Enclosure 1
Presentation Slides for the October 17, 2022
ACRS Kairos Power Subcommittee Briefing

KP-FHR Fuel Qualification Methodology Topical Report

KAIROS POWER

ACRS KAIROS POWER SUBCOMMITTEE MEETING

OCTOBER 17, 2022

OPEN SESSION

Introduction

- Topical Report Applicability
  - This report presents a methodology for qualifying fuel for use in KP-FHRs
    - Qualification subject to the conditions in topical report
  - Demonstration of qualification will be documented in safety analysis report documents as part of licensing applications under Part 50 or Part 52
  - This report is applicable to a test or power KP-FHR provided that the report conditions are met

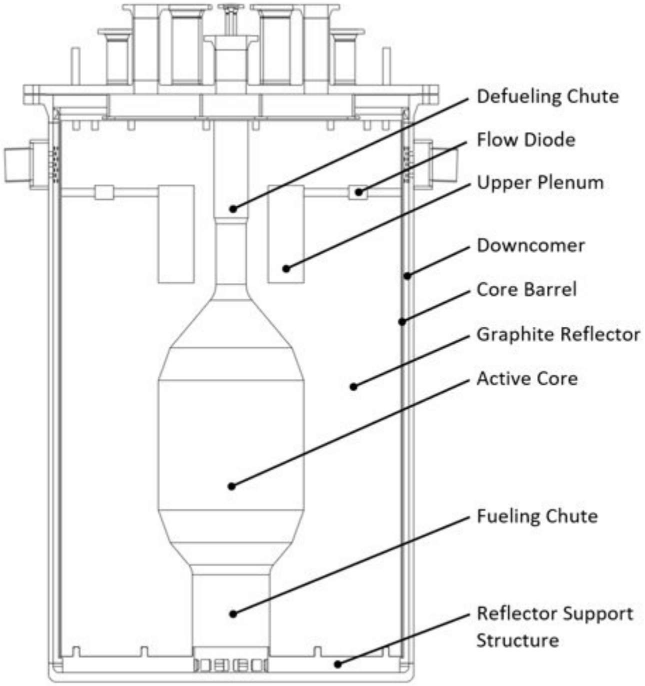
Fuel Qualification

"Qualified fuel" means fuel for which reasonable assurance exists that the fuel, fabricated in accordance with its specification, will perform as described in the safety analysis.

