APPENDIX B

PANEL MEMBER DETAILED PIRT SUBMITTALS FOR OPERATIONS

The INEEL submittal is provided in Appendix B.1 (pages B-2 through B-48).

The ORNL submittal is provided in Appendix B.2 (pages B-49 through B-96).

The SNL submittal is provided in Appendix B.3 (pages B-97 through B-143).

Appendix B.1

Detailed PIRT Submittal by the INEEL Panel Member

D. A. Petti

TRISO Fuel PIRT: Operations

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Fuel element Temperature	Local temperature in the fuel element

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 8	Remedy:
Rationale: (I will assume that by element we mean the matrix material of the fuel pebble or compact.) Temperature drives diffusion and mobility of fission products in all components of the fuel element. Semi-empirical models exist to describe the behavior in the matrix material.	Rationale:	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Fuel element Fast fluence	Accumulated fast neutron fluence greater than 0.18 MeV

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 5	Remedy:
Rationale: Shrinkage of the matrix material is a function of fast fluence. Radiation damage may provide trapping sites to retain fission products in the matrix material	Rationale:	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Fuel element	Power per pebble or compact (W)
	Power density	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 6	Remedy:
Rationale: More important in the particles than in the matrix/element per se. Thermal gradient across pebbles is fairly low.	Rationale:	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Fuel element Temperature difference	Temperature between center or centerline and surface in C

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 7	Remedy:
Rationale: For pebble beds, low temperature differences are expected. Temperature gradients drive the amoeba effect.	Rationale: Correlations exist to describe amoeba effect	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Fuel element Temperature-time histories	Local temporal temperature of fuel element over its lifetime

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 7	Remedy:
Rationale: Fission product release from the fuel depends on the time/temperature history of each layer in the fuel element and models include explicit temperature dependence and thus this effect can be evaluated.	Rationale:	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Fuel element Condensed phase diffusion	Inter-granular diffusion and/or intragrannular solid-state diffusion

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 5	Remedy:
Rationale: Transport of metallic fission products through the matrix is probably via surface diffusion with some trapping or sorption effects.	Rationale: Diffusion and sorption models have been used to characterize solid fission product diffusion through the matrix material. Parameters for sorption exist for U.S. matrix material for Cs, Sr and other fission products. For German matrix material, effective diffusion coefficients exist for Ag, Cs, and Sr. New data may be needed for matrix material because of different starting materials used to make the matrix.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Fuel element Gas phase diffusion	Diffusion of gaseous fission products through layer (Knudsen and bulk diffusion through pore structure, and pressure driven permeation through structure)

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 7	Remedy:
Rationale: Probably the mechanism that best describes the transport of fission gases through the matrix material. The matrix does not hold up fission gases significantly.	Rationale:	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Fuel element Corrosion by coolant impurities	Corrosion of the fuel element surface by part per million level of gaseous impurities in the helium coolant.

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 6	Remedy:
Rationale: Corrosion by moisture or oxygen can oxidize pebble and any exposed kernels contributing to the source term. Allowable concentrations have been established to minimize this effort.	Rationale: Impurities levels have been established to minimize corrosion.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel	Formation of CO from excess oxygen released in fission
	CO production	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H for UO_2, L for UCO	Level: 8 for UO_2, 5 for UCO	Remedy:
Rationale: CO is predicted to form as a result of the reaction of excess oxygen released from fission reacting with buffer carbon. It has been measured in UO_2 particles. It is a pressure source term for structural modeling and can drive kernel migration and SiC corrosion (in the case of a failed IPyC).	Rationale: Measurements on CO in coated UO_2 particles have been made up to 10% burnup. No similar measurements have been made on UCO.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel	Fission of initial metal atoms
	Burnup	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 7	Remedy:
Rationale: Burnup determines the concentration of fission products, especially those like Pd that have been shown to attack the SiC. The higher the concentration of aggressive fission products, the higher the chance of fuel particle failure and fission product release. In addition, burnup influences fuel swelling and the microstructure of the kernel as a result of fission gas generation, transport to the grain boundaries and the formation of interconnected porosity, which allows the gases to escape the kernel. Thus, fission gas release from the kernel depends on burnup.	Rationale: Large database exists for UO_2 coated particles up to 10% FIMA	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel Kernel swelling	Volumetric expansion of kernel resulting from fissioning

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 6	Remedy:
Rationale: Kernel swelling is known to occur in all fuels with values that scale linearly with burnup. Swelling is calculated to be quite high at the high burnups proposed for some coated particle designs, but they are outside the PBMR burnup envelope. However, the buffer does accommodate the swelling to some degree and ameliorate any potential deleterious effects.	Rationale:	Closure Criterion:

Additional Discussion

Life Cycle Phase	**Factor, Characteristic or Phenomenon**	**Definition**
Operations	Kernel Microstructure changes	Change in structure in kernel with burnup, including fission gas bubbles, grain growth and grain disintegration

Importance Rank and Rationale	**Knowledge Level and Rationale**	**Remedy for Inadequate Knowledge/Issue Closure Criteria**
Rank: L	Level: 6	Remedy:
Rationale: Microstructural changes do occur in the kernel however at very high burnups the complete destruction of the crystal structure of kernel is often seen. Some changes are empirically captured in fission product release models via a burnup dependence. The influence on release from the fuel particle is low since these changes do not affect the coatings [in a properly designed particle]. Grain growth is not expected to occur at typical operating temperatures.	Rationale: The experience base from testing of UO_2 to 10% FIMA does not suggest that this is critical.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel Fission product chemical form	Chemical speciation of fission products as a function of burnup and temperature

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 7	Remedy:
Rationale: Volatility of fission products is a function of their chemical form. The chemical form is an important initial condition for transport through the layers.	Rationale: Chemical form of fission products in oxide and oxycarbide fuels has been extensively investigated thermodynamically. Experimental confirmation of the chemical forms is not complete.	Closure Criterion:

Additional Discussion

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Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel Buffer interaction	Mechanical and chemical interactions between the kernel and buffer, e.g., chemical reactions at interface and displacement of buffer by kernel growth.

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 6	Remedy:
Rationale: Mechanical interactions could lead to failure of the buffer layer. But buffer is a sacrificial layer anyway. Chemical interaction of UO_2 with the buffer forms a rind of UC_2 at the interface.	Rationale: Mechanical interaction with the buffer has never been seen in high-density UO_2 kernels. UC_2 rind has been observed.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel	Transport of carbon down the temperature gradient
	Kernel migration (fuel dependent)	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M UO_2 and L UCO	Level: 8	Remedy:
Rationale: Kernel migration is reasonably well known. In UO_2 pebbles, power densities are restricted to limit the temperature gradient and thus the migration that can occur so that migration is not an important failure mechanism. In UCO fuel, the chemistry of the fuel prevents significant migration from occurring.	Rationale: In UO_2, kernel migration has been measured and correlations exist to describe the behavior that depends strongly on the temperature and temperature gradient in the particle.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel Fission product generation	Yield of fission products from uranium and plutonium fission

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 9	Remedy:
Rationale: Yield determines the fission product concentration in the kernel and thus the starting point for source term. It is well known and well characterized.	Rationale:	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel Temperature gradient	Temperature gradient across the kernel

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 6	Remedy:
Rationale: High conductivity of UO_2 and UCO results in modest temperature gradients across the kernel (3 to 5 K across the 500 microns).	Rationale: Can calculate reasonably well even accounting for change in kernel physical form as burning increases	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel Isotopic half life	The time lapse during which a mass of a particular isotope loses half of its radioactivity

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 9	Remedy:
Rationale: Half-life is well known and its influence on short-lived fission gas release is adequately accounted for in the models. For the safety significant isotopes, the half-life is even less important since they either reach an equilibrium in the fuel or they do not decay significantly during operation.	Rationale:	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Buffer layer Pressure	Gas pressure generated in the void volume associated with the buffer layer

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 7 for UCO and 6 for UO_2 at high burnup	Remedy: Will be measured by Europeans in their coated particle fuel program
Rationale: Fission gas and CO (for UO_2 only) contribute to the gas pressure in the particle, which is important in evaluating the structural integrity of the TRISO coating.	Rationale: Fission gas yield and thermodynamic estimates of CO production are used to analytically estimate the pressure. Data on CO release from UO_2 particles exist at low burnup (< 10% FIMA) and a range of temperatures. At high burnups (> 10% FIMA) in UO_2 fuel, there is a need to measure CO release by crushing particles.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Buffer layer	Radiation or otherwise induced dimensional change
	Shrinkage	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 6	Remedy: Await modeling work from DOE/INEEL program
Rationale: Differential shrinkage of the buffer because of temperature gradients can lead to stresses in the layer large enough to cause cracking of the layer. These cracks can result in short-circuit diffusion of fission products to the TRISO coating.	Rationale: Modeling of this phenomenon is ongoing at INEEL.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Buffer layer Cracking	Shrinkage cracks produced in layer during operation

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 5	Remedy: Await modeling work from DOE/INEEL program
Rationale: Cracking can occur as a result of high stresses produced via differential shrinkage of the buffer during irradiation. Some model calculations like STRESS3 suggest that kernel-buffer mechanical interaction can lead to high stresses in the buffer and hence cracking. These cracks can result in short-circuit diffusion of fission products to the TRISO coating.	Rationale: Modeling of this phenomenon is ongoing at INEEL.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Buffer layer Carbonyl vapor species	M-CO species partial pressures

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 3	Remedy:
Rationale: Unknown if such species are at all important.	Rationale:	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Buffer layer Temperature gradient	Temperature difference across the buffer layer

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 5	Remedy:
Rationale: The temperature difference across the layer (which is directly related to the power produced in the particle) can determine the structure integrity of the layer and the thermal diffusion (Soret effect) of some fission products and oxygen and carbon in the kernel. The amoeba effect is one example. Pd and Ag migration in the fuel particle is also thought to be driven by gradients. Modeling of these phenomena is at a fundamental level and is just beginning. Empirical correlations exist to be used in fuel design.	Rationale: Can estimate thermal gradient to some extent. The formation of gaps complicates the analysis and can lead to higher gradients.	Closure Criterion:

<u>Additional Discussion</u>

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Buffer layer	Inter granular diffusion and/or intragrannular solid state diffusion
	Condensed phase diffusion	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 5	Remedy:
Rationale: Probably the mechanism of transport of the metallic fission products through this layer. However, in many cases the buffer cracks which provides a short circuit path for fission product transport.	Rationale: Simple gas phase mass transport coefficients can be calculated. Sorptive effects of the buffer are less well defined.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Buffer layer Gas phase diffusion	Diffusion of gaseous fission products through layer (Knudsen and bulk diffusion through pore structure, and pressure driven permeation through structure).

