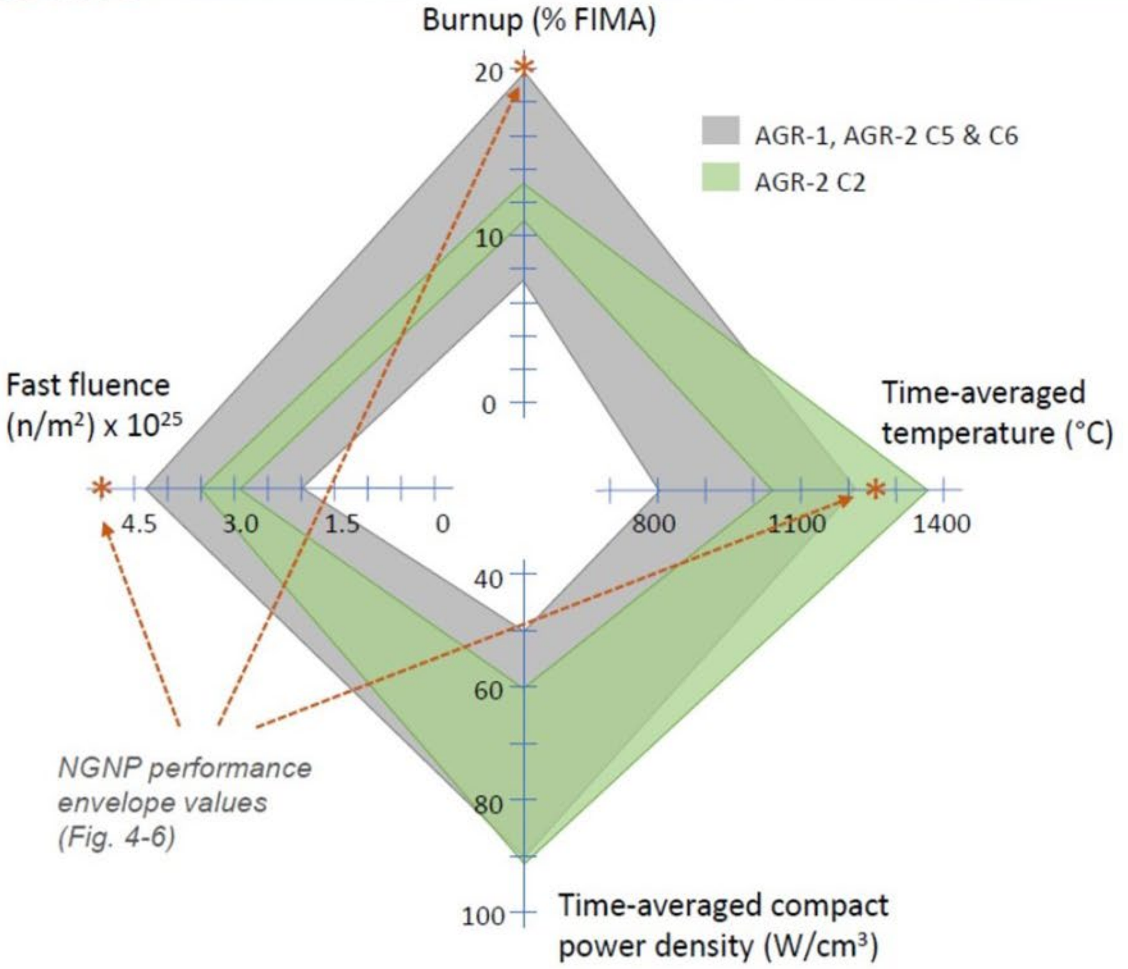
Advanced Gas Reactor TRISO Fuel Qualification Program

AGR-1 and AGR-2 Irradiation Conditions

- Data combined into two sets
  - AGR-1 and AGR-2 Capsules 5 and 6
  - AGR-2 Capsule 2 (higher temperature)

Property	AGR-1 + AGR2 C5&6		AGR-2 C2	
	Max	Min	Max	Min
Burnup (%FIMA)	19.7	7.3	13.2	10.8
Fast fluence ($n/m^2 \times 10^{25}$)	4.30	1.94	3.47	2.88
Time-average temperature (°C)	1210	800	1360	1034
Time-avg compact power density (W/cm^3)	90.2	50.2	92.1	59.9
Time-avg compact power density (mW/particle)	66[a]/86[b]	37[a]/48[b]	88	71

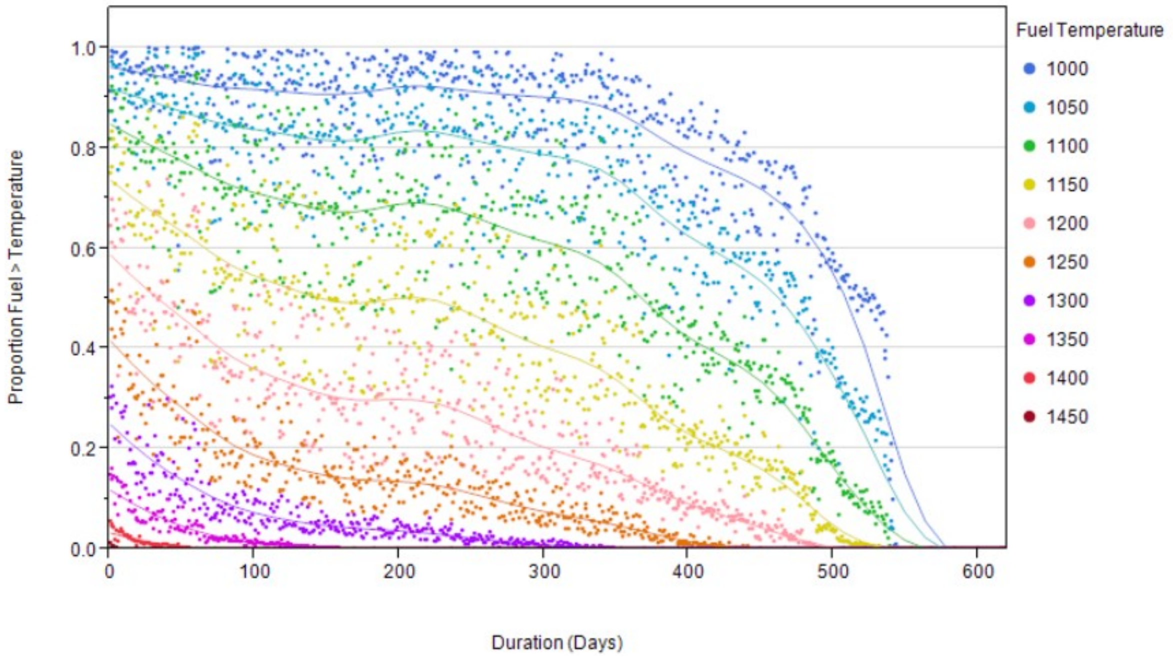
a. AGR-1 values
b. AGR-2 C5 and C6 values

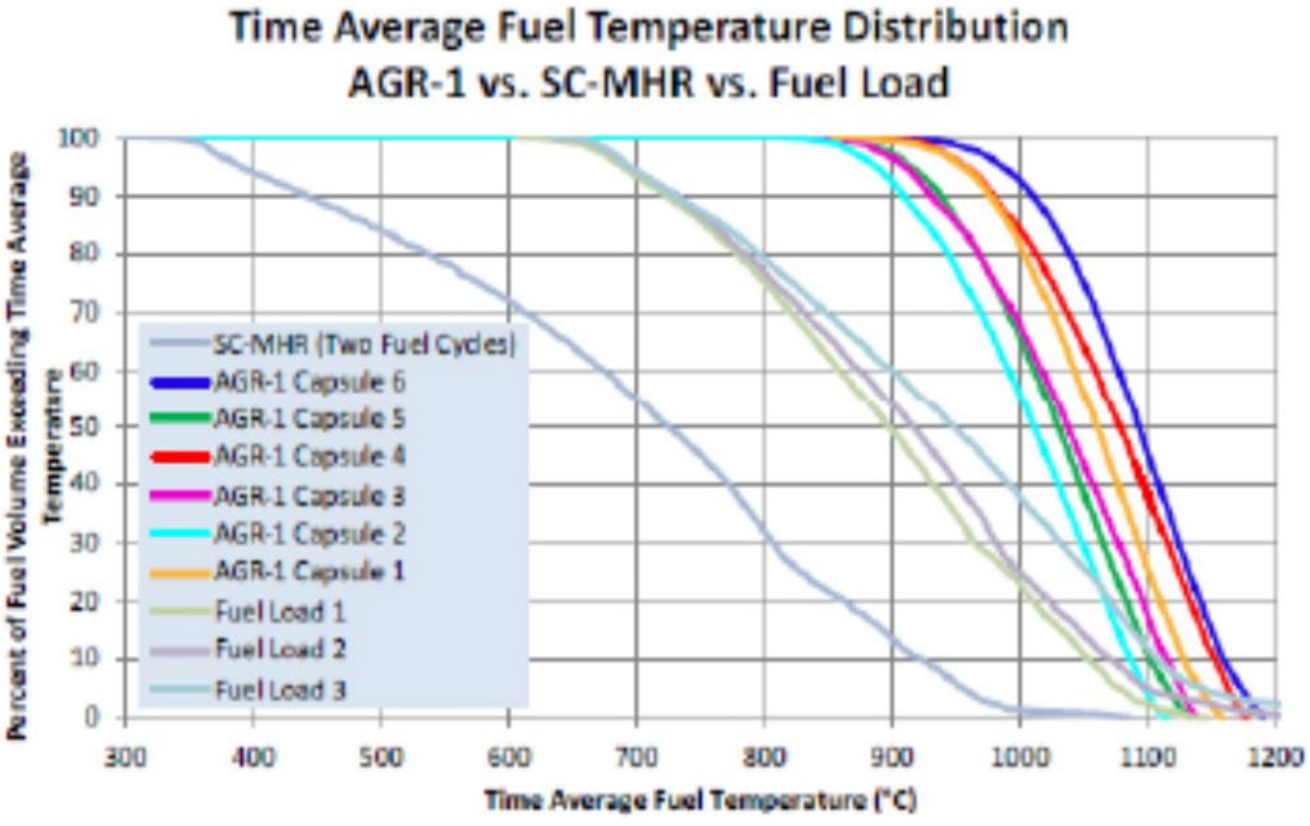


Advanced Gas Reactor TRISO Fuel Qualification Program

AGR-1 Time at Temperature

10% of the AGR-1 fuel experienced temperatures of 1300°C for 100 to 200 days, and a few percent experienced temperatures in excess of 1400°C for 50 days.



