PBMR Fuel Qualification Questions for Exelon

FUEL DESIGN ISSUES/QUESTIONS

Discuss the fuel safety performance acceptance criteria (e.g., peak temperature, maximum oxidation) for the PBMR fuel.

Describe the specific reference characteristics that have been selected to optimize the coated particle fuel design and pebble structure for utilization in a PBMR:

- UO_2 kernel diameter, kernel enrichment
- Pyrolytic Carbon Buffer Layer Thickness, μm
- Inner Pyrolytic Carbon Thickness μm
- Silicon Carbide layer thickness μm
- Silicon Carbide layer strength
- Silicon Carbide layer Young's modulus
- Outer Pyrolytic Carbon Thickness μm
- Protective particle Overcoating Thickness μm
- Fuel Free graphite pebble shell, μm
- Design Temperature Limit, °C
- Design Burnup limit, Gwd/t or FIMA[1]
- Maximum Neutron Fluence, 10^{25} m^{-2}
- # of coated particles per pebble
- pebble diameter

Compare each of these reference characteristics for the PBMR fuel design to the reference characteristics of the coated particle design (e.g., German HTR-Module?) upon which the PBMR particle development and design was meant to be derived.

Discuss the technical basis for optimizing/modifying the specific fuel design characteristic(s) selected for the PBMR pebble fuel for characteristics which are different from the reference coated particle design characteristic(s).

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[1] Fissions per initial (heavy) metal atom

Describe the spectrum of normal operating events, abnormal transient events and design-basis accident events for which the fuel is designed to perform within the acceptance criteria and other design limits. Describe the "beyond-the-design-basis" events (e.g., severe accidents and emergency planning basis accidents) that the fuel performance/failure is to evaluated. Describe the associated significant operating/environmental considerations (e.g., power level, fluence, fuel burn-up, temperature, mechanical loadings, chemical loadings (e.g., oxidation)) for each of the limiting events.

Describe the analytical method(s) and/or empirical data basis that are to be used to predict the coated particle failure rate and fission product gaseous and metallic fission product release rates for the transients and accidents postulated for a PBMR (e.g., heat-up, reactivity insertion, air intrusion, steam intrusion, water intrusion, rapid oxidation) and for establishing the qualification of the PBMR reference coated particle design and pebble structure design. Discuss the particle failure mechanisms that are specifically modeled in the analytical methods. Discuss the basis for these mechanisms, and their completeness.

What are the expected fuel particle and pebble burn-up or FIMA design limits for the PBMR fuel.

Describe the qualification program for your coated particle fuel and pebble fuel structure as it relates to the fuel design.

FUEL FABRICATION ISSUES/QUESTIONS

How is the coated particle defect rate defined (e.g., fraction of particles with a defective SiC layer, sum of the defect fractions in any individual coating layer)?

What will be the coated particle fabrication defect rate (i.e., defect fraction) specification limit for the coated particles in PBMR fuel pebbles? (i.e., what is the fraction of accessible free uranium in (1) uranium in exposed kernels? and (2) uranium contamination in the matrix graphite?)

What is the targeted mean defect rate for the production PBMR fuel particles to be fabricated at the planned fabrication facility. Discuss any production fuel facilities (not laboratories or pilot production lines) that have successfully fabricated fuel particles with this low a particle defect rate.

Describe the technique that will be used to assess the fabrication composite defects including the failures caused by the pressing of the particles in the carbon matrix used to fabricate the pebble balls. What is the specified limit?

What is the free fissile uranium fraction that is assumed for unirradiated fuel?

Describe the characterization/measurement techniques and statistical analysis methods that will be used to determine the actual fabrication-related defective particle rates for each of the critical aspects of the coated particle design and manufacturing process. (i.e., to ensure that the manufactured coated particle defect rates, including uncertainties, are within the specified limits for the manufacturing process).

SiC layer density, SiC layer thickness and SiC layer thickness standard deviation are specified for the SiC layer. However, according to the literature, SiC coatings that have the same value for these parameters may perform differently when irradiated. It has been speculated that SiC layer deposition temperature and contamination may play a role in the uncertainty of the TRISO coated particle fuel strength and irradiation behavior. What has been done to ensure that SiC layer performance is optimum and predictable? How do these measures compare to coated particle manufacturing processes used by others in the past?

Describe the qualification program for your coated particle fuel and pebble fuel structure as it relates to fuel fabrication.

FUEL PERFORMANCE DURING NORMAL OPERATION ISSUES/QUESTIONS

Describe the operational and design limits that will be placed on the fuel pebble operating environment.