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 5	Remedy:
Rationale: Probably the most significant mechanism responsible for gaseous fission product transport through the buffer. However the structure of the buffer changes significantly with fast fluence, which makes the detailed modeling of such transport very difficult. Usually models do not account for transport in this layer. If the buffer cracks (which can occur at high power densities) then fast diffusion to the IPyC layer occurs.	Rationale: Knudsen diffusion estimates suggest rapid diffusion compared to other layers. Diffusion through cracks suggests very rapid diffusion.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Buffer	Buffer damage arising from capture of high-energy fission products
	Recoil effects	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 7	Remedy:
Rationale: Recoil ranges of fission fragments can be on the order of 5-10 μm which is ~5-10% of the buffer layer.	Rationale: Can be calculated using recoil models	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Inner PyC layer Radiation induced creep	Strain release as a result of radiation induced dimensional change

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 5	Remedy: Will be measured in new DOE NERI program. (see ref 4)
Rationale: Very important to know the radiation induced creep rate for IPyC. It counteracts the shrinkage and thus determines tensile stress in the layer. High tensile stresses threaten layer integrity and the integrity of the SiC layer as well via the formation of a stress concentration. It has been shown to be the most important parameter in structural modeling (see refs. 1 and 2)	Rationale: Creep values range widely in the literature (see ref. 3). New more accurate measurements are needed.	Closure Criterion:

Additional Discussion

1. G. K. Miller et al., "Statistical Approach and Benchmarking for Modeling of Multi-dimensional Behavior in TRISO-coated Fuel Particles," J. Nuclear Materials, forthcoming.
2. G.K. Miller et al., 2001, "Consideration of the Effects on Fuel Particle Behavior from Shrinkage Cracks in the Inner Pyrocarbon Layer," *Journal of Nuclear Materials*, Vol. 295, pp. 205-212.

3. D. A. Petti et al., "Development of Improved Models and Design for Coated Particle Gas Reactor Fuels," 2002 Annual Report, INEEL/EXT-02-01493, Nov. 2002.

4. L. L. Snead and D. A. Petti, "Improving the Integrity of Coated Particle Fuels: Measurements of Constituent Properties of SiC and ZrC, Effects of Irradiation and Modeling," NERI Proposal, April 2002.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Inner PyC layer Fast fluence	Accumulated fast neutron fluence greater than 0.18 MeV

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 8	Remedy:
Rationale: Fast fluence affects shrinkage and swelling of the layer. This dimensional change induces stresses in the IPyC layer which if high enough can cause failure.	Rationale: Shrinkage of IPyC layer is a strong function of fast fluence and anisotropy and is well known.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Inner PyC layer	Unrestrained radial and tangential changes with fast fluence
	Dimensional change	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 7	Remedy:
Rationale: Shrinkage rate under irradiation is critical to understanding structural response of IPyC and TRISO coating. The shrinkage is reasonably well known.	Rationale: Shrinkage of IPyC layer is a strong function of fast fluence and anisotropy and is well known.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Inner PyC layer Anisotropy	Operation-induced (thermal + radiation) change in grain orientation along principal directions as measured by the BAF

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 8 (German), 6 (U.S.)	Remedy: Await results from DOE AGR program.
Rationale: The degree of anisotropy is the critical measure of dimensional stability of the PyC under irradiation. If the PyC has too high an anisotropy, the differential shrinkage under irradiation will produce tensile stress in the PyC that can cause it to fail. If the other layers remain intact then little fission product release is expected. However, if the SiC is defective, then some fission product release will occur during normal operation and under off-normal conditions. The technical basis for the PyC BAF is found in Reference 1.	Rationale: There is a significant amount of information in the literature that outlines the importance of anisotropy to performance of PyC under irradiation. (see ref. 2). The ability to accurately measure the BAF has been a problem in U.S. fuel but not in German fuel, which is the reason for the difference in ranking above. (see ref 4) The new DOE AGR program (see ref. 5) will attempt to develop new more accurate methods to measure anisotropy.	Closure Criterion:

Additional Discussion

1. NP-MHTGR Fuel Product Specification Basis Report, CEGA-000396, June 1992
2. D.G., Martin, April 2000, *Pyrocarbon in High Temperature Nuclear Reactor in Irradiation Damage in Graphite due to Fast Neutrons in Fission and Fusion Systems*, Report IAEA-TECDOC-1154.
3. D. A. Petti et al., “Key Differences in the Fabrication, Irradiation, and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance,” INEEL/EXT-02-00300, June 2002.
4. Technical Program Plan for the Advanced Gas Reactor Fuel Development and Qualification Program, ORNL/TM-2002/262, Nov. 2002

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Inner PyC layer Cracking	Lengths, widths, and numbers of cracks produced in layer during operation

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 6	Remedy:
Rationale: Cracking in the IPyC as a result of high tensile stresses in the layer can lead to a stress concentration in the SiC layer that can cause failure and thus fission product release. Fission products are often found near cracks (as a result of the fast diffusion path to the SiC layer).	Rationale:	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Inner PyC layer Debonding	Separation of PyC layer from SiC layer

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 5	Remedy:
Rationale: Debonding can lead to stress concentrations in the SiC layer near the debonding point and cause failure of the SiC layer and fission product release.	Rationale: Debonding of the IPyC layer is often seen in U.S. fuel and rarely if ever in German fuel due to the difference in the interface between the layers. Key issue is the bond strength between the IPyC and SiC.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Inner PyC layer Condensed phase diffusion	Inter granular diffusion and/or intragrannular solid-state diffusion

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 7	Remedy:
Rationale: Probably the mechanism of transport of the metallic fission products through this layer, along crystallite edges and between graphite layers etc.	Rationale: Effective diffusion coefficients have been measured for metallic fission products (Cs, Ag) through IPyC	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Inner PyC layer Gas phase diffusion	Diffusion of gaseous fission products through layer (Knudsen and bulk diffusion through pore structure, and pressure driven permeation through structure)

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 7	Remedy:
Rationale: May be the mechanism responsible for the transport of gaseous fission products through the IPyC layer.	Rationale: Effective diffusion coefficients exist for noble gases through the IPyC. Detailed models for gas phase diffusion that take into account explicitly the porosity and void structure do not exist.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	SiC Layer	Kernel migration (amoeba effect)
	Kernel interaction with SiC layer	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 8	Remedy:
Rationale: Kernel migration is not a major failure mechanism in UCO fuels. In UO_2 fuels in pebble beds like PBMR, the limits imposed on power per particle in the design limit migration.	Rationale: Kernel migration has been measured in coated particle fuel with UO_2 kernels. No significant migration has been observed in UCO. It is a function of temperature and temperature gradient.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	SiC Layer Fission product corrosion	Attack of layer by fission products, e.g., Pd

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 6	Remedy:
Rationale: Fission product attack of the SiC layers has been observed in many irradiation experiments. The attack is thought to be a function of concentration of the fission product (burnup), temperature and temperature gradient across the particle (power density of the particle).	Rationale:	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	SiC Layer Heavy metal attack	Damage to layer due to fissioning of heavy metals dispersed in the layer

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 6	Remedy:
Rationale: This was a problem in early coated particle fuel because during SiC formation in the coater, chlorine decomposed from the MTS used to make the SiC would attack the kernel and form uranium chloride which is volatile and would become trapped in the SiC layer during the CVD process. Subsequent irradiation of the fuel causes the uranium in the SiC layer to fission damaging the layer.	Rationale: Modern fabrication methods limit this effect to very low levels.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	SiC Layer Cracking	Lengths, widths and numbers of cracks produced in layer during operation

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 7	Remedy:
Rationale: Cracking of the SiC layer will allow metallic fission products to be released from the coated particle. (Fission gases will still be retained if the OPyC is intact).	Rationale:	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	SiC Layer Condensed phase diffusion	Inter granular diffusion and/or intragrannular solid-state diffusion

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 7	Remedy:
Rationale: Surface or grain boundary diffusion is probably the mechanism responsible for Cs and Sr transport through the SiC layer. Activation energies in coated particle fuels are similar to that expected for grain boundary diffusion (~ equal to the heat of vaporization for the fission product).	Rationale: Effective diffusion coefficients have been measured for fission products of interest.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	SiC Layer Gas phase diffusion	Diffusion of gaseous fission products through layer (Knudsen and bulk diffusion through pore structure, and pressure driven permeation through structure)

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 7	Remedy:
Rationale: Probably the mechanism responsible for gaseous fission product transport through the layer.	Rationale: Models have not been developed that correlate the observed release with the microstructural features such as pores, microcracks, tortuosity, etc. that would be needed for a gas transport model. Instead effective diffusivities have been measured.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Outer PyC layer Radiation induced creep	Strain release as a result of radiation induced dimensional change

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 6	Remedy:
Rationale: Irradiation induced creep is important in determining the structural stability of the layer but it is much less important than in the IPyC, thus its influence on fission product release is not very important.	Rationale: Has been measured and stress models suggest it is not very important	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Outer PyC layer	Unrestrained radial and tangential changes with fast fluence
	Dimensional change	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 7	Remedy:
Rationale: Determines stresses in the OPyC layer and its propensity to fail. Need to have other layers (e.g. SiC) failed as well to have releases of fission products.	Rationale: Shrinkage rate under irradiation is reasonably well known.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Outer PyC layer Anisotropy	Operation-induced (thermal + radiation) change in grain orientation along principal directions as measured by the BAF

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 7	Remedy:
Rationale: The degree of anisotropy is critical measure of dimensional stability of the PyC under irradiation. If the PyC has too high an anisotropy, the differential shrinkage under irradiation will produce tensile stress in the PyC that can cause it to fail. If the other layers remain intact then little fission product release is expected. However, if the SiC is defective then some fission product release will occur during normal operation.	Rationale: Anisotropy has not been a big problem with OPyC layer unlike the situation with the IPyC layer.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Outer PyC layer	Solid state diffusion
	Condensed phase diffusion	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 7	Remedy:
Rationale: Probably the mechanism of transport of the metallic fission products through this layer, along crystallite edges and between graphite layers etc.	Rationale: Effective diffusion coefficients have been measured for metallic fission products (Cs, Ag) through IPyC.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Outer PyC layer Gas phase diffusion	Transport through pores and void structures by vapors, e.g., noble gases

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 7	Remedy:
Rationale: May be the mechanism responsible for the transport of gaseous fission products through the OPyC layer.	Rationale: Effective diffusion coefficients exist for noble gases through the OPyC. Detailed models for gas phase diffusion that take into account explicitly the porosity and void structure do not exist.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Outer PyC layer Cracking	Lengths, widths and numbers of cracks produced in layer during operation

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 3	Remedy:
Rationale: Cracking of the OPyC does not result in fission product release directly. The SiC must also be failed to result in fission product release. OPyC has never failed of it own accord but usually because of interactions with the matrix material in U.S. fuel.	Rationale:	Closure Criterion:

Additional Discussion

Appendix B.2

Detailed PIRT Submittal by the ORNL Panel Member

R. Morris

TRISO Fuel PIRT: Operations

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Fuel element	Local temperature in the fuel element
	Temperature	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 7	Remedy: Continue to improve material properties to reduce the uncertainty.
Rationale: The temperature of the fuel strongly affects its performance and drives the diffusion of fission products in the matrix.	Rationale: The core can be modeled fairly well; uncertainties come from material properties. Core modeling at present is adequate for the concept development.	Closure Criterion: Fuel temperatures uncertainties that are within acceptable limits. The current level of knowledge is likely acceptable.