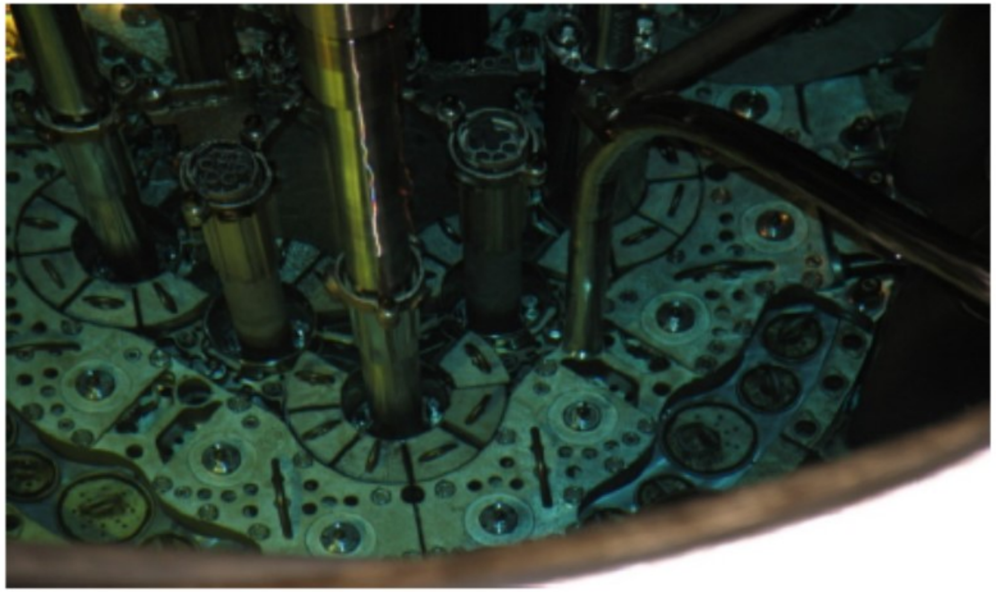


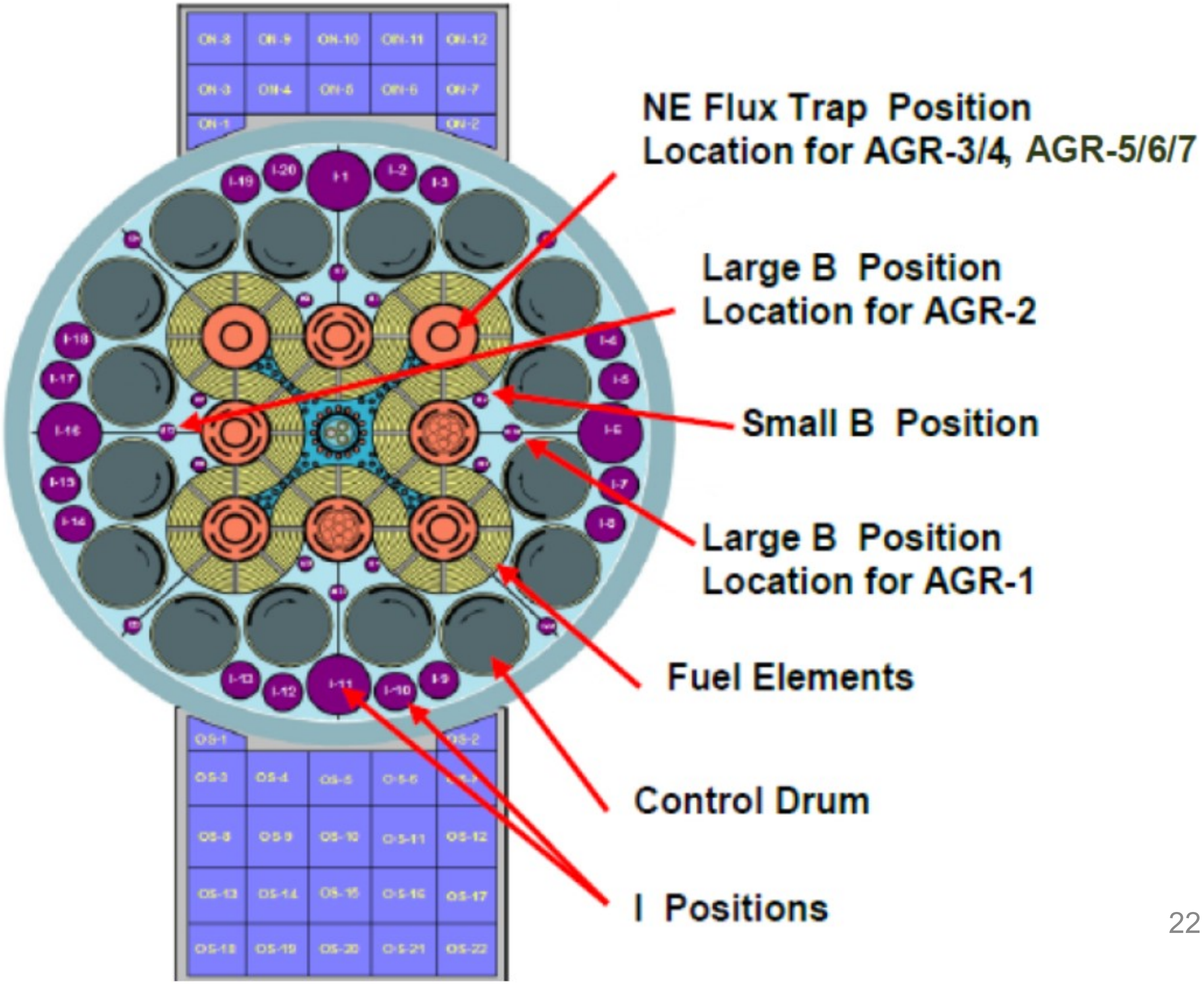
AGR Experiments Fuel Temperature "waterfall" vs. TRISO Fuel Temperatures in HTGRs

Advanced Gas Reactor TRISO Fuel Qualification Program

AGR TRISO Fuel Irradiation Experiments

- **AGR-1**
  - Irradiation campaign Dec. 2006 – Nov. 2009
    Completed PIE, safety tests in 2014
- **AGR-2**
  - U.S. UCO and UO2 TRISO particles
    Includes commercially-made French compacts and S. African particles
  - Irradiation June 2010--Nov. 2013
  - Begin PIE, safety tests in FY 2014



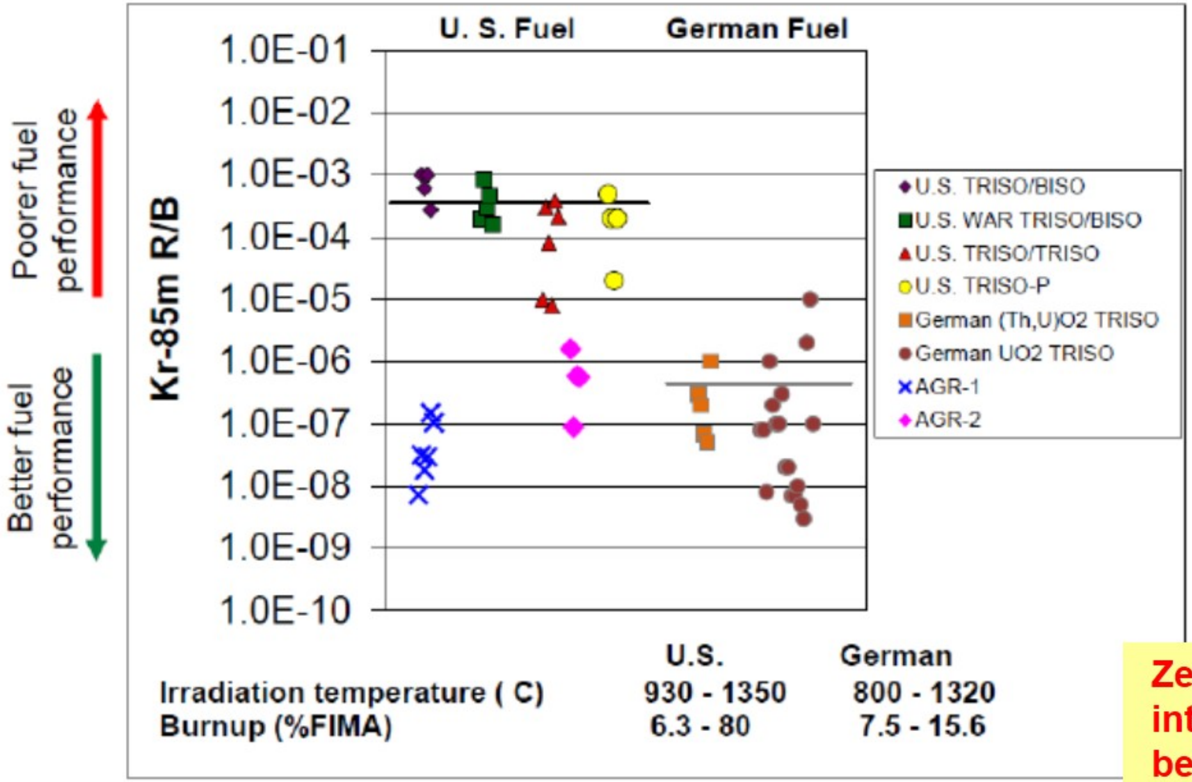


Advanced Gas Reactor TRISO Fuel Qualification Program

AGR-1 and AGR-2 Irradiation Test Results

AGR Fuel Irradiation Performance

German fuel has historically demonstrated ~1,000 times better performance than U.S. fuel.