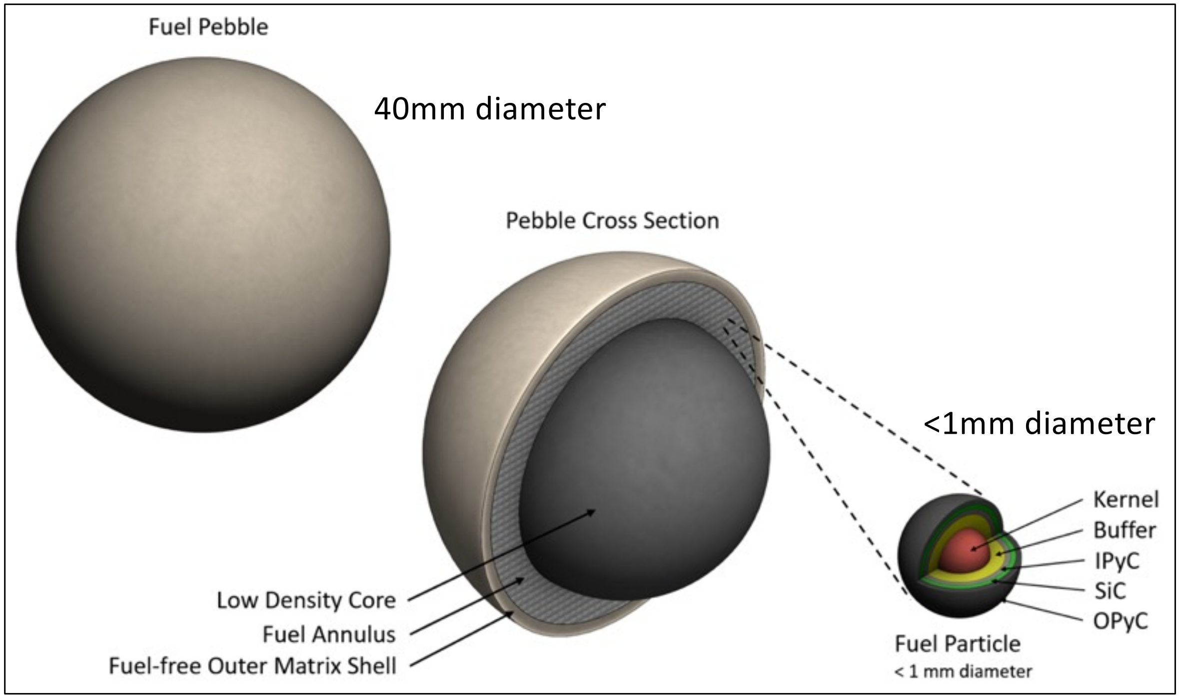
KP-FHR and Fuel Design

KP-FHR Overview

Parameter	Description / Value	
Reactor Name	Hermes	KP-X
Reactor Type	Non-Power Test Reactor	Commercial Electric Power Reactor
Reactor Vessel Size	3 m dia., 4.4 m ht.	4 m dia., 6 m ht.
Coolant / Reflector	Flibe / Graphite	Flibe / Graphite
Reactor Thermal / Electric Power	35 MWth / N/A	320 MWth / 140 MWe
Reactor Operating Pressure	<0.2 MPa	<0.2 MPa
Reactor Inlet / Outlet Temperature	550°C / 620°C	550°C / 650°C



Annular Fuel Pebble and TRISO Particle Design



Particle Design

Fuel System Component	Purpose
UCO Kernel **UO_2 + UC + UC_2**	• The kernel contains the fissile material. • The addition of a limited amount of uranium carbide suppresses CO production mitigating kernel migration, particle over-pressure, and corrosion of the SiC layer. • Oxygen remains sufficient to oxidize fission products that would otherwise diffuse through the IPyC and attack SiC in the higher mobility carbide form.
Porous Carbon Buffer Layer	• The porous carbon buffer layer provides void volume to accommodate fission product gases limiting pressure as burnup increases. • This layer mechanically de-couples the kernel from the outer coating layers and accommodates fuel kernel swelling. • This layer protects the IPyC from damage by fission product recoil.
IPyC Layer	• This coating layer is considered to be the secondary structural and fission product gas barrier after the SiC layer. • This layer introduces a compressive stress on the SiC layer that reduces SiC deformation and the risk of SiC layer failure during irradiation. • This layer serves to protect the SiC from fission product attack. • The IPyC layer protects the kernel from chlorine attack during SiC deposition in the manufacturing process.

Particle Design *(continued)*

Fuel System Component	Purpose
SiC Layer	• The SiC layer is the primary structural layer and fission product barrier. • This layer is a diffusion barrier to mobile metallic and gaseous fission products.
OPyC Layer	• This coating layer is considered to be a secondary structural and fission product gas barrier after the SiC layer. • This layer introduces a compressive stress on the SiC layer during irradiation that reduces SiC deformation and the risk of SiC layer failure. • The OPyC layer protects the SiC layer during manufacture separating the SiC layer from the carbon over-coat.
Pebble - Particle Carbon Over-Coat	• The TRISO particle overcoat with carbon matrix material prevents particle-to-particle contact during manufacture. • The overcoat also facilitates obtaining the nominal packing fraction in the pebble fuel region during manufacture.

Pebble Design *(continued)*

Fuel System Component	Purpose
Low-density Carbon Core	• Reduces the pebble density ensuring pebble has net positive buoyancy in the Flibe coolant.
Fuel Region	• The fuel region is a shell of carbon matrix material surrounding the porous carbon inner core. • Embedded with TRISO fuel particles at the nominal packing fraction. • This region locates fuel near the coolant decreasing the thermal resistance allowing particle powers to be high while keeping fuel temperatures within limits.
Fuel-Free Carbon Outer Shell	• The fuel-free carbon outer shell protects the fuel region from mechanical damage and separates the fuel particles from the coolant.