Additional Discussion

The average fuel temperature probably has less uncertainty than the local temperature peaks. Since the fission product release can be dominated by a small number of particles, knowledge of the peak temperatures and the associated fuel volume is important. Likewise diffusion is driven by temperature.

Additional uncertainties have been observed in pebble bed reactors (AVR melt-wire experiments), where observed peak temperatures were significantly higher than expected. This could be due to higher-than-expected flux peaking (e.g., adjacent to reflectors) or to localized cooling deficiencies. There is a basic problem of temperature measurement at the high temperatures (thermocouple accuracy and stability), and there is no reasonable way to insert probes into the pebble bed.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Fuel element Fast fluence	Accumulated fast neutron fluence greater than 0.18 MeV

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 7	Remedy: Examine the fluence behavior if the fuel is to function outside of the tested limits or if new fuel designs are forthcoming.
Rationale: The fast fluence causes material changes that affect the performance of the fuel, generally in a negative way.	Rationale: For modest burnup fuel (~10%) at temperatures somewhat lower than those in the gas turbine pebble bed, reasonable limits for the fluence are known and have been tested. These limits may change if higher burnups and temperatures are pursued.	Closure Criterion: Satisfactory fuel performance.

Additional Discussion

Extensive testing was done of German coated particle fuel for steam cycle and process heat conditions. For a summary of the testing see:

Performance Evaluation of Modern HTR TRISO Fuel, R. Gontard, H. Nabielek, HTA-1B-05/90, July 1990

A comparison of US and German results are examined in (with an examination of fast flux behavior):

Key Differences in the Fabrication, Irradiation and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance, D.A. Petti, et. al., Nuclear Engineering and Design, 222 (2003) 281-297.

For an example of a design flaw and its interaction with fast flux see:

MHTGR TRISO-P Fuel Failure Evaluation Report, DOE-HTGR-90390, 1993

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Fuel element Power density	Power per pebble or compact (W)

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 7	Remedy: None if the current operation and testing methods are acceptable.
Rationale: Power level is one factor than controls the fuel temperature. Also, past accelerated testing of US fuel has cast concerns on the acceptable test power per particle level.	Rationale: Fuel performance has been satisfactory at the German (normal and modest time acceleration) testing levels. The affects of much higher power levels are not clear. No mechanisms have come to light identifying problems, but the US fuel experience casts doubts on highly accelerated fuel testing. The important parameter is power per particle rather than the fuel element power.	Closure Criterion: Satisfactory performance.

Additional Discussion

The affects of accelerated irradiations have been of some conjecture, but no hard results have been generated. Some discussion on this topic is in:

Key Differences in the Fabrication, Irradiation and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance, D.A. Petti, et. al Nuclear Engineering and Design, 222 (2003) 281-297.

Generally, normal power levels in the particles are in the range of 0.040 to 0.100 watts per particle. Much higher levels, ~1 watt per particle, may be detrimental.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Fuel element Temperature difference	Temperature between center or centerline and surface in C

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 7	Remedy: None at present.
Rationale: The temperature difference determines the gradient across the fuel element. An excessive gradient can drive the amoeba effect.	Rationale: Modern analysis codes should allow reactor modeling to a high degree, thus great uncertainty is not expected in this area. The major source of uncertainty is likely to be the material properties and the manner in which they change with irradiation.	Closure Criterion: Verify that the codes properly predict reactor behavior.

<u>Additional Discussion</u>

Also see the entry on kernel migration. The temperature gradients in a pebble bed reactor are generally small and do not effect operation. This issue is much more important in the prismatic designs.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Fuel element Temperature-time histories	Local temporal temperature of fuel element over its lifetime

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 7	Remedy: Nothing at present unless a new design challenges the computational tools.
Rationale: Higher temperatures increase the rates of fission product diffusion and attack of the SiC coating, The average temperature would not allow one to properly predict fission product diffusion or coating attack.	Rationale: Modern analysis codes should allow reactor modeling to a high degree, thus great uncertainty is not expected in this area. The major source of uncertainty is likely to be the material properties and the manner in which they change with irradiation.	Closure Criterion: Verification of the code results.

Additional Discussion

The fission product releases from a number of different fuels at temperatures below accident temperatures are summarized in:

Fission-Product Release During Postirradiation Annealing of Several Types of Coated Fuel Particles, R.E. Bullock, Journal of Nuclear Materials, 125 (1984), pages 304-319

Fuel Performance and Fission Product Behavior in Gas Cooled Reactors, IAEA-TECDOC-978 (1997)

Also see the entry on SiC corrosion.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Fuel element Condensed phase diffusion	Inter-granular diffusion and/or intra-granular solid-state diffusion

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 6	Remedy: Defer to fission product transport area.
Rationale: The major barriers to fission product release are the particle coating layers. The diffusion through the fuel element matrix is considered to be high.	Rationale: Fuel element matrix sorption has been investigated to some extent during fuel element testing. It appears to hold up the less volatile metals to a considerable extent.	Closure Criterion: None

<u>Additional Discussion</u>

Diffusion through the fuel element matrix is fairly rapid compared to the particle coating layers. The fuel element matrix sorbs some of the released fission products (metals), but it is not a major barrier to the release of fission products. It provides some attenuation of the metal releases. This is more of an issue for general fission product transport rather than fuel behavior.

The GT-MHR may change its matrix composition from the historical resins; if so, additional investigations may be necessary. This area is generally covered in fission product transport with the core. See:

Fuel Performance and Fission Product Behavior in Gas Cooled Reactors, IAEA-TECDOC-978 (1997)

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Fuel element Gas phase diffusion	Diffusion of gaseous fission products through layer (Knudsen and bulk diffusion through pore structure and pressure driven permeation through structure)

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 7	Remedy: None
Rationale: Fission gases are assumed to rapidly move through fuel element matrix material. Transport is assumed to be 100% in a short time interval. In fact, monitoring of released gases is a way to infer fuel behavior	Rationale: Testing has shown that gas transport through the matrix material is rapid. Little holdup has been shown.	Closure Criterion: None

Additional Discussion

The release to birth rate, R/B, of the fission gases is routinely monitored as an indicator of fuel performance because the gas transport through the fuel element matrix is so high.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Fuel element	Corrosion of the fuel element outer surface by part per million level of gaseous impurities in the helium coolant
	Corrosion by coolant impurities	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 7	Remedy: None
Rationale: Coolant impurities can corrode the fuel elements over their lifetime in the core and reduce their integrity.	Rationale: Testing has shown that the present fuel elements do not suffer in the proposed helium environment.	Closure Criterion: None

Additional Discussion

Control of the helium impurities is important to assure that the fuel elements are not damaged. Processing conditions can affect fuel element performance.

The selection of the 1800-1950C temperature range for final heat treatment is partly due to the need to control coolant corrosion of pebbles. See:

Fuel Compact Design Basis Report, DOE-GT-MHR-100212, 1994

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel	Formation of CO from excess oxygen released in fission
	CO production	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 7	Remedy: If burnup beyond the German experience is necessary, complete the development of the proposed fuel type.
Rationale: CO production influences the particle pressure and amoeba behavior. It can also corrode the SiC under some conditions.	Rationale: Experiments have been conducted as well as thermochemical analyses. However, a proposed kernel type, UCO, has not been extensively tested.	Closure Criterion: Proven fuel behavior.

Additional Discussion

See the entries on kernel migration. Also:

Production of Carbon Monoxide During Burn-up of UO_2 Kerneled HTR Fuel Particles, E. Proksch, et. al., Journal of Nuclear Materials, 107 (1982) pages 280-285.

Restoration of Carbon Monoxide Equilibrium in Porous Oxide High-Temperature Reactor Fuel Particles, A. Strigl and E. Proksch, Nuclear Technology, 35 (1977), pages 386-391.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel	Fission of initial metal atoms
	Burnup	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 7	Remedy: Collect higher burnup data to fill in the database.
Rationale: Fuel performance is a function of burnup among other things. Performance appears to deteriorate with burnup. The German program saw indications of worse accident behavior at burnups in the 14% range.	Rationale: A considerable experience base exists for German based fuel at burnups in the range of 10% (In this case the level is closer to 8). However, at the higher burnups of interest to the gas turbine pebble bed and the GT-MHR, much less data is available.	Closure Criterion: Acceptable fuel behavior under the conditions of interest.

Additional Discussion

For a summary of high quality fuel performance focused toward the stream cycle pebble bed reactor see (but at burnups much lower than required by the GT-MHR):

Performance Evaluation of Modern HTR TRISO Fuel, R. Gontard, H. Nabielek, HTA-1B-05/90, July 1990

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel Kernel swelling	Volumetric expansion of kernel resulting from fissioning

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 6	Remedy: None.
Rationale: In principal, the kernel could swell up and break through the layers. In practice this has not been an important problem.	Rationale: A considerable database exists and the kernels are known to distort during irradiation and even extrude into IPyC cracks. However, this behavior has not been connected with fuel problems.	Closure Criterion: None.

Additional Discussion

Below is a picture of a kernel swelling and extruding into IPyC cracks. This particle's performance was poor due to IPyC and OPyC cracking caused by poor irradiation behavior rather than any kernel behavior. The buffer layer will generally accommodate a considerable amount of distortion.