Plot of Kr-85m release-to-birth ratio for various fuel types

AGR-1:
- Zero TRISO failures out of ~300,000 particles in the experiment
- Peak burnup ~20% FIMA

AGR-2
- 0 or 1 exposed kernel at beginning of irradiation in each capsule
- Possibility of small number of failures during irradiation

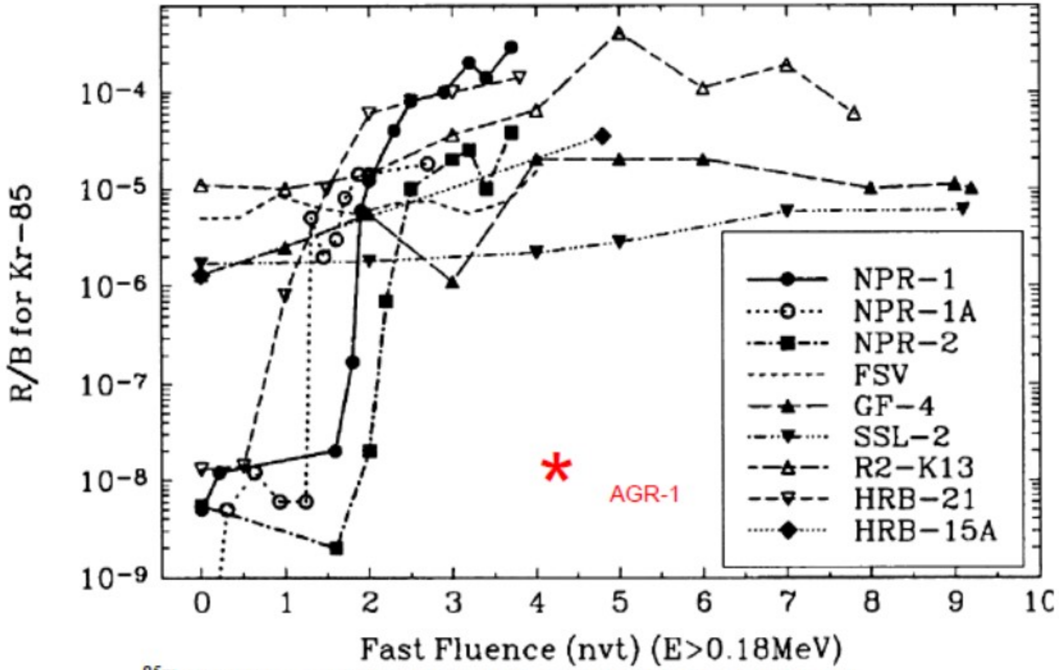
- **AGR-1 and AGR-2 Irradiation Results show UCO effectively controls CO gas production, kernel migration**

Zero AGR-1 capsule fuel failures (low Kr-85m R/B) translates into a 95%/95 confidence failure fraction of <1 E-5 or 20 times better than NGNP failure fraction requirement of 2 E-4 !!

Today, in-reactor AGR TRISO fuel performance is as good as German fuel at twice the burnup

Advanced Gas Reactor TRISO Fuel Qualification Program

US Historical TRISO Fuel Experience vs. AGR-1 fuel performance

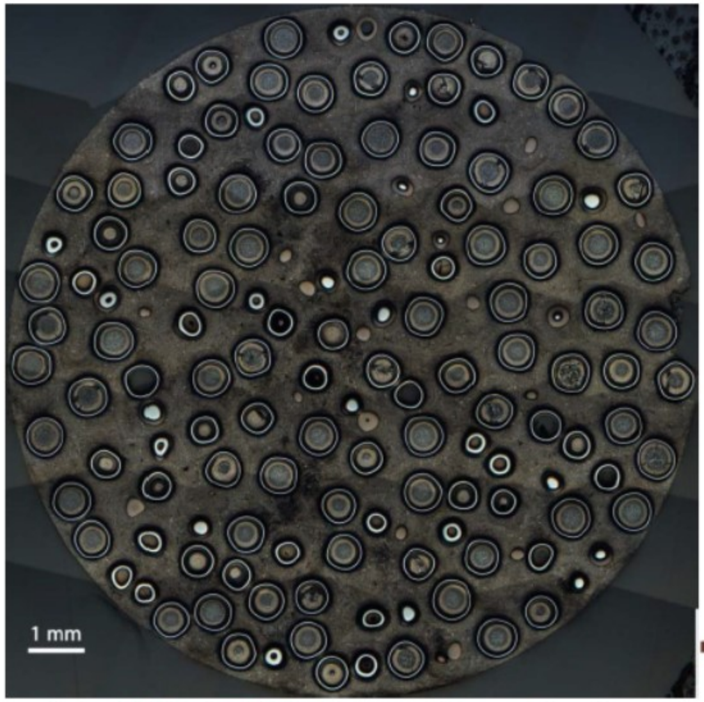


^{85m}Kr R/B versus fast fluence for various U.S. irradiations.

- Earlier US TRISO fuel experienced early particle failures under irradiation
- NPR and MHTGR capsules failed at ~1.7 x 10^{25} n/m2.
- AGR-1 (11/6/09) reached 4 x 10^{25} n/m^2 peak fast fluence (E>0.18) MeV and 19 % FIMA peak burnup, 16 % FIMA average burnup at 610 EFPD.

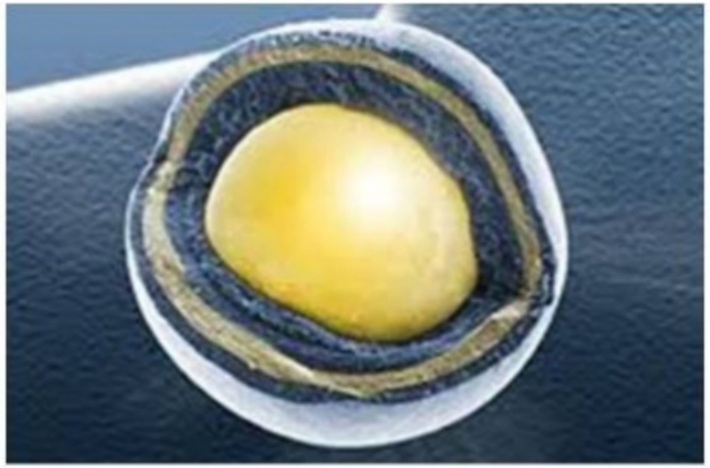
Advanced Gas Reactor TRISO Fuel Qualification Program

AGR-1 Post Irradiation Evaluations – Ceramography and Safety Testing

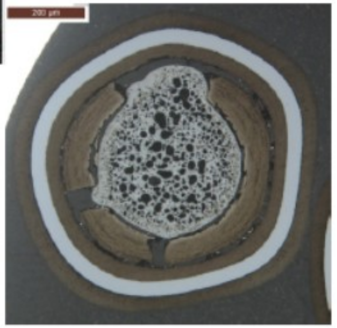


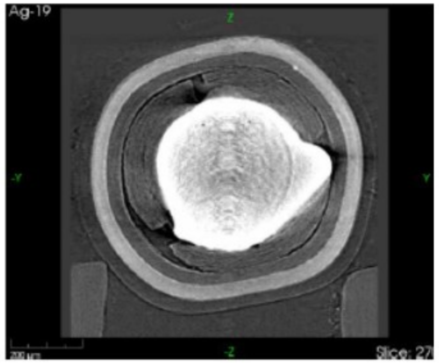
Irradiated AGR-1 TRISO Compact Cross Section
AGR-1 Compact 2-1-3, at 18% FIMA burnup
All SiC coating layers are still intact!!!

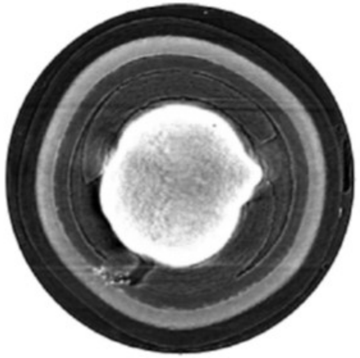
- AGR-1 PIE includes ceramography, SEM, TEM, chemical analyses, gamma-scanning and safety heat-up testing in furnaces at INL and ORNL.
- AGR-1 PIEs characterize kernel and coating condition to better understand irradiation effects
- PIE methods provide microscopic details of isotopic migration and fuel damage effects



TRISO coated particle fuel





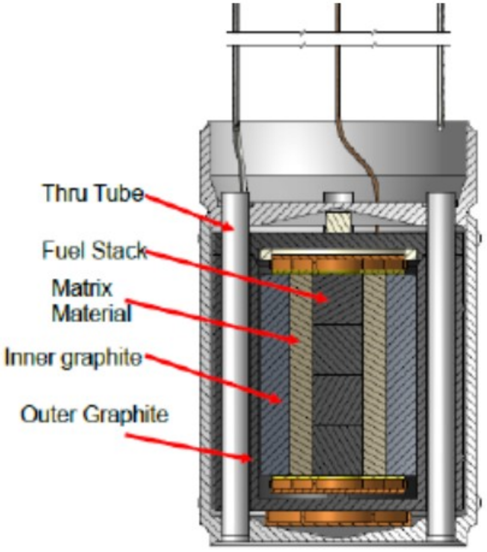


X-ray tomogram of an irradiated AGR-1 particle with fission product attack on its SiC layer

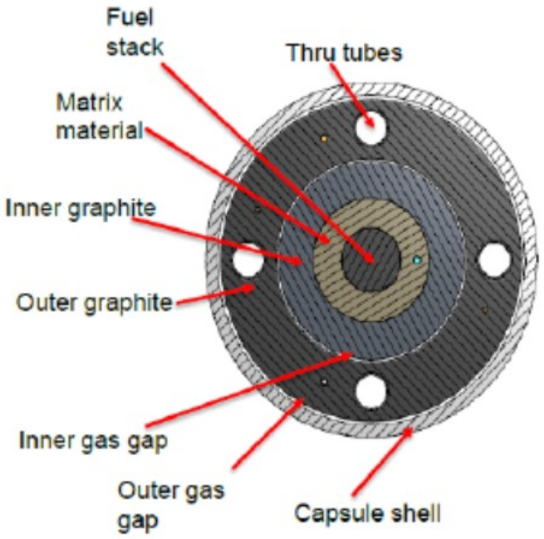
Advanced Gas Reactor TRISO Fuel Qualification Program