Describe the core monitoring instruments and analysis methods will be used to verify that the fuel operating conditions are maintained within the specified design envelop for temperature, power level, coolant chemistry, etc.

Describe the methods that will be used to ensure that the fuel management and ex-reactor fuel handling and storage system operation will ensure that burn-up limits are not exceeded.

Describe the fuel integrity monitoring system(s) and analysis methods that will be used to monitor fuel performance in reactor during the in normal operation (in-reactor fuel cycle). Describe the fuel parameters and design limits for which fuel the integrity monitoring system will be used to monitor fuel performance.

On a per pebble (or 10^5 particle) basis, discuss the assumed number (and the basis for the assumed number) of “equivalent” defective particles due to the sum of initial fabrication defects plus the additional in-reactor irradiation-induced defects at EOL.

Discuss the fuel performance (and failure) models that will be used to assess the adequacy of the PBMR fuel particle design (and the additional in-reactor failures of adequately manufactured fuel particles) during normal operation and operational transients. Identify the key design, fabrication and environmental parameters that are accounted for in the fuel performance models.

For the PBMR core (diameter) discuss downward movement the fuel pebbles at the outer periphery of the core and explain the basis for assuring sufficient downward velocity that fuel burnup limits are not exceeded for these pebbles. Describe the velocity analysis or core pebble mockup testing basis for the vertical velocity profile in the PBMR involving continuous on line refueling.

FUEL OPERATING EXPERIENCE AND ACCIDENT ANALYSIS/TESTING EXPERIENCE

For TRISO particle fuel design(s) on which the PBMR fuel design and fabrication is to be based provide the following:

Operating Experience

Describe the: Fuel source/suppliers; Fuel design characteristics; Reactors Involved; Important in-reactor operating conditions (e.g., power density); Fuel burnups; particle in-reactor failure rates; post -irradiation testing and fuel failure results.

Accident Analysis/Testing Experience

Describe the: Fuel source/suppliers; Fuel design characteristics; Reactors Involved; in-reactor operating preconditioning characteristics (e.g., operating fuel temperatures, fuel burnup); Transient /accident experiments conducted and fuel failure results.

Discuss the results of tests and experiments that have been conducted to assess the chemical interaction characteristics of the pebble ball outer graphite coating when exposed to air, steam, or water at high temperatures

FUEL PERFORMANCE DURING POSULATED ACCIDENTS AND TRANSIENTS (TECHNOLOGY DEMONSTRATIONS)

Describe the in-reactor demonstration testing that either has been completed or is planned for the exact fuel design and exact manufacturing process that will be used for the fuel for the PBMR for simulating normal operating conditions, and postulated transients and accidents.

Compare the in-reactor proof test irradiation conditions (e.g., power level, fuel temperatures, fluence, fast flux energy level) to the in-reactor conditions (e.g., power level, maximum fuel temperatures, maximum neutron fluence, fast flux energy level) that are postulated or a PBMR.

Describe the in-reactor demonstration testing that either has been completed or is planned for qualifying the fuel performance (and failure) codes, models and methods.

Describe the post-irradiation proof (e.g., heating, air, steam, water) tests that have been completed or are planned for the exact fuel design characteristics and fuel manufacturing process that will be used for the PBMR for normal operating conditions, for postulated accident conditions.

Describe that fuel technology demonstration testing that either has been or will be completed to validate the significant models and methods used in the PBMR safety analyses. In general the fuel technology demonstration program must explicitly demonstrate the correlations between the reference fuel design and its response to the postulated events.

Discuss the plans for post-irradiation testing of PBMR production fuel, fabricated in the PBMR fuel fabrication facility and irradiated in the prototype PBMR.

Comparison of TRISO Coated Fuel Particle Designs

Country	Kernel Composition	Fuel Kernel Enrichment %235	Fuel Kernel Size µm	Pyrolytic Carbon Buffer Layer µm	Inner Pyrolytic Carbon µm	Intermediate Silicon Carbide µm	Outer Pyrolytic Carbon µm
FRG AVR	BISO	BISO	BISO	BISO	BISO	BISO	BISO
FRG THTR	BISO	BISO	BISO	BISO	BISO	BISO	BISO
FRG HTR	UO_2	10.6	500	95	40	35	40
US MHTGR	UCO	19.9	350	100	35	35	40
	$U_{nat}CO$	natural	500	65	40	35	40
Japan HTTR	UO_2	3.3-9.9	600	60	30	25-35	45
Russian VGM 80 GWd/t	UO_2	8.0	500	90-100	70-80	60	60
China HTR-10 88 Gwd/t		17	501	92	39	36	34
PBMR	UO_2	?	?	?	?	?	?