HRB-21 fuel (ORNL)

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel Microstructure changes	Change in structure in kernel with burnup, including fission gas bubbles, grain growth and grain disintegration

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 6	Remedy: None if fuel performs as expected at the desired burnup, but testing is likely for burnups > 10%.
Rationale: At low burnup, the crystal structure of the kernel can influence the hold up of fission products. As the burnup increases, however, the structure becomes disordered and the kernel becomes less able to contain fission products within its crystal matrix.	Rationale: At low burnups, the structure of the kernel is more regular and single crystal experiments reveal that fission product hold up is better than at high burnup. The best performing fuel has been at the 10% burnup region, before extensive changes to the kernel takes place.	Closure Criterion: Acceptable performance.

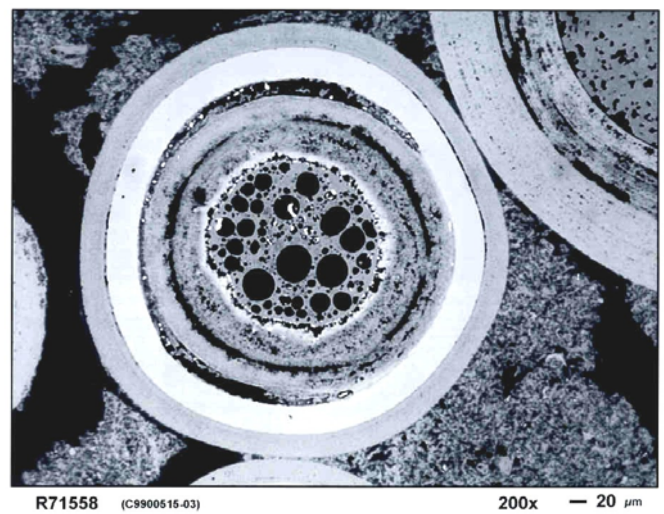
Additional Discussion

Models have been developed for the release of fission products from the fuel kernel (See the LWR literature). However, for coated particle fuel, the fission product releases (except for perhaps silver) are governed strongly by the coatings. Retention of corrosive fission products and the general immobilization of fission products are important. The fission product releases from a number of different fuel types (kernels and coatings) are summarized in:

Fission-Product Release During Postirradiation Annealing of Several Types of Coated Fuel Particles, R.E. Bullock, Journal of Nuclear Materials, 125 (1984), pages 304-319

Fuel Performance and Fission Product Behavior in Gas Cooled Reactors, IAEA-TECDOC-978 (1997)

At the right is a highly burned up (~70%) plutonium fuel (ORNL). Note the complete loss of structure in the kernel and the large voids. In this case, Pd had migrated from the kernel to the SiC coating, but the attack was minimal.



Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel Fission product chemical form	Chemical speciation of fission products as a function of burnup and temperature

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 6	Remedy: If fuel kernels other than UO_2 are to be used, testing is required to assure that they work as expected.
Rationale: The chemical form of the fission products determines their mobility within the kernel and affects the CO pressure (along with amoeba behavior) in the particle. The goal of kernel design is to minimize the migration of fission products and the particle pressure.	Rationale: A considerable amount of work has been done with kernel composition to limit the migration of fission products and control CO pressure. However, only UO_2 has been extensively tested in a high quality fuel.	Closure Criterion: Demonstrated performance under the conditions of interest.

Additional Discussion

For a discussion on kernel design to minimize CO and immobilize key fission products see:

Stoichiometric Effects on Performance of High-Temperature Gas-Cooled Reactor Fuels from the U-C-O System, F.J. Homan, et. al., Nuclear Technology, 35, pages 428-441.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel Buffer interaction	Mechanical and chemical interactions between the kernel and buffer, e.g. chemical reactions at interface and displacement of buffer by kernel growth.

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 6	Remedy: None other than to verify that the fuel performs as expected.
Rationale: In principal, interactions between the kernel and buffer could cause problems either by stresses or chemical reactions.	Rationale: A reaction layer often forms around the kernel, but no serious problems have become apparent. The major concern has been the amoeba effect, which is covered elsewhere.	Closure Criterion: Verified performance.

Additional Discussion

Thus far, the kernel-buffer interaction has not been a serious issue with the fuel. A small reaction zone forms, but its effect is limited.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel	Transport of carbon down the temperature gradient
	Kernel migration (fuel dependent)	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 7	Remedy: None other than to verify that the fuel performs as expected.
Rationale: The macro temperature difference determines the gradient across the fuel element. An excessive gradient can drive the amoeba effect.	Rationale: The amoeba effect has been experimentally investigated to a considerable extent and methods to overcome it developed.	Closure Criterion: Verified performance.

<u>Additional Discussion</u>

The amoeba effect, driven by oxygen/carbon transport, results in the kernel moving up the temperature gradient and damaging the SiC layer. See

Amoeba Behavior of UO_2 Coated Particle Fuel, M. Wagner-Loffler, Nuclear Technology, 35, pages 393-402

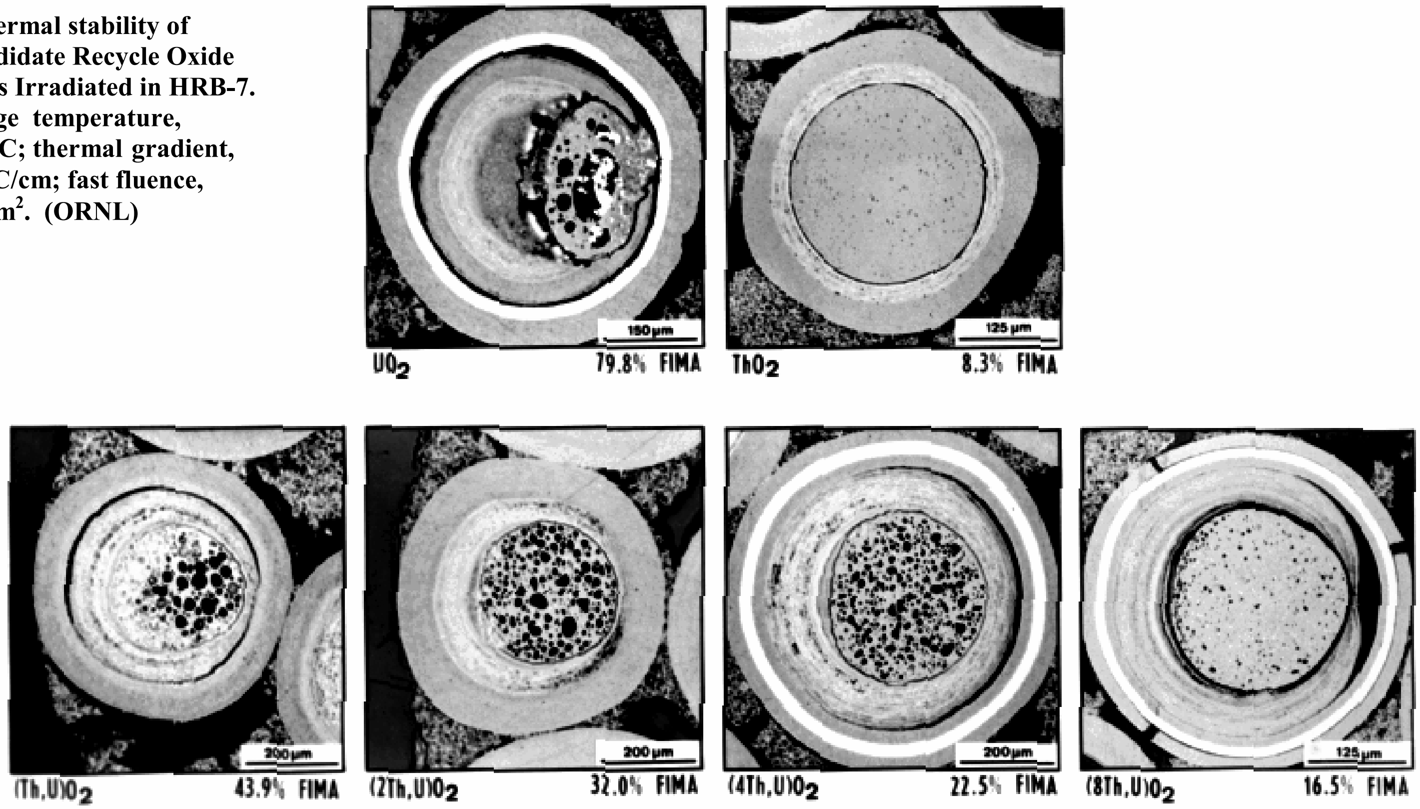
Kernel Migration in Coated Carbide Fuel Particles, O.M. Stansfield, et. al., Nuclear Technology, 25, pages 517-530

Stoichiometric Effects on Performance of High-Temperature Gas-Cooled Reactor Fuels from the U-C-O System, F.J. Homan, et. al., Nuclear Technology, 35, pages 428-441.

for an analysis of the problem and proposed fixes. The German fuel operated with low temperature gradients, so the amoeba effect was only a minor issue.

The microphotograph below illustrates the behavior.

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



Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel Fission product generation	Yield of fission products from uranium and plutonium fission

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 8	Remedy: None
Rationale: The fission products and their compounds determine the chemical behavior within the kernel.	Rationale: The yields of fissile isotopes have been investigated for some time and should be well known.	Closure Criterion: None.

Additional Discussion

This issue should present no difficulties for modern physics codes and databases. Plutonium fissions yield more noble metals, which have been implicated in SiC corrosion.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel Temperature gradient	Temperature gradient across the kernel

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 7	Remedy: None other than to verify that the fuel performs as expected.
Rationale: The temperature gradient due to the kernel (micro-gradient, not fuel element gradient) is small. Large gradients can drive fission product transport, but the in-service kernel gradients are 10-50ºC	Rationale: Experiments have not noted any significant behavior due to the small kernel microgradient.	Closure Criterion: Verified performance.

Additional Discussion

If the kernel gradients were to become large, it may be possible to drive fission product diffusion. However, for the cases of interest, the kernel gradients are small. See the entry on kernel migration for the effects of fuel element macro-gradients. Some modeling in this area is underway. It may be an issue if the fuel is pushed to its limit.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel Isotopic half life	The time lapse during which a mass of a particular isotope loses half of its radioactivity

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 8	Remedy: None
Rationale: If the half-life is greater than the diffusion time, an isotope can survive the journey from the fuel to the coolant. The half-life enters into many physics calculations. Most of the isotopes of interest will make it into the coolant	Rationale: Modern databases have collected this information to the necessary accuracy.	Closure Criterion: None

Additional Discussion

This data should not be an issue.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Buffer layer Pressure	Gas pressure generated in the void volume associated with the buffer layer

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 6	Remedy: Determine the margin the calculations and see if more work is needed.
Rationale: The pressure in the particle is important in determining the stresses in the particle layers.	Rationale: The pressure can be calculated from thermodynamic factors and fission yields. Also, some measurements have been made.	Closure Criterion: Good irradiation performance.