AGR TRISO Fuel Irradiation Experiments

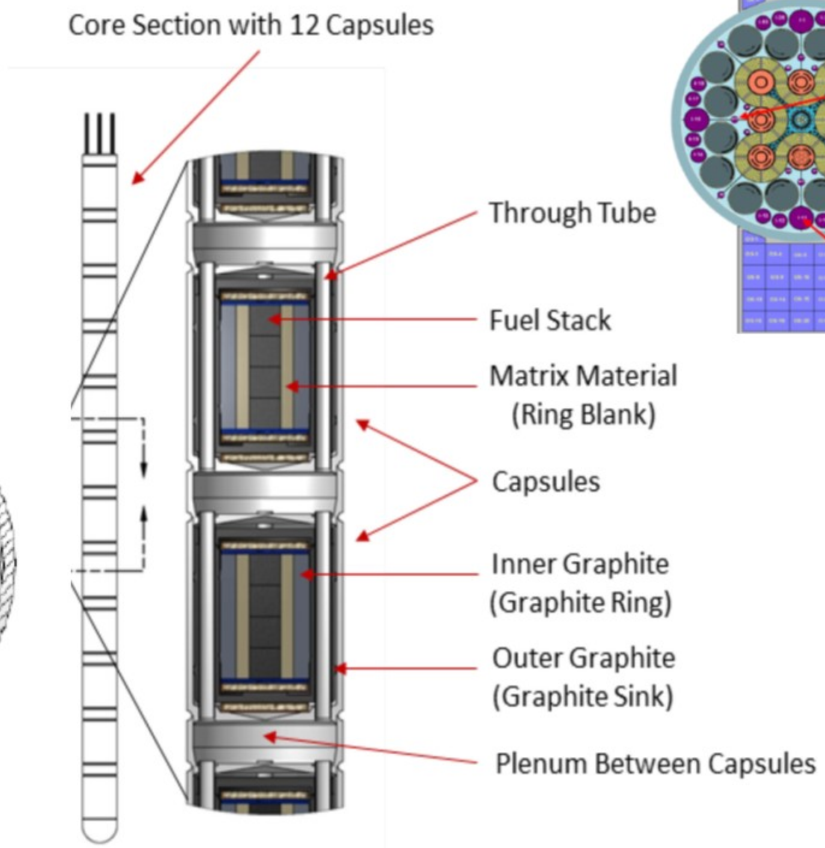
- **AGR-3/4**
  - Contains driver fuel and “designed-to-fail” TRISO particles in center of compact
  - Irradiation Dec. 2011—April 2014 in the ATR Northeast flux trap (NEFT)
  - NEFT replicates VHTR thermal flux and lower power density conditions
  - DTF particles began to fail as predicted by Jan. 5 2012

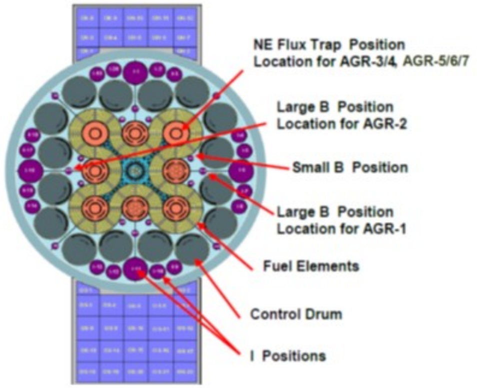


Standard Capsule



AGR-3/4 Capsule Cross Section



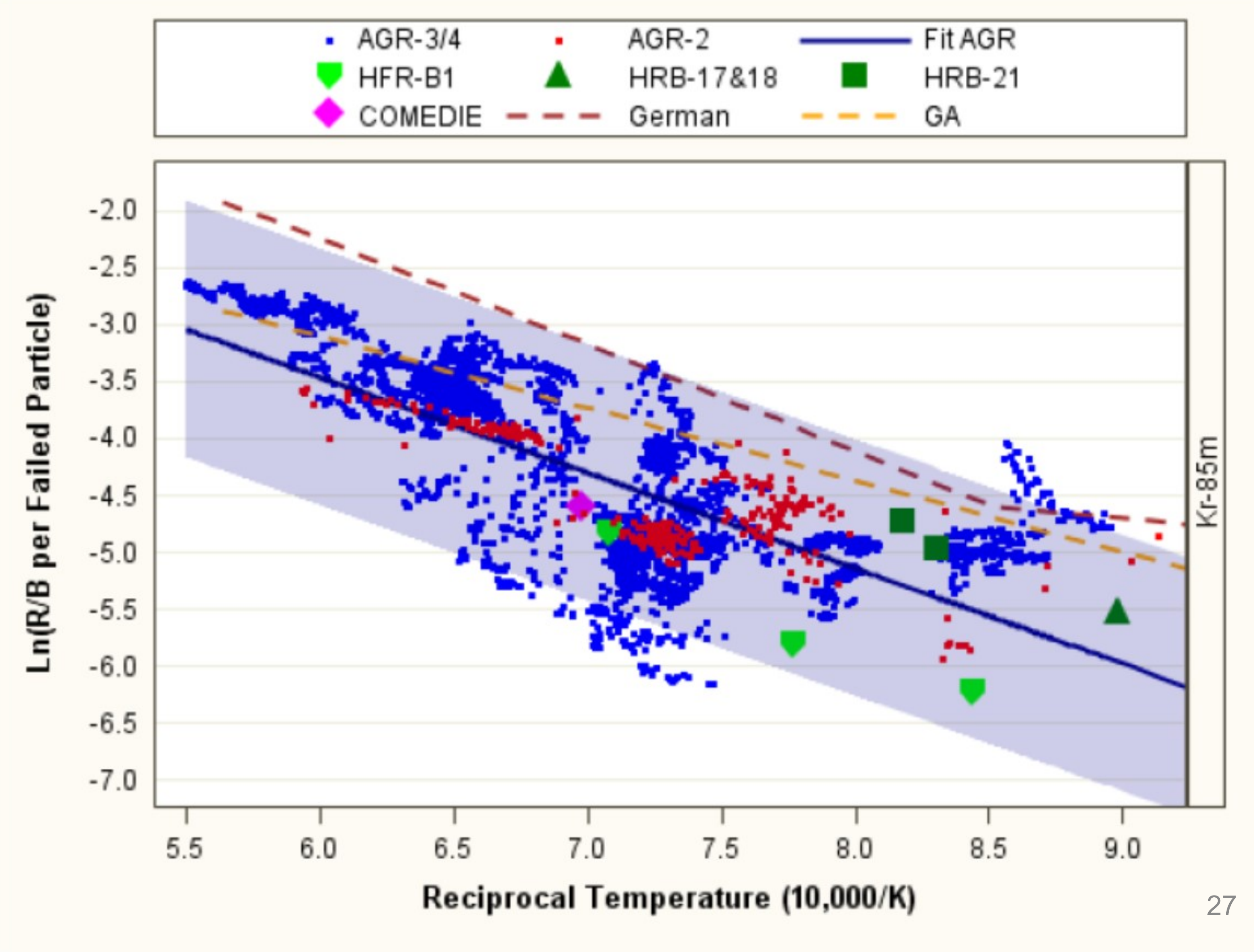


AGR-3/4 has 12 axial capsules

Advanced Gas Reactor TRISO Fuel Qualification Program

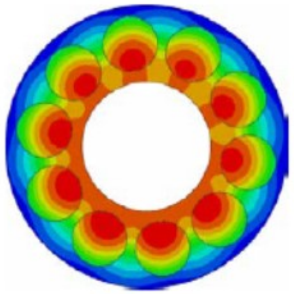
AGR-2, AGR-3/4 R/B per failed particle vs. historical tests:

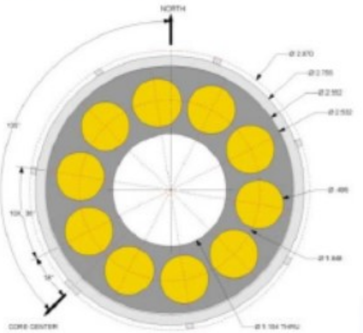
- AGR-2, AGR-3/4 consistent R/B data, comparable to historical tests.
- AGR fuel has lower correlated R/B as a function 1/T, showing robust performance.
- AGR-3/4 results be used by HTGR designers to estimate fission gas releases for source term calculations.
- Combined AGR fitted line and R/B per failed particle data for AGR irradiations, historical irradiations, and models (the blue shaded area is 95% bounds of the fitted line).



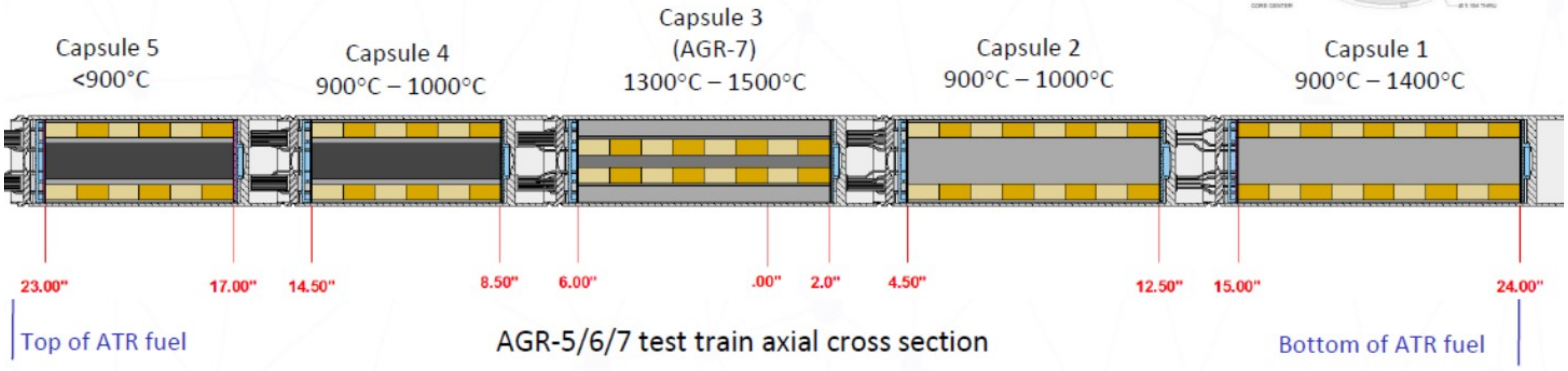
AGR-5/6/7 irradiation test

- Final AGR program fuel qualification irradiation; demonstrate performance of fuel fabricated on an engineering-scale pilot line
- Fuel performance margin test (AGR-7); extremely high irradiation temperature
- 194 UCO fuel compacts (~570,000 particles)
- Burnup: ~6-18% FIMA
- Fast fluence: ~$1.5\text{-}5 \times 10^{25}$ n/m^2
- Compact average temperatures (AGR-5/6): 600 – 1400°C
- Peak temperature (AGR-7): 1500°C
- Irradiation started Feb 2018