Fuel Qualification Methodology

Fuel Qualification Methodology

- U.S. and International Experience
  - Foundation of TRISO fuel particle technology
  - NRC SER on EPRI TRISO topical report
- Kairos Fuel Pebble and Particle PIRT
  - The fuel element PIRT is used to identify high priority phenomena for investigation in the fuel qualification program
- Fuel Specification, Manufacturing, and Quality Control through Inspection
  - Fuel specification equivalent to the AGR program with quality controlled through inspection
- Fuel Qualification Envelope
  - Operation is within the bounds of qualification envelope, otherwise an irradiation test is needed to expand the operational envelope

Fuel Qualification Methodology *(continued)*

- Fuel Pebble Laboratory Testing
  - Demonstrate reasonable assurance that pebble will meet functional requirements
- Fuel Irradiation Testing
  - An irradiation test of a statistically significant number of TRISO fuel particles at conditions that extends the bounds of AGR irradiation test data to support a wider operational envelope
- Fuel Performance Model
  - Physics based models in KP-BISON are a quantifiable representation of fuel knowledge used for core design and source term analysis
- Fuel Surveillance Program
  - Ongoing confirmation of fuel performance

U.S. and International Experience

Summary of U.S. and International Experience

- The use of UO_2 TRISO-coated particle fuel first occurred in the UK in the early 1960s with irradiation the Dragon Reactor.
- The German pebble-bed reactor designs (mid-1970s thru 1988) led to extensive testing and "real time" irradiation in the AVR of full commercial scale production fuel
- China and Japan have successfully developed TRISO fuel production and irradiated fuel in prototype and commercial reactors of the prismatic and pebble bed type
- In the US, General Atomics operated prototype and demonstration gas reactors using uranium/thorium carbide based coated fuel particles in prismatic cores
- The AGR program was built on this extensive experience to qualify a UCO TRISO coated fuel particle, Kairos Power leverages this DOE program

National Program	Average Particle Power (mW)	Peak Temperature (°C)	Peak Burnup (%FIMA)	Peak Fluence ($x10^{25}n/m^2$, E>0.1MeV)
German	100 - 250	800 - 1320	6.7 - 15.6	0.2 - 8.5
Chinese	150 - 250	1017 - 1067	9 - 11	3.8 - 4.9
Japanese	550	1156	6.7	2.8
U.S. Legacy	100 - 400	915 - 1350	12 - 80	2.1 - 11.5
U.S. AGR	55 - 140	800 - 1500	13.2 - 19.6	3.5 - 8.1

DOE AGR and German Irradiation Test Data

Test	Time (EFPD)	Peak Particle Power (mW)	Ave. Particle Power (mW)	Peak Burnup Compact (%FIMA)	Time-Ave. Peak Temp. Compact (°C)	Peak Fluence Compact ($x10^{21}$ n/cm^2, E > 0.1 MeV)
AGR-1	620	104	56	19.6	1197	4.7
AGR-2	559	155	73	13.2	1360	3.8
AGR-3/4	369	98	65	15.3	1418	5.8
AGR-5/6	361	247	107	15.3	1210	6.0
AGR-7	361	238	148	15.0	1405	6.1

Test	Number of Compacts	Number of Particles	SiC Failures		TRISO Failures	
			Number of Failures	95% Confidence	Number of Failures	95% Confidence
US DOE						
AGR-1	72	298,000	4	$\leq 3.1 x 10^{-5}$	0	$\leq 1.1 x 10^{-5}$
AGR-2	36	114,336	4	$\leq 8.1 x 10^{-5}$	≤4	$\leq 8.1 x 10^{-5}$
Aggregate	108	412,336	8	$\leq 3.6 x 10^{-5}$	≤4	$\leq 2.3 x 10^{-5}$
German MTR Irradiation Tests of LEU UO_2 TRISO Fuel Particles in 60mm Diameter Fuel Pebbles						
Pebbles	---	277,000	---	---	0	$\leq 1.1 x 10^{-5}$

The AGR irradiation tests have demonstrated performance equivalent to the German experience which has historically been considered the standard for TRISO fuel performance.