Additional Discussion

Also see the entry on kernel CO.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Buffer layer	Radiation or otherwise induced dimensional change
	Shrinkage	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 6	Remedy: None if fuel performs well.
Rationale: The buffer layer provides void volume for the released gases, shields the IPyC from fission recoils, and distorts to compensate for kernel swelling.	Rationale: Performance of the buffer layer has been satisfactory in the high quality fuel, at least at the 10% burnup level. It is desired to keep it from cracking to minimize kernel extrusion and maintain good thermal properties, but no serious problems surround the buffer layer.	Closure Criterion: None.

Additional Discussion

Also see kernel swelling. The buffer functions as a thermal path for the kernel heat. Distortion of the buffer could increase the thermal impedance, which may influence fission product transport.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Buffer layer	Shrinkage cracks produced in layer during operation
	Cracking	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 6	Remedy: None
Rationale: The buffer layer provides void volume for the released gases, shields the IPyC from fission recoils, and distorts to compensate for kernel swelling. Cracks can focus recoils and fission products on an area of the IPyC.	Rationale: It is desired to limit cracking to minimize kernel extrusion and avoid exposing the IPyC to recoils, but no serious problems surround the buffer layer in the German material (pebbles).	Closure Criterion: None

Additional Discussion

See buffer layer shrinkage**.** Some US fuel tests have seen cracking of the buffer layer.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Buffer layer	M-CO species partial pressures
	Carbonyl vapor species	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 1	Remedy: Determine if such species can exist under the conditions of interest.
Rationale: There is no evidence that these species cause any problems. If necessary, the thermochemical analysis can be done to see if they can even exist under coated particle conditions.	Rationale: There has been no reason to search for unusual chemical species to date.	Closure Criterion: Good fuel performance.

Additional Discussion

Compounds of this nature do not appear to be necessary to explain the fuel behavior. If the situation arises, a thermochemical analysis can be performed to investigate their likely existence and behavior.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Buffer layer Temperature gradient	Temperature difference across the buffer layer

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 6	Remedy: None if present design and fabrication methods are observed.
Rationale: An excessive temperature gradient across the buffer layer can lead to higher kernel temperatures and perhaps greater fission product movement or particle pressures.	Rationale: Excessive temperature gradients might come from high power operation, a much thicker than designed buffer layer, or a poor particle design. Present design and fabrication methods are expected to resolve problems of this nature.	Closure Criterion: None.

Additional Discussion

Also see the entries on CO and kernel migration.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Buffer layer	Inter-granular diffusion and/or intra-grannular solid-state diffusion
	Condensed phase diffusion	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 5	Remedy: None
Rationale: The buffer layer is porous and is not expected to retain fission products to a significant degree.	Rationale: The fission product retaining layers are considered to be the PyC and SiC layers, little credit is given to the buffer.	Closure Criterion: None

<u>Additional Discussion</u>

Diffusion though the buffer layer is generally high; cracks in the buffer layer can allow fission products to concentrate in specific areas on the IPyC. Currently, modeling is underway to understand the effects of short diffusion paths.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Buffer layer Gas phase diffusion	Diffusion of gaseous fission products through layer (Knudsen and bulk diffusion through pore structure and pressure driven permeation through structure)

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 6	Remedy: None
Rationale: The buffer layer is porous and is not expected to retain fission products to a significant degree.	Rationale: Testing with cracked layer particles has shown that gases rapidly move through the buffer. The fission product retaining layers are considered to be the PyC and SiC layers, little credit is given to the buffer.	Closure Criterion: None

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Buffer layer	Buffer damage arising from capture of high-energy fission products
	Recoil effects	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 5	Remedy: If this is an issue, consider using radiation damage models to sort out the effects.
Rationale: High energy recoils can cause a great deal of material damage. The buffer layer is the layer of first contact.	Rationale: The buffer layer was added to help protect the IPyC from recoil damage as well as gas expansion volume. Results to date indicate that it is working in a satisfactory manner. However, the damage due to recoil damage versus that due to fast fluence is not clear.	Closure Criterion: None

Additional Discussion

The Buffer layer is damaged by both recoils from the kernel and the fast flux. In principal, cracks in the buffer can allow recoils to strike the IPyC and damage it, although this effect has not been examined in great detail. This is one area where burnup acceleration might have an effect, other things being equal. The greater acceleration would cause a greater damage rate to the buffer.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Inner PyC layer Radiation induced creep	Strain release as a result of radiation induced dimensional change

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 5	Remedy: Devise better ways to characterize PyC.
Rationale: The structural properties of IPyC are important for maintaining the integrity of the particle. Creep relieves some of the stresses caused by shrinkage.	Rationale: Much data is available on the subject, but variabilities in PyC and difficulties in PyC material measurements lead to uncertainties.	Closure Criterion: Irradiation performance that can be correlated with material properties.

Additional Discussion

Recent PyC issues are discussed in:

Key Differences in the Fabrication, Irradiation and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance, D.A. Petti, et. al., Nuclear Engineering and Design, 222 (2003) 281-297.

TRISO Fuel Particle Coating Design Basis, DOE-GT-MHR-100225

MHTGR TRISO-P Fuel Failure Evaluation Report, DOE-HTGR-90390

For background see:

Nuclear Technology, 35 (1977), Number 2 (Entire issue devoted to coated particle fuel)

A somewhat dated, but still useful reference is:

Coated-Particle Fuels, ORNL-4324 (1968)

PyC material properties have been difficult to characterize in a way that correlates with irradiation behavior.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Inner PyC layer fast fluence	Accummulated fast neutron fluence greater than 0.18 MeV

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 6	Remedy: Devise better ways to characterize PyC
Rationale: The structural properties of IPyC are important for maintaining the integrity of the particle.	Rationale: Much data is available on the subject, but variabilities in PyC and difficulties in PyC material measurements lead to uncertainties.	Closure Criterion: Irradiation performance that can be correlated with material properties.

Additional Discussion

See entries on creep and anisotropy. Also, see buffer recoil damage.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Inner PyC layer Dimensional change	Unrestrained radial and tangential changes with fast fluence

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 5	Remedy: Devise better ways to characterize PyC
Rationale: The structural properties of IPyC are important for maintaining the integrity of the particle.	Rationale: Much data is available on the subject, but variabilities in PyC and difficulties in PyC material measurements lead to uncertainties.	Closure Criterion: Irradiation performance that can be correlated with material properties.

<u>Additional Discussion</u>

See entries on creep and anisotropy.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Inner PyC layer Anisotropy	Operation-induced (thermal + radiation) change in grain orientation along principal directions as measured by the BAF

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 5	Remedy: Devise better ways to characterize PyC
Rationale: The structural properties of IPyC are important for maintaining the integrity of the particle.	Rationale: Much data is available on the subject, but variabilities in PyC and difficulties in PyC material measurements lead to uncertainties. In particular, the BAF measurement has been troublesome.	Closure Criterion: Irradiation performance that can be correlated with material properties.

Additional Discussion

A major goal of HTGR fuel research is to better relate material properties to irradiation performance.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Inner PyC layer	Lengths, widths, and numbers of cracks produced in layer during operation
	Cracking	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 5	Remedy: See issues surrounding general IPyC material properties.
Rationale: Cracks in the IPyC can lead to stress risers that fracture the SiC and avenues for SiC corrosion.	Rationale: This issue is similar to that surrounding the BAF as the cracks come from the dimensional instability.	Closure Criterion: Acceptable and predictable performance.

<u>Additional Discussion</u>

See entries on creep and anisotropy.   Also see debonding.

Also see:

Consideration of the Effects on Fuel Particle Behavior from Shrinkage Cracks in the Inner Pyrocarbon Layer, G.Miller, et. al., Journal of Nuclear Materials, 295 (2001), pages 205-212.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Inner PyC layer	Separation of PyC layer from SiC layer
	Debonding	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 3	Remedy: Determine if this is a real issue
Rationale: If the IPyC is strongly bound to the SiC, it can impose tensile forces on the SiC as it shrinks. This can change the force distribution of the particle somewhat and make the SiC layer more susceptible to failure if the IPyC cracks.	Rationale: There is very little data on the strength of this bond. The strength of this bond is unknown and some researchers doubt that it could be very strong. Others see it playing an important role.	Closure Criterion: Resolution of the binding strength.

Additional Discussion
For a discussion of this issue see:

Key Differences in the Fabrication, Irradiation and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance, D.A. Petti, et. al., Nuclear Engineering and Design, 222 (2003) 281-297.

MHTGR TRISO-P Fuel Failure Evaluation Report, DOE-HTGR-90390

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Inner PyC layer Condensed phase diffusion	Inter granular diffusion and/or intragrannular solid-state diffusion

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 6	Remedy: See issues surrounding general IPyC material properties.
Rationale: The IPyC retains gases well, but not volatile metallic fission products like cesium. It also is important in retaining CO to limit SiC corrosion.	Rationale: IPyC transport has been studied to a fair degree. The major two issues are protecting the kernel from Cl during SiC deposition and metallic fission product transport.	Closure Criterion: Acceptable and predictable performance

Additional Discussion

See fission product release section of Nuclear Technology, 35 (1977), Number 2 (Entire issue devoted to coated particle fuel). Also see:

Fuel Performance and Fission Product Behavior in Gas Cooled Reactors, IAEA-TECDOC-978 (1997)

Metal retention is not considered to be very good with PyC, but it does delay the migration of metallic fission products.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Inner PyC layer Gas phase diffusion	Diffusion of gaseous fission products through layer (Knudsen and bulk diffusion through pore structure and pressure driven permeation through structure)

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 7	Remedy: None
Rationale: The layer retains gases well, but will transmit volatile metallics. Transport coefficients are determined by element. Generally, an effective diffusion coefficient is computed without breaking it down to this level of detail. PyCs made by different gases have different coefficients, so structure may have an effect.	Rationale: Generally fission product diffusion has been studies to a fair degree. PyC fabrication is really based on irradiation stability.	Closure Criterion: None

Additional Discussion

See fission product release section of Nuclear Technology, 35 (1977), Number 2 (Entire issue devoted to coated particle fuel). TRISO fuel depends heavily on the SiC layer. Also see:

Fuel Performance and Fission Product Behavior in Gas Cooled Reactors, IAEA-TECDOC-978 (1997)

Gas retention generally has been good. The major issue is stability under irradiation.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	SiC Layer	Kernel migration (amoeba effect)
	Kernel interaction with SiC layer	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 7	Remedy: None other than to verify that the fuel performs as expected.
Rationale: Migration of the kernel into the SiC will destroy the particle. See the kernel migration entry for details.	Rationale: The amoeba effect has been experimentally investigated to a considerable extent and methods to overcome it developed.	Closure Criterion: Verified performance.