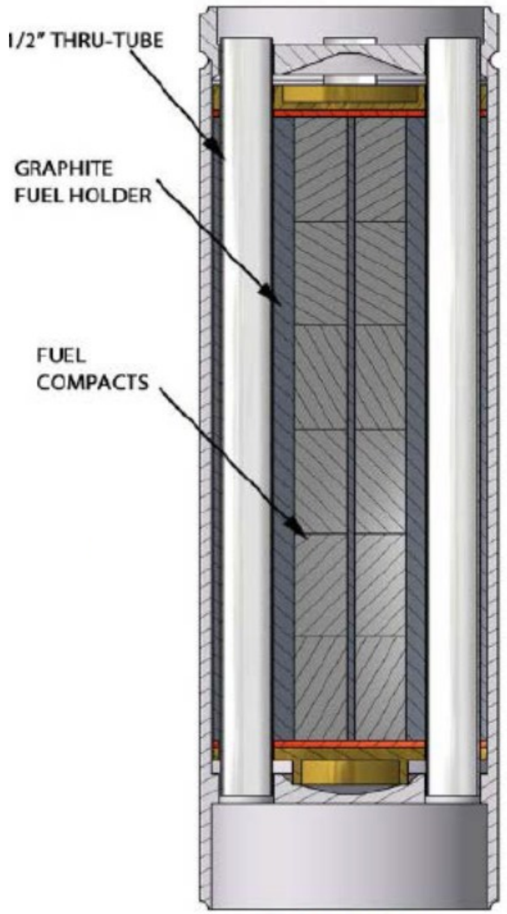




Capsule 1



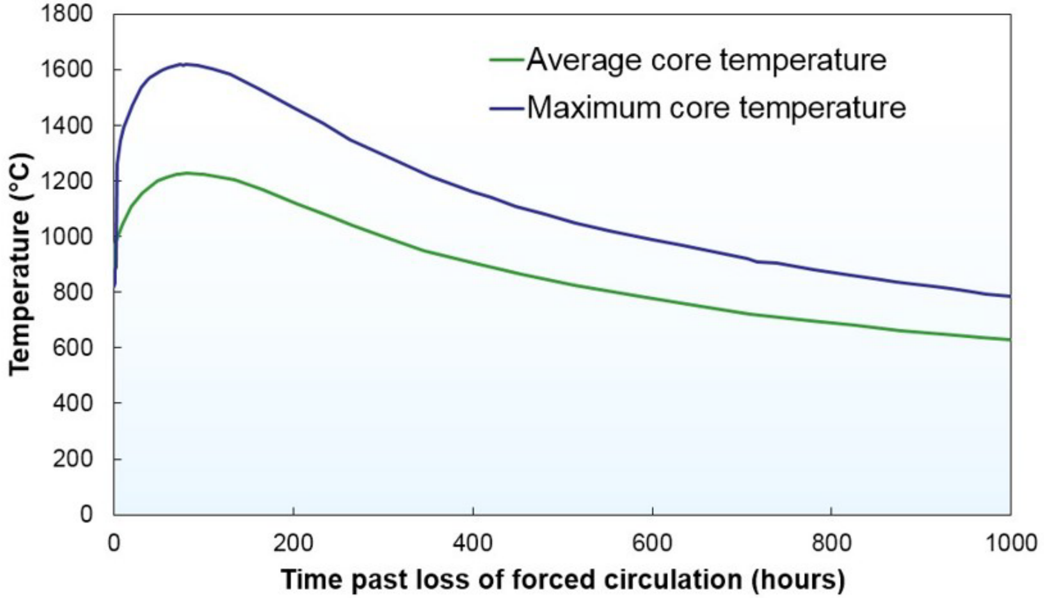
AGR-5/6/7 test train axial cross section

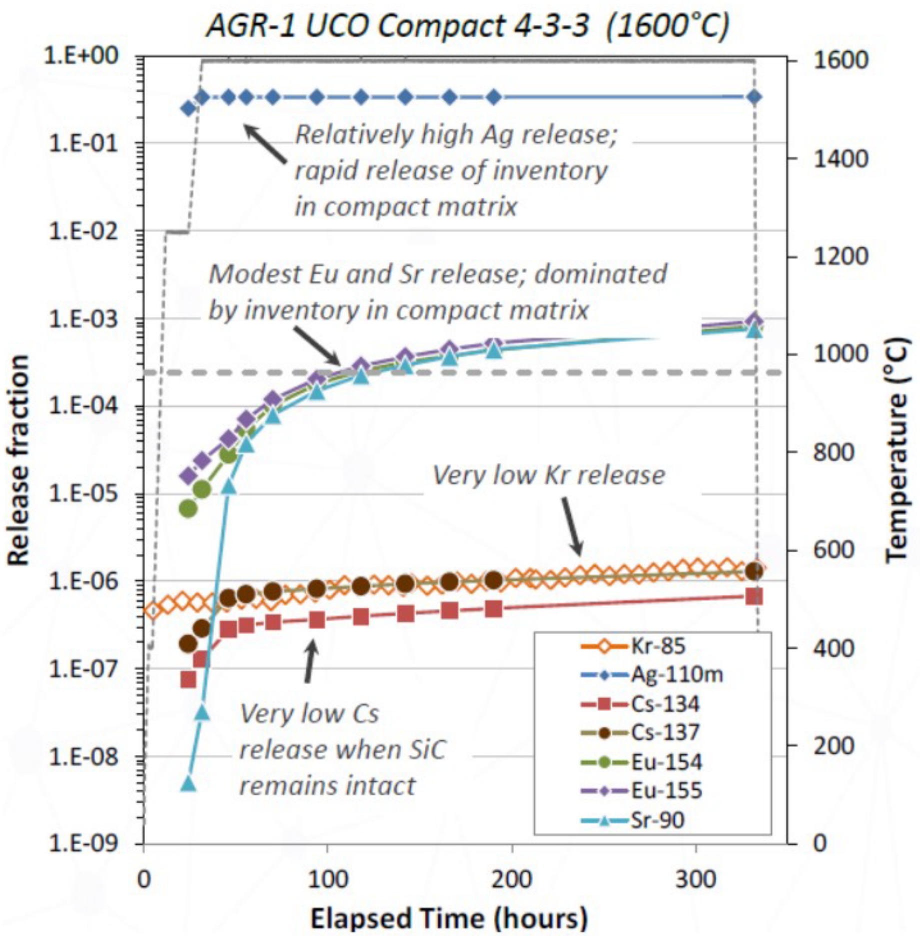


AGR-5/6/7 Representative Capsule

High Temperature Accident Safety Testing of TRISO Fuel

- HTGR temperature transients are relatively slow (20 days), with only a small fraction of the fuel at or near peak temperatures (hours).
- Peak fuel temperatures are limited to ~1600°C in modular HTGR designs
- Fuel particles are designed to withstand accident conditions while still retaining key safety-significant fission products
- Assess fuel performance by measuring fission product releases in post-irradiation tests in dedicated furnaces at 1600-1800°C



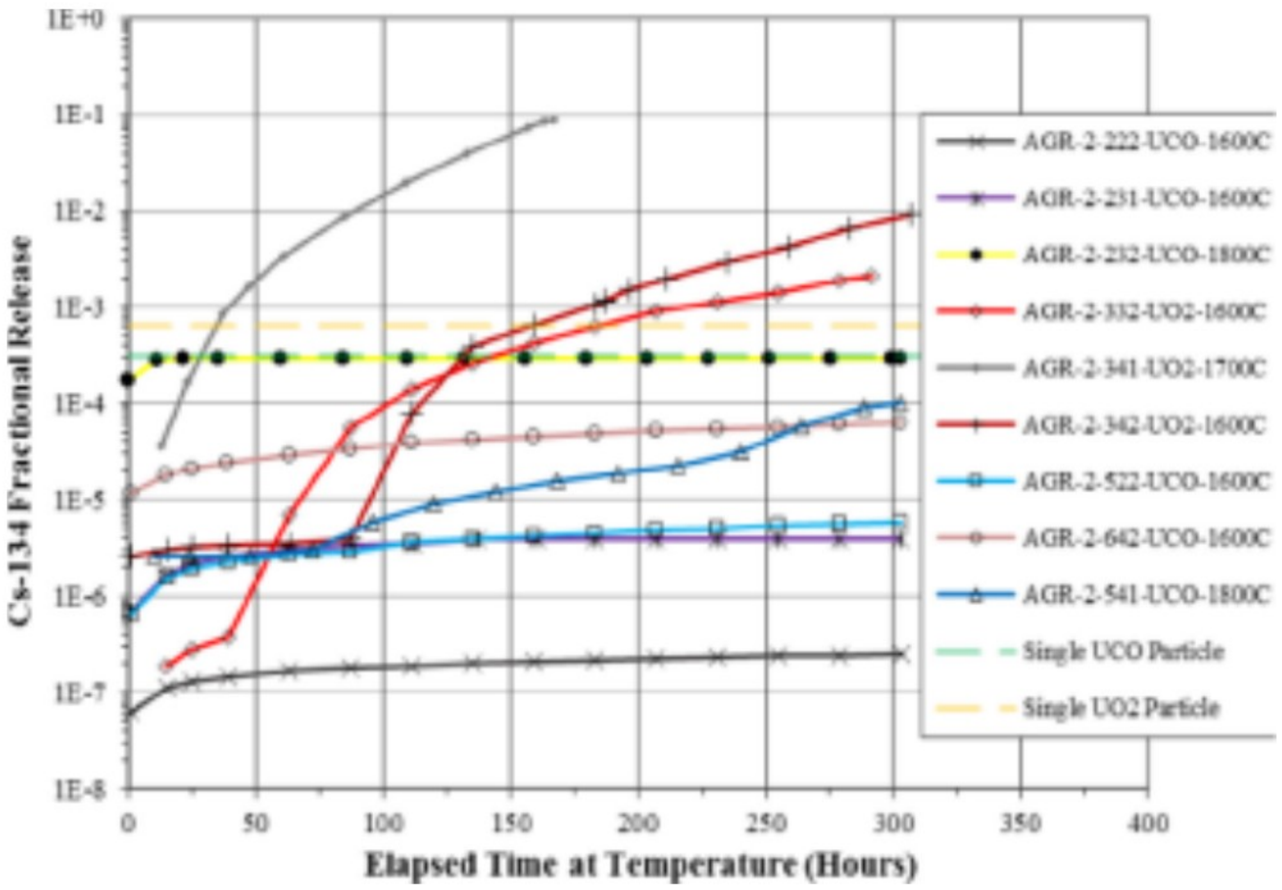


AGR TRISO fuel has successfully survived 300+ hour safety tests at 1600 C, 1700 C, and 1800 C.

High Temperature Accident Safety Testing of TRISO Fuel

- No UCO particle failures were detected by continuous online monitors during AGR-1 and AGR-2 irradiation tests.
- No AGR-1 TRISO failures were observed in the 1600–1700 °C safety tests, and failure rates between 1700 and 1800 °C were far lower than vendor performance requirements.
- AGR-2 UCO fractional release of Cs-134 remained under 1.E-3 (single particle release) for 1600, 1700 and 1800 °C safety tests.
- Higher AGR-2 in-pile irradiation temperatures resulted in higher Europium and Strontium release rates.
- AGR-2 UO2 failed for 1600, 1700 and 1800 °C safety tests within 200 hours.