DOE AGR and German Furnace Safety Test Data

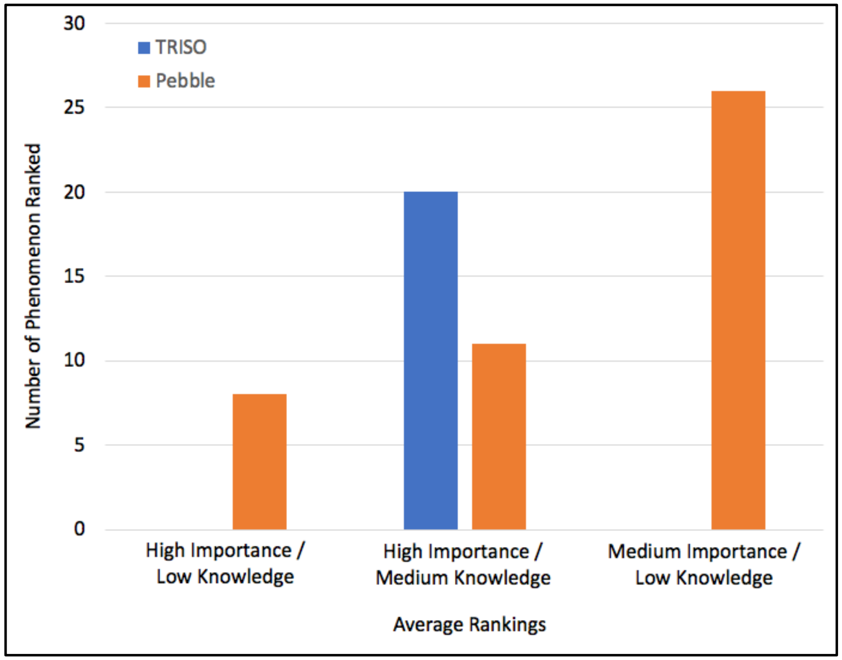
Test Temperature (°C)	Number of Compacts	Number of Particles	SiC Failures		TRISO Failures	
			Number of Failures	95% Confidence	Number of Failures	95% Confidence
AGR-1						
1600	8	33,100	3	$\leq 2.4 \times 10^{-4}$	0	$\leq 9.1 \times 10^{-5}$
1700	3	12,400	7	$\leq 1.1 \times 10^{-3}$	0	$\leq 2.5 \times 10^{-4}$
1800	4	16,500	23	$\leq 2.0 \times 10^{-3}$	2	$\leq 3.9 \times 10^{-4}$
AGR-2						
1600	4	12,704	0	$\leq 2.4 \times 10^{-4}$	0	$\leq 2.4 \times 10^{-4}$
1800	3	9,528	1	$\leq 5.0 \times 10^{-4}$	1	$\leq 5.0 \times 10^{-4}$
AGR-1 and AGR-2						
1600	12	45,804	3	$\leq 1.7 \times 10^{-4}$	0	$\leq 6.6 \times 10^{-5}$
1800	7	26,028	24	$\leq 1.3 \times 10^{-3}$	3	$\leq 3.0 \times 10^{-4}$
German Tests of LEU UO_2 TRISO Fuel Particles in 60mm Diameter Fuel Pebbles						
1600	19	287,480	---	---	5	$\leq 3.7 \times 10^{-5}$

AGR and German furnace safety testing data demonstrates the high reliability of TRISO fuel particles up to 1600°C and above.

Kairos Fuel Pebble and Particle PIRT

Fuel Particle and Pebble PIRT

- Foundation 2004 TRISO PIRT – NUREG/CR-6844
- Fuel element PIRT identifies high priority phenomena to investigate in relation to the FOM fission product transport and release
- Kairos PIRT
  - 199 Phenomenon Identified
  - TRISO fuel particles only had Rank 2 (High importance, medium knowledge level) rankings
  - Pebble fuel elements had more diverse rankings due to the novel design, manufacturing, and performance of the annular pebble



Fuel Particle and Pebble PIRT

PIRT Findings are Addressed:

- Manufacturing Development Program
  - Leverages German and AGR program experience
- Fuel Pebble Laboratory Testing Program
  - Mechanical – Tribology, Compression, Impact, Molten Salt Infiltration
  - Material Compatibility – Pebble in Flibe, Pebble in Air