Additional Discussion

See the kernel migration entry.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	SiC Layer	Attack of layer by fission products, e.g., Pd
	Fission product corrosion	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 6	Remedy: Monitor irradiation testing to insure this issue is under control
Rationale: Some fission products and CO can attack the SiC layer, penetrating it or weakening it so accident behavior is worsened.	Rationale: These elements and affects have been observed and studied. Controlling the production of the offending elements (burnup and kernel composition) and temperature are the normal methods of mitigation. Gettering has been used in some instances.	Closure Criterion: Satisfactory performance.

Additional Discussion

Palladium is one element that is of great concern for high temperature corrosion of SiC and temperature is an important driving factor. Corrosion rates are strong functions of temperature. See:

Fission Product Pd-SiC Interaction in Irradiated Coated-Particle Fuels, T.N. Tiegs, Nuclear Technology, 57, pages 389-398.

Silicon Carbide Corrosion in High-Temperature Gas-Cooled Reactor Fuel Particles, H. Grubmeier, et. al., Nuclear Technology, 35 (1977), pages 413-427

Out-of-Reactor Studies of Fission Product-Silicon Carbide Interactions in HTGR Fuel Particles, R. Lauf, et. al., Journal of Nuclear Materials, 120 (1984), pages 6-30

Carbon Monoxide-Silicon Carbide Interaction in HTGR Fuel Particles, K. Minato, et. al., Journal of Materials Science, 26 (1991), pages 2379-2388

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	SiC Layer Heavy metal attack	Damage to layer due to fissioning of heavy metals dispersed in the layer

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 7	Remedy: None – monitor fuel quality
Rationale: During the SiC coating process, Cl is released and this Cl may attack the kernel and transport U to the SiC layer if the IPyC is permeable.	Rationale: This effect has been studied in detail and contemporary fabrication methods limit this effect to very low levels. It is primarily a factor during fabrication.	Closure Criterion: Acceptable performance

Additional Discussion

For a discussion of fuel quality control methods see:

MHTGR Fuel Manufacturing Quality Assurance Plan, DOE-HTGR-88091

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	SiC Layer Cracking	Lengths, widths and numbers of cracks produced in layer during operation

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 6	Remedy: Continue with model development and data collection.
Rationale: SiC cracking during operation would cause the particle to release metallics, but not gases if the PyCs remain intact. They also increase the probability of later complete coating failure.	Rationale: Fuel performance models have produced rough agreement with in reactor performance.	Closure Criterion: Acceptable performance

Additional Discussion

For an application of the German and Japanese computer codes to reactor normal operation with high quality fuel see:

Modeling of Fuel Performance and Metallic Fission Product Release During HTTR Normal Operating Conditions, K. Verfondern, Nuclear Engineering and Design, 210 (2001), pages 225-238

For more on fuel performance see:

Fuel Performance and Fission Product Behavior in Gas Cooled Reactors, IAEA-TECDOC-978 (1997)

Cracking is predicted to come from particle overpressure or stresses inducted by failed or unstable PyCs. See the Design table PIRT for modeling issues.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	SiC Layer	Inter-granular and/or intra-granular solid-state diffusion.
	Condensed phase diffusion	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 6	Remedy: The best course of action is to duplicate the tested SiC.
Rationale: This layer is the primary fission product barrier for the fuel. Its behavior is very important. Generally, an effective diffusion coefficient has been assigned to the layer without regard for microstructure, although this feature is believed to affect transport.	Rationale: Many in reactor and accident tests have been done for the high quality German fuel. Excellent behavior has been observed for this particular SiC. However, this SiC must be duplicated in the next generation of fuel and face the more demanding conditions of a gas turbine	Closure Criterion: Verify the quality of the SiC through irradiation testing.

Additional Discussion

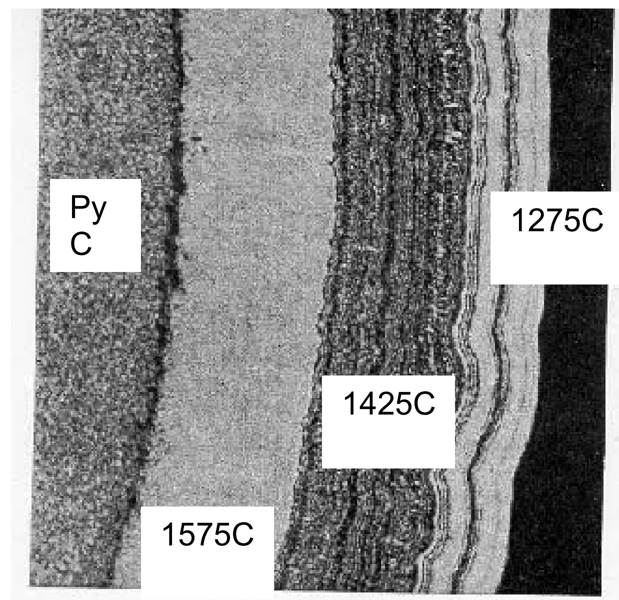
The SiC structure is usually determined by the coating conditions – gas mixtures, deposition rate, etc. – rather than a microstructure specification, although one is often included. Specific coater operation leads to a specific SiC structure. For a discussion of the desired SiC and coater conditions see:

TRISO Fuel Particle Coating Design Basis, DOE-GT-MHR-100225

For additional background see (note that he advocates a somewhat higher deposition temperature than above):

Properties of Silicon Carbide for Nuclear Fuel Particle Coating, R. Price, Nuclear Technology, 35 (1977), pages 320-336

Silver may diffuse through the grains, but this has not been resolved.



Temperature affects the coating properties of SiC.
(Etched to show behavior, from ORNL/TM-5152)

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	SiC Layer Gas phase diffusion	Diffusion of gaseous fission products through layer (Knudsen and bulk diffusion through pore structure and pressure driven permeation through structure).

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 7	Remedy: The best course of action is to duplicate the tested SiC.
Rationale: This layer is the primary fission product barrier for the fuel. Its behavior is very important. Generally, an effective diffusion coefficient has been assigned to the layer without regard for microstructure, although this feature is believed to affect transport.	Rationale: Many in reactor and accident tests have been done for the High quality German fuel. Excellent behavior has been observed for this particular SiC. However, this SiC must be duplicated in the next generation of fuel and face the more demanding conditions of a GT-MHR	Closure Criterion: Verify the quality of the SiC through irradiation testing.

Additional Discussion

See the previous entry.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Outer PyC layer	Strain release as a result of radiation induced dimensional change
	Radiation induced creep	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 5	Remedy: Devise better ways to characterize PyC
Rationale: The structural properties of OPyC are important for maintaining the integrity of the particle. Creep relieves some of the stresses caused by shrinkage. It is less important than the IPyC.	Rationale: Much data is available on the subject, but variabilities in PyC and difficulties in PyC material measurements lead to uncertainties.	Closure Criterion: Irradiation performance than can be correlated with material properties.

Additional Discussion

See the same entry for IPyC as the same issues apply.

For more on fuel performance see:

Fuel Performance and Fission Product Behavior in Gas Cooled Reactors, IAEA-TECDOC-978 (1997)

See fission product release section of Nuclear Technology, 35 (1977), Number 2 (Entire issue devoted to coated particle fuel).

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Outer PyC layer Dimensional change	Unrestrained radial and tangential changes with fast fluence

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 5	Remedy: Devise better ways to characterize PyC
Rationale: The structural properties of OPyC are important for maintaining the integrity of the particle. Also, these dimensional changes also interact with the fuel element matrix material. Its failure modestly increases the particle failure rate (modeling).	Rationale: Much data is available on the subject, but variabilities in PyC and difficulties in PyC material measurements lead to uncertainties.	Closure Criterion: Irradiation performance than can be correlated with material properties.

Additional Discussion

See the same entry for IPyC as the same issues apply. For matrix interactions see:

Fuel Compact Design Basis Report, DOE-GT-MHR-100212

For more on fuel performance see:

Fuel Performance and Fission Product Behavior in Gas Cooled Reactors, IAEA-TECDOC-978 (1997)

See fission product release section of Nuclear Technology, 35 (1977), Number 2 (Entire issue devoted to coated particle fuel).

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Outer PyC layer Anisotropy	Operation-induced (thermal + radiation) change in grain orientation along principal directions as measured by the BAF

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 5	Remedy: Devise better ways to characterize PyC
Rationale: The structural properties of OPyC are important for maintaining the integrity of the particle.	Rationale: Much data is available on the subject, but variabilities in PyC and difficulties in PyC material measurements lead to uncertainties. In particular, the BAF measurement has been troublesome.	Closure Criterion: Irradiation performance than can be correlated with material properties.

Additional Discussion

See the same entry for IPyC as the same issues apply.

For more on fuel performance see:

Fuel Performance and Fission Product Behavior in Gas Cooled Reactors, IAEA-TECDOC-978 (1997)

See fission product release section of Nuclear Technology, 35 (1977), Number 2 (Entire issue devoted to coated particle fuel).

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Outer PyC layer	Solid state diffusion
	Condensed phase diffusion	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 6	Remedy: None
Rationale: PyC generally has only limited ability to hold metallic fission products. The OPyC can hold up gases well.	Rationale: Generally fission product diffusion has been studied to a fair degree.	Closure Criterion: None

Additional Discussion

See the fission product entries for IPyC as the same issues apply.

For more on fuel performance see:

Fuel Performance and Fission Product Behavior in Gas Cooled Reactors, IAEA-TECDOC-978 (1997)

See fission product release section of Nuclear Technology, 35 (1977), Number 2 (Entire issue devoted to coated particle fuel).

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Outer PyC layer Gas phase diffusion	Transport through pores and void structures by vapors, e.g. noble gases

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 7	Remedy: None
Rationale: See fission product transport. The layer retains gases well, but will transmit volatile metallics. Transport coefficients are determined by element. Generally, an effective diffusion coefficient is computed without breaking it down to this level of detail. PyCs made by different gases have different coefficients, so structure may have an effect.	Rationale: Generally fission product diffusion has been studied to a fair degree. There has not been a need to finely split the diffusion coefficients based on microstructure. PyC fabrication is really based on irradiation stability.	Closure Criterion: None

Additional Discussion

See the same entry for IPyC as the same issues apply.