AGR-2 **UCO** TRISO fuel has successfully survived 300 hour safety tests at 1600 C, 1700 C, and 1800 C.



AGR-2 UCO and UO2 Cs-143 release from compacts

Advanced Gas Reactor TRISO Fuel Qualification Program

AGR TRISO Fuel Program Path Forward

Activity	Objective	Timing
Complete AGR-2 PIE and safety testing	• Verify performance of pilot-scale TRISO fuel • Compare UCO to UO_2 performance	2020
Complete AGR-3/4 PIE	• Collect necessary fission product transport data to refine source term models	2022
Complete AGR-5/6/7 irradiation, PIE, and safety testing	• Verify performance of pilot-scale fuel made at commercial vendor	2021, after CIC by 2023
Perform key safety tests in oxidizing atmospheres (AGR-2, AGR-3/4, and AGR-5/6/7 specimens)	• Verify TRISO performance in oxidizing atmospheres • Determine effect of oxidizing atmospheres on fission product release from exposed kernels, matrix, and graphite	2020- 2024
Code comparisons to data Support NRC interactions on licensing	• Assess model effectiveness and refine models	2020-2024

Submitted FIRST AGR TRISO Topical Report to NRC May 2019, expected NRC Safety Evaluation Report June 2020.

Anticipated future topical reports: (1) AGR-3/4 fission product transport in 2023, source term, (2) AGR-5/6/7 results in 2025.

Beyond the AGR TRISO Program

Moving from BWXT Pilot Scale to Full Scale Commercial NRC-Licensed Fabrication

TRISO fuel vendors:

- **X-energy** pilot line at ORNL
- **X-TRISO** facility under design
- **BWXT** removed AGR TRISO pilot scale equipment, but intends to rebuild capability
- TRISO fuel vendor’s commercial “proof fuel” will need to be irradiated (“AGR-8”), PIEs and safety tested under NRC’s 10 CFR Appendix B Rule, and will be compared to AGR TRISO Program results

Beyond the AGR TRISO Program

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Can TRISO fuel be used in other reactor designs?

- Molten Salt-cooled (e.g., FLiBe, FLiNaK,) reactor concepts use graphite matrix TRISO fuel directly, e.g. Kairos Power based on University of California – Berkeley pebble bed design

- Fast Gas Reactors, using SiC or other non-graphitic matrix compacts
  - French helium fast gas design ZrO_2 coating
  - UC fuel kernels in metallic cladding
  - GA's EM^2 alternate design

- Encapsulated fuel for LWR Accident Tolerant Fuel
  - TRISO in SiC matrix with SiC tubes or Zircalloy cladding (ORNL)

- Fast sodium/metal cooled reactors
  - Dispersion fuels, TRISO-like fuel in metallic matrix, metallic clad
  - TRISO in SiC Mixed Oxide fuel pellets (FFTF or MOX cores)

- Extreme high temperature reactors using refractory metals, UC or UN fuels
  - Space reactors, or niobium (Nb), tantalum (Ta), molybdenum (Mo), rhenium (Re), vanadium (V) and tungsten (W) alloys.

Beyond the AGRTRISO Program

Reactor Design Concepts and Advanced Fuel Designs Using TRISO Fuel

Company or Research Group	TRISO Fuel Form, Reactor Type, Design Concept	Deployment (target date)
Near-term Fuel and Reactor Concepts		
X-Energy	TRISO pebble bed HTGR **Xe-100 Reactor, TRISO-X fabrication facility** (Current funding: ART-15, 2 Industry FOAs, ORNL CRADA at $11.5M); Collaboration with Global Nuclear Fuel for DOD Micro-reactor and NASA nuclear thermal propulsion for space exploration. Collaboration with Centrus for X-energy TRISO fabrication facility	2024-2030
NGNP Alliance/**AREVA**	TRISO compacts, prismatic TRISO fueled HTGR **SC-HTGR** (steam cycle)	2027-2030
NC-II **AREVA** (Poland)	TRISO compacts, prismatic HTGR **SC-HTGR** (steam cycle) for Europe, Poland	2027-2030
Dept. of Defense	TRISO fueled mobile micro-reactors for strategic combat locations. Possible designs: HALOS, GA-vSMR, BWXT Nuclear, etc.	2025 demo 2028 FOAK
BWXT	TRISO fuel fabrication for DOD microreactors, Potential DOD microreactor	2022 (DOD)
Kairos Power	TRISO pebble bed, fluoride salt (Li_2BeF_4) cooled FHR, 3 cm dia. Pebbles, **Mark 1 Pebble-Bed FHR** (DOE Funding: 2 Industry FOAs announced)	2030 Demo, 2035 FOAK
Urenco, Amec Foster-Wheeler	TRISO compacts, prismatic HTGR, UCO or Th/U/O TRISO kernels for **U-Battery** 10 MW and 20 MW. Canadian review underway	2025 Demo 2030 FOAK
StarCore Power (USA)	TRISO in graphite matrix pebbles, helium-cooled HTGR, 20 or 80 MW, **STARCORE 20, STARCORE 80,** StarCore Nuclear (Canada) Canadian review underway.	2025-2030
General Atomics	UC bare kernels in SiC tubes. May use TRISO-like coating(s) as an optional design for fast-gas reactor **Energy Multiplier Module (EM^2)**	2030-2035
ORNL Accident Tolerant Fuel	FCM TRISO particles in SiC matrix pellets inside Zr, SiC or Stainless Steel cladding, as future LWR **ATF replacement** fuel	2030-2035
Longer-term Fuel and Reactor Concepts		
NASA	TRISO fueled compact reactor for future long-range missions for Mars for Space Nuclear Thermal Propulsion (UC or UN)	
MIT (Forsberg)	TRISO compacts, prismatic HTGR Fluoride salt (Li_2BeF_4) cooled FHR	
UltraSafe Nuclear	Various TRISO fuel forms: FCM TRISO in SiC matrix pellets in SiC tubes to replace LWR fuel pins, CANDU bundle rods, TRISO with refractory coatings for Space Applications, Canadian review underway.	

Abbreviations:
FCM Fully Ceramic Micro-Encapsulated
CANDU Canadian Deuterium U reactor
HTGR High Temperature Gas Reactor
LWR Light Water Reactor

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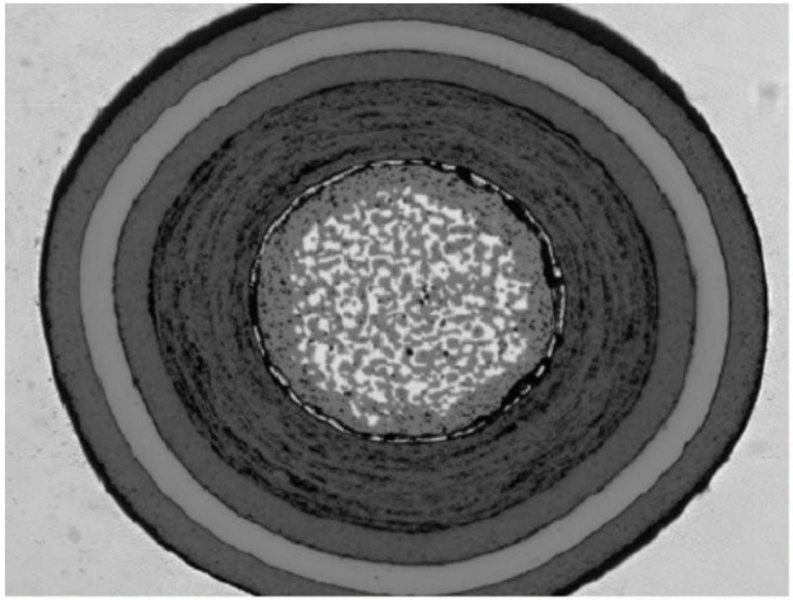
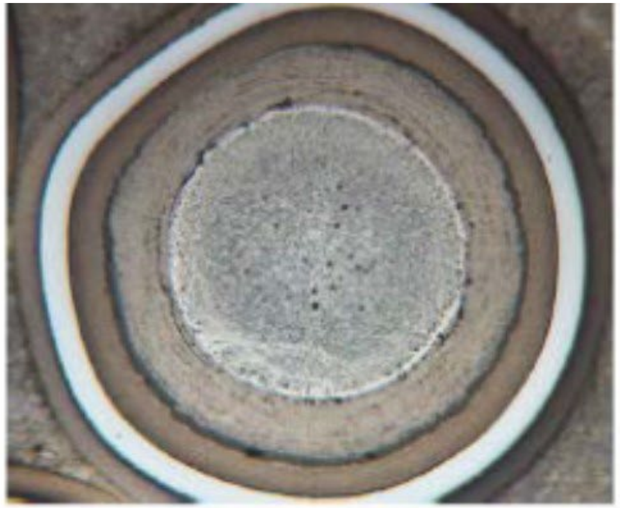
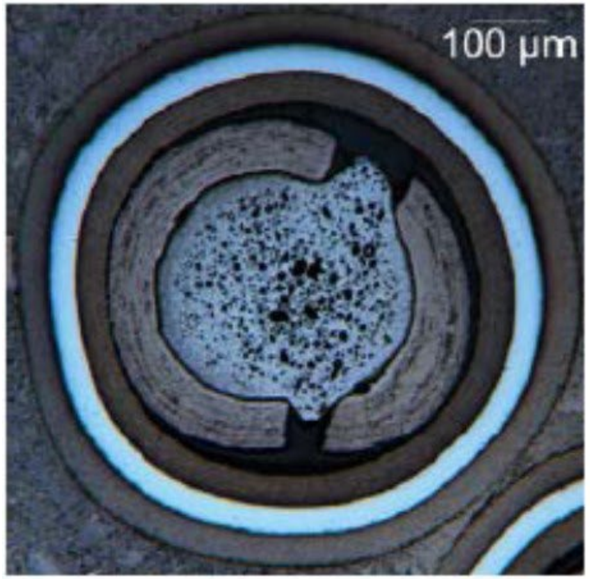
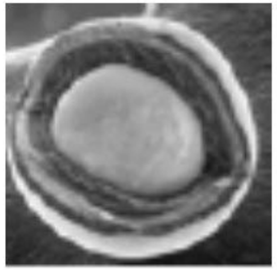
Any questions?