Fuel Specification, Manufacturing, and Quality Control through Inspection

Fuel Specification, Manufacturing, and Quality Control

- TRISO Particle Specification Based on AGR Specification
  - Equivalent specification to AGR-2 and AGR-5/6/7 TRISO fuel particles
- Pebble Specification
  - Similar to historic HTGR fuel pebbles with features for FHRs
- Manufacturing
  - Kernels fabricated using sol-gel process to form microspheres
  - Coated particles are fabricated in a fluidized bed through a continuous chemical vapor deposition (CVD) process
  - Pebbles are formed from a mixture of matrix graphite powders, binder, and TRISO fuel particles and pressed to shape and heat treated
- Inspection
  - Products are characterized to demonstrate compliance with specifications

Fuel Specification, Manufacturing, and Quality Control

Source Material or Fabricated Component	Measured Characteristic in Inspection Program
U_3O_8	U-235 enrichment, uranium content, impurities, boron equivalent
Kernel	Diameter, density, sphericity, stoichiometry, impurities
TRISO fuel particle	Layer thickness, density, PyC anisotropy, SiC aspect ratio, surface and free uranium content
Natural and petroleum coke graphite	Density, grain size, surface area, impurities, boron equivalent
Binder material	Viscosity, molecular weight, melting point, impurities
Pebble fuel	Density, diameter, thermo-physical properties, mechanical properties, thickness of fuel free outer shell, surface defects, fraction of defective SiC layers (burn leach), uranium loading, uranium contamination in carbon matrix, ash and lithium content, boron equivalent

Fuel Qualification Envelope

Fuel Operating Envelope

- Key Parameters
  - Power
  - Burnup
  - Temperature
  - Fast Fluence
- The KP-FHR operating conditions for steady state and transients must be within the fuel qualification envelope
  - The basis of the qualification envelope are the AGR-2 irradiation conditions defined in the EPRI TRISO topical report

Fuel Operating Envelope and Qualification Limits

Parameter	Proposed Qualification Envelope	Anticipated Non-Power Test KP-FHR Conditions	Anticipated Commercial Electric Power KP-FHR Conditions
Normal Operation			
Peak SiC Layer Temperature (°C)	1360	< 900	< 1100
Burnup (%FIMA)	13.2	< 10	< 20
Peak Particle Power (mW)	155	< 155	< 350
Peak Fluence ($x10^{25} n/m^2$, E>0.1MeV)	3.8	< 2.0	< 4.0
Postulated Events			
Peak SiC Layer Temperature (°C)	1600	< 1200	< 1200
Peak Kernel Temperature (°C)	2350	< 1500	< 1500

Fuel Pebble Laboratory Testing

Laboratory Test Program

- Fuel Pebble Laboratory Test Program will demonstrate that annular fuel pebbles meet functional requirements
  - Mechanical Tests
  - Tribology
  - Buoyancy and Molten Salt Infiltration
  - Material Compatibility

Mechanical Tests and Tribology

- Demonstrate pebbles do not fracture from static and dynamic loads in the reactor and wear behavior is acceptable for a pebble's lifetime
- Compression test
  - Compression test (crush test)
  - Pebble is loaded in compression until failure
- Impact test
  - Pebble fracture under cyclic impacts
- Tribology
  - Wear rate and coefficient of friction

Buoyancy, Molten Salt Infiltration (MSI) Tests and Material Compatibility

- Flibe Infiltration and Buoyancy
  - Demonstrate pebbles are buoyant
  - Test temperature up to 900°C and pressure up to 500 kPa
  - Measurement of weight change
- Flibe Compatibility
  - Pebble carbon matrix interaction with Flibe
- Air Compatibility
  - Oxidation rate behavior of pebble carbon matrix in Air
  - Oxidation tests in the temperature range 450-700°C
  - Measurement of mass loss with time to create an Arrhenius correlation

Laboratory Test Program Acceptance Criteria

Laboratory Test Program	Measured Parameter	Acceptance Criteria
Compression	Crush strength	The crush strength at room temperature is greater than the maximum calculated load in the core, PHSS, and during receipt and inspection.
Impact	Pebble fracture	The pebble will not fracture under cyclic impact in the core, PHSS, and during receipt and inspection.
Tribology	Wear rate	The wear determined by a conservative analysis of wear over the lifetime of a pebble does not result in damage to the TRISO particles.