For more on fuel performance see:

Fuel Performance and Fission Product Behavior in Gas Cooled Reactors, IAEA-TECDOC-978 (1997)

See fission product release section of Nuclear Technology, 35 (1977), Number 2 (Entire issue devoted to coated particle fuel).

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Outer PyC layer	Lengths, widths and numbers of cracks produced in layer during operation
	Cracking	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 5	Remedy: See issues surrounding general IPyC material properties.
Rationale: Cracks in the OPyC can change the stress loading of the SiC and increase the probability of failure.	Rationale: This issue is similar to that surrounding the BAF as the cracks come from the dimensional instability. They can also come from matrix interactions.	Closure Criterion: Acceptable and predictable performance.

Additional Discussion

See the same entry for IPyC as the same issues apply. For matrix interactions see:

Fuel Compact Design Basis Report, DOE-GT-MHR-100212

Appendix B.3

Detailed PIRT Submittal by the SNL Panel Member

D. A. Powers

TRISO Fuel PIRT: Operations

I have addressed these questions assuming that there was regulatory interest in the releases of fission products during normal operations both because of the environmental qualification issues and because of the potential for producing a 'lift off ' source term in the event of an accident. I have also presumed that a predictive capability for this release is needed since it is unlikely that at the license certification stage sufficient information will have been generated to provide a completely empirical characterization of the radionuclide release.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Fuel element	Local temperatures in the fuel element
	Temperature	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level:8	Remedy no remediation needed:
Rationale: The local temperatures in the fuel elements will be of some importance in the prediction of the transport of fission products released from fuel particles to the surfaces of the fuel elements	Rationale: Of course, now we have no idea what the temperatures of fuel elements in the reactor core will be since there is only the barest of perhaps fanciful conceptual designs. But once a design has been done, there is the technological capability to rather accurately predict what the volume averaged temperatures of the fuel elements will be	Closure Criterion:

Additional Discussion

fe Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Fuel element Fast fluence	Accumulated fast neutron fluence greater than 0.18 MeV

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 5	Remedy:Analysis needs to be done to determine how badly damaged fuel particles will be by radiation fluxes and whether this damage will make the fuel particles incapable of significant retention of the more volatile fission products
Rationale:Radiation damage will affect the properties of the fuel element and the fuel particles the elements contain. Damage accumulation will cause the elements to swell perhaps in ways that interfere in reactor control. The accumulated damage will represent an important heat source in the event that fuel elements become overheated or undergo chemical reaction. The damage in the particles will be even more profound. Swelling of the pyrolytic graphit layers or the silicon carbide layer can rupture the particles or just create pathways of preferential mass transport of fission products through the layers. Irradiation of the kernel can cause swelling and at burnups in excess of about 70 GWd/t lead to a restructuring that expels volatile fission products from nanobubbles within fuel grains into more macroscopic bubbles from which the fission products can be readily released	Rationale: We now quite a lot about the radiation damage to urania fuel and to graphitic carbons. There does seem to be some perception in the technical community that the only energy retained in graphite as a result of radiation damage is the Wigner energy. This is quite untrue. There are types of crystallographic damage that are not annealed at the modest temperatures that will anneal Wigner energy. These types of damage will be annealed with the release of energy at much higher temperatures characteristic of the accidents of interest for these gas cooled plants. Literature data suggest that temperatures in excess of 2000 K will be needed to anneal all the radiation damage. What we do not have is much data on how the fluence of neutrons affects the release of radionuclides or their transport through the layers of the fuel particles. An open question of some importance is how sophisticated models of fission product release and transport need to be concerning the effects of radiation damage. For current LWRs where the problem is not so profound, the models take rather little account of radiation damage on release and no account of radiation damage on transport.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Fuel element	Power per pebble or compact (W)
	Power density	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level:6	Remedy:This is just another way of expressing the effects of radiation damage to the integrity of fuel elements and fuel particles. Data bases suitable for validation of quantitatively accurate models need to be available.
Rationale:The operating power provides a vicarous indication of the mean operating temperature and the neutron flux in the elements. These affect the evolution of the element and particle structures in ways that probably are not quantitatively predictable now, but certainly qualitatively understood. The qualitative effects of these changes in structure are understood, but again the effort needed to quantitatively predict these changes and their effects on release and transport has not been the subject of significant critical studies	Rationale: Effects on structure and release of fission products are at least qualitatively understood, but quantitatively accurate predictions are not possible. Data bases are too limited to develop any model confidently.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Fuel element	Temperature between center or centerline and surface in C
	Temperature difference	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level:7	Remedy: We need to do analyses to determine if thermal transport of fission products across graphite barriers significantly augments the mass transport across these boundaries by conventional diffusion
Rationale: Mass transport leading to the release of fission products from fuel or transport of released fission products across the layers in fuel particles is usually thought of as a chemical diffusion problem as it is in conventional fuels that do not have large temperature gradients during accidents (Though they have substantial gradients during operations and these gradients are known to cause movement of fission products between the centerline of the fuel and the periphery.) In coated particle fuels there will be gradients of temperature and these can be significant – perhaps large enough that they cause thermal diffusion of radionuclide species to become commensurate with chemical diffusion	Rationale: Not even the models for thermal diffusion along with multicomponent diffusion have been setup for the coated particle fuels. We have no idea how big is the thermal diffusion effect during either normal operations nor during accident conditions. Test data on fission product release has been taken under conditions where the coated particle fuels are held isothermal so there is no information on the thermal diffusion effects. We do know that there can be an effect on the structure of fuel particles as oxidation of graphite to CO and subsequent deposition of carbon and formation of carbon dioxide cause apparent motions of kernels through the particle, thereby weakening if not destroying the layer structure of the particles	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Fuel element Temperature-time histories	Local temporal temperature of fuel element over its lifetime

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level:7	Remedy: We need to decide if we will build fuel performance models of the scope that needs to take such information into account.
Rationale: This is just the history aspect of an earlier question on the temperature of a fuel element. Perhaps it was thought that another question was needed to see if there is some consistency in the answers. Again, this is okay information to have. It is not, however, the information you want which is temperatures locally at each fuel particle and at each layer within a fuel particle.	Rationale: Again, we don't have this information for a reactor that has yet to be designed. Presumably we can get relative good information about fuel element temperatures once the machine is designed.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Fuel Element Condensed phase diffusion	Inter grannular diffusion and/or intra-grannular solid-state diffusion

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 4	Remedy: Another of the phenomena that must be considered in the development of models of fission product release during normal operations and upset conditions for coated particle fuels
Rationale: diffusion is a persistent process in the release during operations. This sets the initial conditions for release during upset events.	Rationale: Bulk and grain boundary diffusion in mildly graphitized carbon of the fuel elements are difficult to distinguish because it is not clear how to treat axial and basal plane diffusion. It is likely that diffusion on the surfaces of graphitized regions will dominate during normal operations. It is known that such diffusion is peculiar to the material of the fuel element. Though we have some useful generic understanding, we really do not now have the data for the specific material of the fuel elements	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Fuel element Gas phase diffusion	Transport through pores and void structures by vapors

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 5	Remedy: We need models of the structure and the tortuosity of the void network. We also need to decide if a fully mechanistic model of fission product release needs to be developed or we can treat the process more empirically as has been done for LWR fuel. The changes in LWR fuel microstructure are not especially dramatic from about 17 to 50 GWd/t so empirical treatments suffice. It is not clear that such empiricism will work for coated particle fuel where damage to the fuel element by irradiation is more dramatic and the eventual burnup of the fuel can be higher.
Rationale: Vapor transport through voids and pore networks is an essential step in the release process	Rationale: Once we know the structure of the void or pore network, vapor transport can be calculated with a well-developed technology. We don't really know much about the structure of the void network for the coated particle fuel elements especially as this network evolves during irradiation.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Fuel element Corrosion by coolant impurities	Transport through pores and void structures by vapors

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 4	Remedy:
Rationale: Low concentrations of oxidizing impurities will preferentially attack the pore network of the element matrix, opening the pathways for fission product transport especially under accident conditions. The attack will be slow, but it will go on for a long time. Experience indicates that graphite in use is affected in this way by gas phase impurities.	Rationale: We have a reasonably good, mechanistic understanding of the attack on graphite by low concentration impurities. We don't have data on the fuel matrix material such porosity, tortuosity, permeability. Nor can we be confident in how the effects of irradiation will interact with the slow attack on the element matrix by low levels of impurity in the gas phase.	Closure Criterion:

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel CO production	Formation of CO from excess oxygen released in fission

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level:2	Remedy: The reaction and subsequent behavior of CO will have to be included in any models of fuel performance and fission product release.
Rationale: This is an important phenomenon unique to coated particle fuels. The reaction of carbon with the uranium dioxide not only destroys the microstructure of the fuel, but produce reducing conditions that can enhance the volatility of some fission products (notable SrO, BaO, La2O3 and CeO2/CeO1.5) and depress the volatilities of others (notable Ru, Pd and Mo). Further more the product CO can pressurize the SiC 'pressure vessel' of the fuel particle. More interesting still is the fact that in a thermal gradient (which all fuel particles will be in) the product CO can transport along the gradient shifting the equilibrium to C and carbon dioxide. This results in an apparent movement of the fuel kernel across the particle impacting and even rupturing the layers that constitute barriers to fission product release from the fuel particle.	Rationale: Many of the phenomena associated with the formation of CO and its subsequent behavior can be recounted qualitatively. The quantitative, predictive modeling of these phenomena is much more difficult. For instance the kinetics of reaction of irradiated carbon and irradiated fuel are not readily modeled. CO transport in a multicomponent gas mixture in a thermal gradient is difficult to model. The heterogeneous decomposition of CO into carbon and carbon dioxide is a challenge	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel Burnup	Fission of initial metal atoms

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 2	Remedy: no remediation needed
Rationale: The fission of atoms is what gives rise to the inventory of fission products and what produces radiation damage to the fuel kernel and fuel particles. It is important in this sense. But , it can be estimated well. Assumed if need be. In fact, most accident analyses are done taking either an end of life core or some equally arbitrary, but high, value for the fuel burnup.	Rationale: We can estimate the extent of fission far more accurately than we need for predicting fuel performance and fission product release. But, we don't know when in the life of the core that we will have an accident.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel Kernel swelling	Volumetric expansion of kernel resulting from fissioning