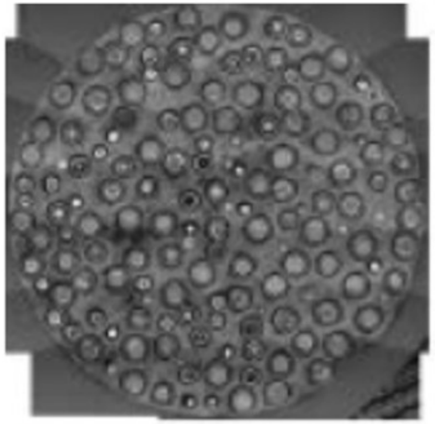


AGR-1 4-1-3 (19.3% avg burnup)





10 mm



Cross-section of Compact

100 µm

Micrograph of Particles

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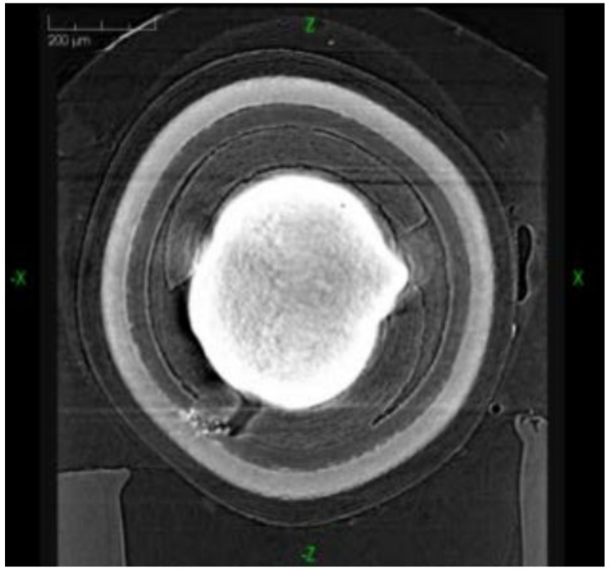
Upcoming Webinars

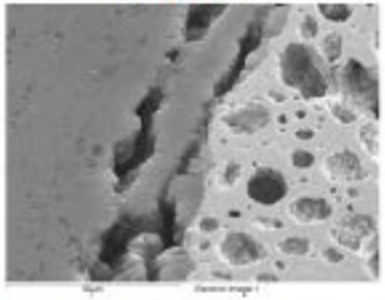
29 January 2020	Thermal Hydraulics in Liquid Metal Fast Reactors	Dr. Antoine Gerschenfeld, CEA, France
26 February 2020 at 8 pm (EST)	SFR Safety Design Criteria (SDC) and Safety Design Guidelines(SDGs)	Mr. Shigenobu Kubo, JAEA, Japan
26 March 2020	MicroReactors: A Technology Option for Accelerated Innovation	Dr. DV Rao, LANL, USA and Dr. Jess Gehin, INL, USA

Backup slides



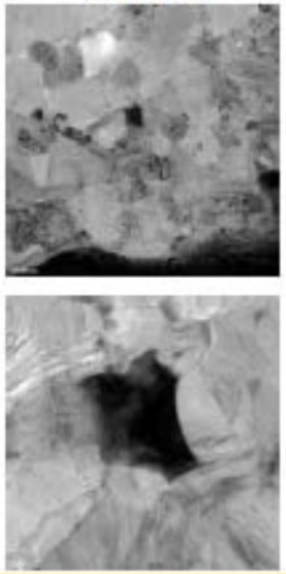
3-D Radiography with high resolution X-Radia

1 µm

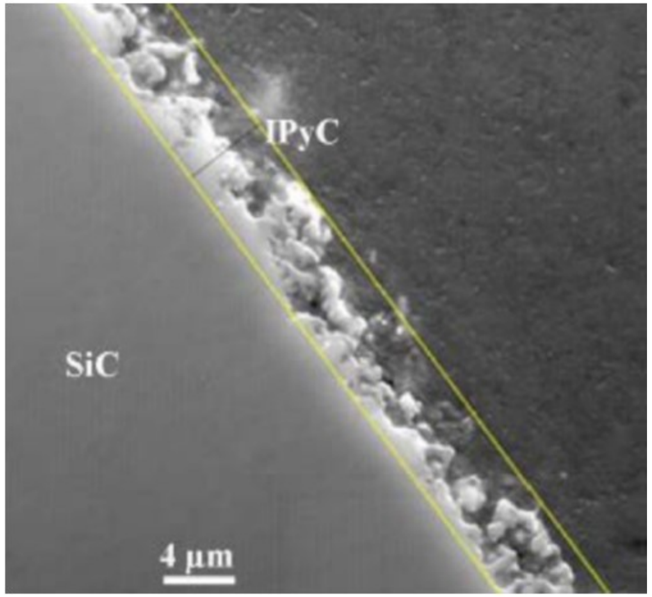


SEM Image of Buffer Kernel Interface in Particles

1 nm



High resolution FIB/TEM images of precipitate near IPyC/SiC Interface



SEM image SiC-IPyC interlayer thickness marked between the yellow lines

TRISO coated fuel retains fission products during normal operations and design basis accidents

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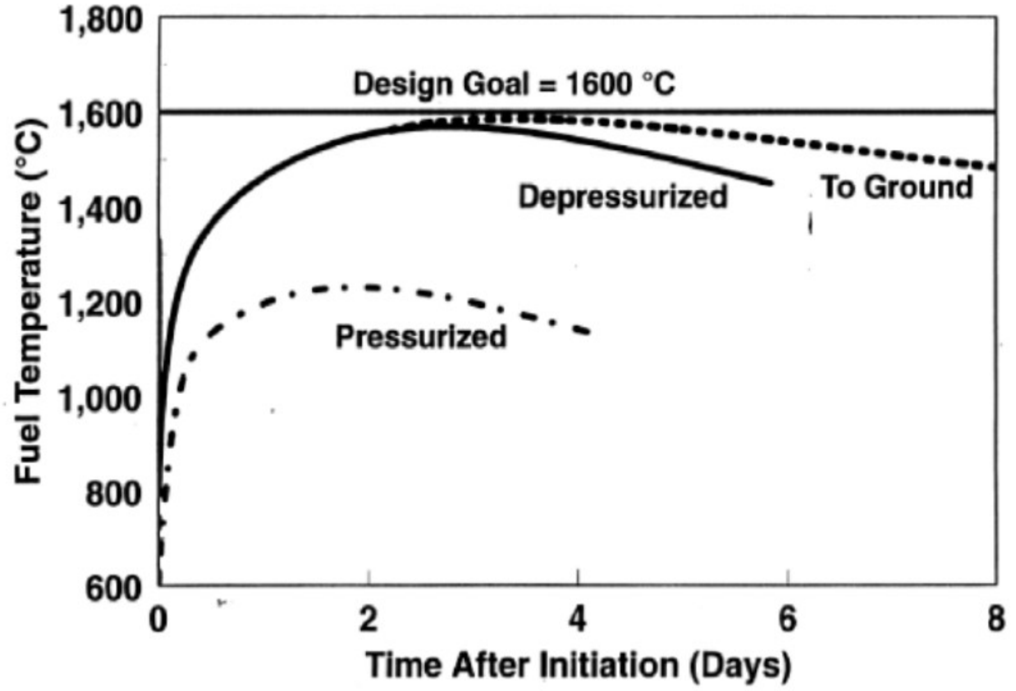
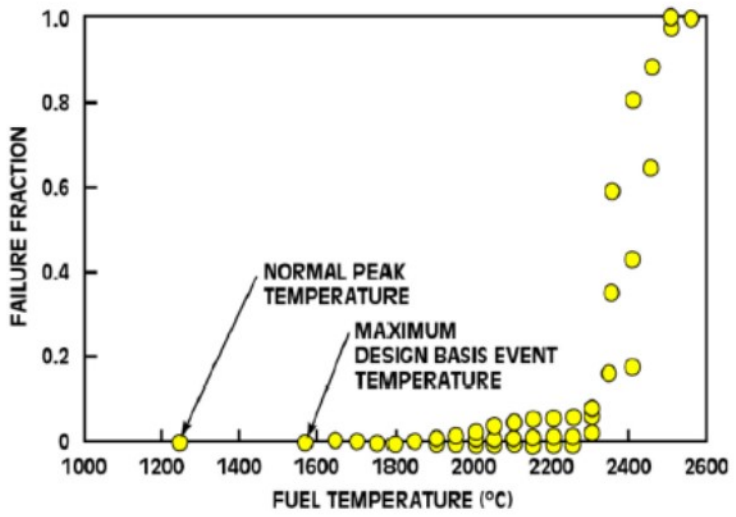
TRISO fuel take many hours, days to heat up, even for extreme accidents, but fuel temperatures remain ~ 200-250 C below release temeratures!



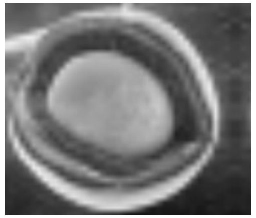


The multilayer TRISO coated particle fuel is engineered to retain fission products during normal operating conditions (~1000-1400 C) and all gas reactor licensing design basis accident events (~1600 C), including a Depressurized Cooldown Event (loss of coolant), the worse event for a HTGR.