Laboratory Test Program Acceptance Criteria

(continued)

Laboratory Program Test	Measured Parameter	Acceptance Criteria
Buoyancy	Density (mass and volume), coefficient of thermal expansion	Measurements of pebble density and Flibe density made over the operating range ensure that the pebble remains buoyant.
Buoyancy	Flibe infiltration	Flibe infiltration measured over operating range as well as the range of all transients to ensure the pebble remains buoyant.
Material Compatibility	Corrosion rate of the pebble carbon matrix in Flibe	Flibe interaction with the pebble does not result in damage to the fuel region of the pebble.
Material Compatibility	Corrosion rate of pebble carbon matrix in air	Air material compatibility tests analyzed over the lifetime of a pebble does not result in damage to the fuel region of the pebble.

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Fuel Irradiation Testing

Irradiation Testing

- Irradiation testing expands the fuel qualification envelope
  - Testing is required for the commercial electric power reactor
- Tests would be performed in a non-KP-FHR test facility
- Online fission gas release data used to determine the TRISO fuel particle failure fraction
- Destructive PIE is used to confirm the TRISO fuel particle failure fraction
- Acceptance criteria
  - TRISO fuel particle failure fraction with a 95% one-sided upper confidence bound

Fuel Performance Model

Fuel Performance

- KP-BISON used to analyze response of the fuel during normal operation and transients
- Fuel Pebble DEM modeling
- Fuel Pebble Finite Element Modeling

Fuel Surveillance Program

Fuel Surveillance Program

- Fuel surveillance in Hermes confirms fuel performance
- Fission product monitoring
  - Cover gas
  - Flibe coolant
- PHSS pebble inspection system checks burnup and physical condition
- Post irradiation examination in Hermes (and initial KP-X)
  - TRISO particle failure fraction
  - Pebble surface wear
  - Molten salt infiltration

Summary

- Over fifty years of operating experience and testing of TRISO fuel including extensive testing of TRISO fuel particles in AGR-1 and AGR-2, including for both steady state and transient conditions.
- Successful completion of a KP-FHR fuel element PIRT and implementation of associated actions to further the understanding of the annular fuel pebble and TRISO fuel particles.
- Manufacturing and inspection of the KP-FHR fuel to a specification that ensures the fuel is equivalent in performance to the fuel tested in AGR-2, and meets the conditions in the EPRI TRISO topical report SER (Reference 13).
- Operation within a set of defined fuel qualification limits which ensure that the fuel remains within its qualification envelope during both normal operation and licensing basis events.

Summary *(continued)*

- Irradiation testing (if TRISO fuel particle will operate outside of the AGR-2 fuel performance envelope)
- Surveillance program confirms that the pebble form does not have an adverse impact on the fuel particles.
- The ability to examine fuel pebbles as they exit and re-enter the core over their expected lifetime, including the ability to remove them if necessary for disposal or PIE.

Limitations

- The design of the annular pebble, TRISO particle-based fuel and the KP-FHR design overview are as described in Section 1.1.2, including the presence of a Flibe primary coolant.
- Operating and transient conditions for the KP-FHR are demonstrated in safety analysis reports submitted with license applications under 10 CFR 50 and 10 CFR 52 to remain within the fuel qualification envelope values specified in Table 3-11, which is based on the AGR program.
- If the fuel qualification envelope is to be extended beyond the AGR-2 based limits, an irradiation test program will be conducted.
- Demonstration that the conditions and limitations of the EPRI TRISO Topical Report Safety Evaluation Report are met for the KP-FHR fuel design.
- Future license applications for commercial electric power KP-FHRs will include justification (testing or analysis based on an approved methodology) of the applicability of this methodology during rapid reactor transient events for irradiated fuel.
- Future license applications for commercial electric power KP-FHRs will include additional justification (testing or analysis based on an approved methodology) that Flibe does not adversely impact irradiated fuel pebble buoyancy.
- This methodology applies only to KP-FHRs with a safety-related positive flux rate trip.
- SER limitation to justify applicability of this methodology to a test reactor for rapid transients.

End of Presentation

Questions?