TRISO Particle Fuel Design

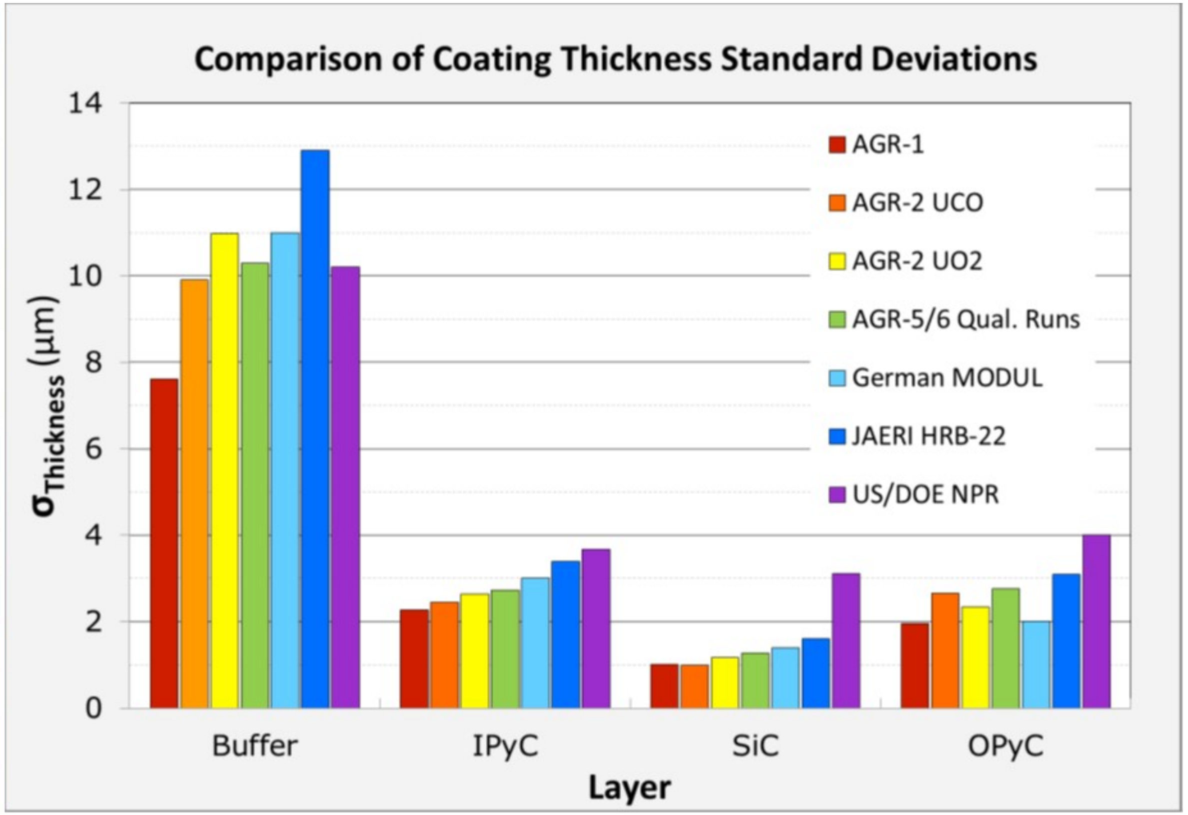
Improving TRISO Fuel Performance using UCO Fuel Kernels vs. UO2 Kernels

- UCO (UCxOy) is UO2 with UC and UC2 added
- UCO designed to provide superior fuel performance at high burnup
  - Kernel migration suppressed (most important for prismatic designs because of larger thermal gradients)
  - Eliminates CO formation; internal gas pressure reduced
  - Fission products still immobilized as oxides
  - Allows longer, more economical fuel cycle
- UCO fuel kernels are used in the reference Next Generation Nuclear Plant High Temperature Gas Reactor prismatic block fuel reactor design
- Potential higher burnup alternative for pebble bed HTGRs



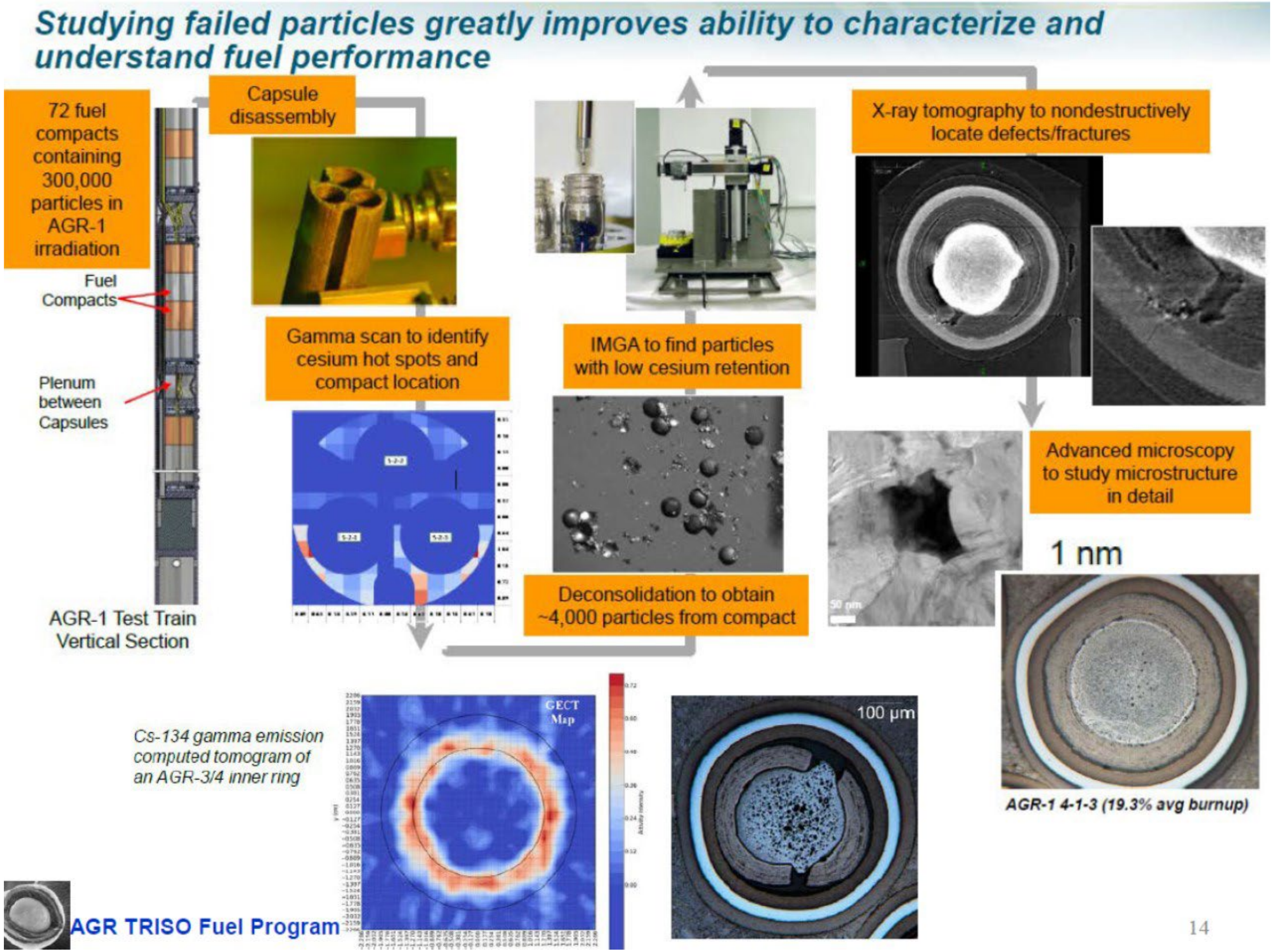
Comparison of AGR-1 and AGR-2 Particles to Historical NPR, Japanese and German data

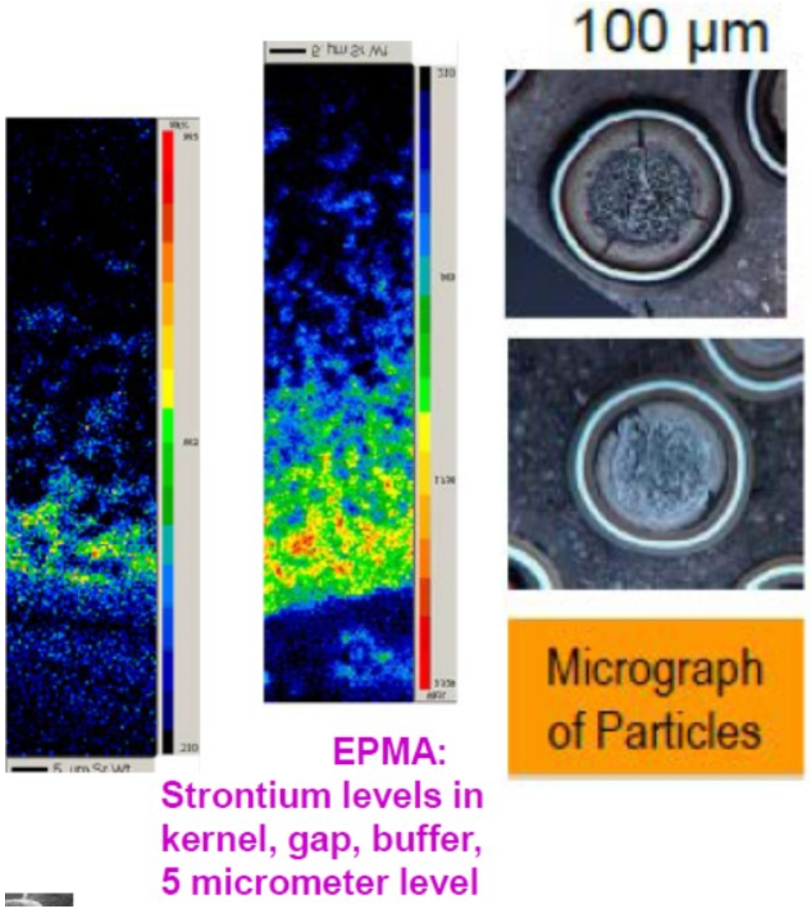
Mean properties	Buffer	IPyC	SiC	OPyC
Layer Thickness				
AGR-1, µm	102.4-104.2	39.4-40.5	35.0-35.9	39.3-41.1
AGR-2, µm	98.9	40.4	35.2	43.4
German, µm	92-102	38-41	33-36	38-41
Layer Density				
AGR-1 ρ, g/cm³	1.1	1.90	3.208	1.90
AGR-2 ρ, g/cm³	1.04	1.89	3.197	1.91
German ρ, g/cm³	1.00-1.10	1.86-1.92	3.19-3.20	1.88-1.92
Anisotropy				
AGR-1 BAF_o		1.022/1.033		1.019/1.033
AGR-2 BAF_o		1.035/1.046		1.026/1.043
German BAF_o		1.042		1.024
Aspect Ratio				
AGR-1				1.055 ± 0.019
AGR-2			1.035 ± 0.011	1.051 ± 0.016
German			1.07 ± 0.02	1.09 ± 0.02



Standard deviations of AGR-1 and AGR-2 particle populations are as good as or better than historical fuels indicating the AGR TRISO Fuel has better process control and higher characterization accuracy

Advanced Gas Reactor TRISO Fuel Qualification Program





AGR TRISO Fuel PIE and Accident Heat-Up Safety Tests

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ORNL Core Conduction Cooldown Test Furnace

- Use IMGA to find irradiated fuel defects
- Heat up specimens to 1800 C for 300 +hours
- Graphite resistance furnace for heating fuel compacts in flowing He
- Liquid nitrogen-cooled carbon traps for detecting Kr-85 release
- Water-cooled deposition cup for collecting condensable fission products
- Airlock for periodic exchange of deposition cups

INL Fuel Accident Condition Simulator (FACS) Furnace

- Dedicated HFEF Hot Cell
- Automated sampling system and handling
- Rated up to 2000 C for 300+ hr tests
- Can replicate transient temperatures vs. time with advanced programing
- Mock-up testing, repeated operator training before HFEF installation allows for better maintenance, parts change-out and reliable performance