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 5	Remedy: Whereas, it is a phenomenon that needs to be recognized in fuel behavior codes, it is relatively well understood. More important will be the modeling of more dramatic changes in fuel microstructure that will be discussed further below.
Rationale: Fuel swelling does occur and is responsible for the development of interconnected pore pathways in the fuel as burnup progresses. These pathways are essential for the release of fission products form the fuel. But, the formation of these pathways is not usually explicitly modeled in detail in the empirical models of release. Swelling of fuel kernels in coated particle fuels may have more profound consequences since the swelling can impose stresses on the layers that provide barriers to fission product release. Simple swelling is not the biggest issue associated with the planned protracted burnup of coated particle fuels. The restructuring of the kernel at the elevated operational temperatures and extended burnups is a far more important thing for coated particle fuels.	Rationale: We know a lot about the extent of swelling of fuel for burnups up to about 45 GWd/t. At higher levels of burnup there is a restructuring of the fuel to form what is called the rim region in LWR fuels. This profound change in microstructure is difficult to model as will be some of the more dramatic changes in microstructure of coated particle fuel observed in some tests	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel Microstructure changes	Change in structure in kernel with burnup, including fission gas bubbles, grain growth and grain disintegration

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level:5	Remedy In a mechanistic model of fission product release from fuel these phenomena will have to be taken into account
Rationale: The more dramatic changes in fuel microstructure associated with burnup have been discussed above. Restructuring that takes place to form fine-grained material is most important because it expels fission products into macroscopic bubbles from which they are released easily. Grain growth is seldom a major issue because grain boundaries get pinned by fission products on the grain boundaries	Rationale: We know a lot about the individual phenomena except the restructuring to form the rim region at burnups in excess of about 50 GWd/t. It has not been necessary to model these phenomena in great detail to get adequate empirical models of fission product release for LWR fuel. It is not clear if detailed modeling will be necessary for coated particle fuel that will be used to higher burnups for longer times	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel Fission product chemical form	Chemical speciation of fission products as a function of burnup and temperature

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level:5	Remedy: Experience with the VICTORIA code has shown it to be of use to model speciation in void structure of fuel to get useful models of fission product release.
Rationale: Within fuel grains themselves, there really is no speciation of fission products. They are present as substitutional or interstitial atoms or ions. The speciation of interest takes place in the grain boundaries and in the pore structure of the fuel. It has not been necessary to be exacting in the modeling of speciation in these regions to get adequate release models	Rationale: We know quite a lot about the speciation of fission products in the fuel kernels at the oxygen potentials encountered in high burnup fuel. At the much lower oxygen potential that can be maintained by the reaction of fuel with carbon, we are less well informed though speciation is usually simpler at lower oxygen potentials. An interesting issue of formation of vapor phase carbides and carbonyls arises elsewhere in this questionnaire and is an issue that has not been confronted by the reactor safety community. It might be a mechanism for the release of refractory metal fission products such as Ru, Pd and Re which are ordinarily quite nonvolatile at low oxygen potentials	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel Buffer interactions	Mechanical and chemical interactions between the kernel and the buffer, e.g., chemical reactions at interface and displacement of buffer by kernel growth

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 3	Remedy: Must be modeled in fuel behavior and fission product release codes
Rationale: Rationale discussed above in connection with the generation of CO and below in connection with the migration of the kernel. An additional consideration is the release associated with the conversion of grains of uranium dioxide to either a carbide or an oxycarbide.	Rationale: Kinetics and even the products of reaction are not known well	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel	Kernel migration (fuel dependent
	Kernel migration (fuel dependent)	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 3	Remedy: Must be modeled in fuel behavior and fission product release codes
Rationale: Rationale discussed above in connection with the generation of CO	Rationale: The problem involves transport of gases in a multicomponent mixture in a thermal gradient – a challenging problem to do correctly. It also involves the heterogeneous nucleation of carbon from the gas which is always most difficult to do without a much richer database. Out of pile tests that do not have the ambient radiation field may not properly encourage the nucleation of carbon.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel Fission product generation	Yield of fission products from uranium and plutonium fission

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 9	Remedy:no remediation needed
Rationale: We know the fission yields of uranium and plutonium isotopes far better than we know any other aspect of the fission product release and transport problem. Release modeling is not enormously dependent on the precise concentrations of the fission products. In fact, the burnup level considered for accident analysis will be quite arbitrary and it will be important that the results are not especially sensitive to the detailed inventories since we have no idea when an accident will occur.	Rationale: Source codes have been upgraded now to treat extended burnups anticipated for coated particle fuels. The inventories of fission products can be calculated far more accurately now than any other aspect of the source term problem.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel Temperature gradient	Temperature gradient across the kernel

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level:3	Remedy: Analyses and even experiments will have to be done to ascertain if the temperature gradients across fuel elements and fuel particles are important to the phenomena of release and transport
Rationale: Thermal gradients of fuel particles embedded in conductive graphite are unique to coated particle fuel. The importance to fission product release and fuel behavior has yet to be established in a quantitative sense. That is, we know the gradients can be big enough to potential make thermal transport commensurate with chemical transport. Whether this actually occurs will depend on the quantitative analysis. We do know about the movement of kernels as a result of CO formation and decomposition in a thermal gradient. So real effects can occur.	Rationale: The quantitative importance of the thermal gradient on fuel behavior and fission product release has not yet been quantitatively established. There are not the data needed to assess the importance of the gradient such as thermal diffusion coefficients or heat of transport values for most of the fission products of interest.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Kernel Isotopic half life	The time lapse during which a mass of a particular isotope loses half of its radioactivity

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 9	Remedy: no remediation needed
Rationale: So few isotopes have half-lives commensurate with the period of an accident that it has seldom been necessary to include decay effects on fission product concentrations in release and transport models. They are needed for consequence modeling.	Rationale: We know half lives of isotopes far more accurately than we know most aspects of fission product release and fuel behavior	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Buffer layer Pressure	Gas pressure generated in the void volume associated with the buffer layer

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level:4	Remedy: phenomenon that needs to be recognized in models of fission product release and fuel behavior
Rationale: Pressurization threatens of course the integrity of the barriers to fission product release. Pressurization also reduces the gas phase diffusion coefficients of vaporized fission products. Pressurization comes from both CO formation (discussed above) and fission gas release from the fuel	Rationale: We have some understanding of fission gas release from the kernel to the rest of the coated fuel particle. We are less confident in predicting the magnitude of CO formation.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Buffer layer	Radiation or otherwise induced dimensional change
	Shrinkage	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 2	Remedy:We really do not know how important the radiation damage is to the buffer layers within the fuel particle. Analyses need to be done to see how well these damage processes must be modeled in fission product release models and fuel behavior modesl
Rationale:Radiation damage can compromise the integrity of barriers, but the 'integrity' of buffer layers is not so essential. Really the question at hand is whether the radiation damage sustained by the buffer layer makes it more reactive toward with fission products or the fuel.	Rationale: I am not aware of data on the kinetics of irradiated carbon reactions with either fission products or irradiated fuel that would suggest that irradiation inhibits or accentuates fission release or transport.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Buffer layer Cracking	Shrinkage cracks produced in layer during operation

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level:3	Remedy Data or analyses are needed to ascertain if sophisticated modeling of the cracking in layers needs to be included to have an adequate model of fission product transport across the layers from the fuel
Rationale: Rupture of the layer provides a pathway for facile transport of fission products across the layer. (Cracks also provide high energy surfaces that might absorb fission products at low concentrations in ways that uncracked material does not do.) Perhaps of more importance than shrinkage cracks is either thermal shock or thermal fatigue of the material during shutdown and start up of the reactor	Rationale: I am not aware of models that will reliable predict the cracking of the layer materials in coated particle fuel. The database that could be used for developing such a model is thin.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Buffer layer Carbonyl vapor species	M-CO species partial pressures

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 4	Remedy: Analyses and literature reviews need to be undertaken to identify potential carbonyl – especially mono- and dicarbonyls that could contribute to the vapor pressures of fission products
Rationale:Within the ‘pressure Vessel’ of the coated particle fuels, rather high partial pressures of CO can develop - ~50 atms. At these elevated pressures especially the noble metals such as Ru, Pd, Re, Rh, etc, can react to form vapor phase carbonyls such as PdCO etc. Such carbonyls are not considered in the analyses of fission product release from LWR fuel because the environments do not have high enough partial pressures of CO and thermal conditions would likely lead to the quantitative reductions of such carbonyls to metals or oxidation to oxides. They may be unique to the coated particle fuels while the SiC layer is sufficiently intact to maintain pressure.	Rationale: We do know that the refractory metal fission products of interest can under some circumstances form carbonyls. The circumstances where this has been studied involve lower temperatures and partial pressures of CO about what is anticipated to exist in fuel particle. There has been less study of high temperature carbonyls of lower order (mono- and di-carbonyls) that may be sufficiently stable to augment the fission product vapor pressure. The literature may not be an adequate source of information on such species since there has been little incentive to explore the vapor phase for such species. Computational chemistry has advanced sufficiently that it may be possible to use *ab initio* techniques to search for stable carbonyls that will affect fission product vaporization.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Buffer layer Temperature gradient	Temperature difference across the buffer layer

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level:3	Remedy:Analyses and even experiments need to be undertaken to see if thermal gradients in the fuel particles are large enough to affect the transport of fission products
Rationale: Buffer layers act as insulating layers so there can be large thermal gradients across these layers that may affect fission product transport from the fuel kernel to the bulk fuel element	Rationale: I am not aware of significant studies of the effects of thermal gradients on fission product transport in a multicomponent gas environment where the vapors have relatively high molecular weights and the ambient gas has relatively low molecular weight	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Buffer layer	Inter grannular diffusion and/or intra-grannular solid-state diffusion
	Condensed phase diffusion	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level:2	Remedy: phenomenon that must be included in models of fission product transport from fuel kernels to the ambient fuel element
Rationale: Intergrannular diffusion or more usually grain boundary diffusion is a faster mechanism for fission product transport across buffer materials than intra grannular diffusion at the temperatures of operations.	Rationale: I am not aware of data on grain boundary diffusion coefficients for important radionuclides in buffer materials	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Buffer layer Gas phase diffusion	Diffusion of gaseous fission products through layer (Knudsen and bulk diffusion through pore structure, and pressure driven permeation through structure)

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level:5	Remedy: phenomenon that must be included in a model of fission product transport from the fuel kernel to the ambient fuel element
Rationale: Vapor transport through the void network in the buffer material is the fastest way to transport fission products across the layer. The transport may be by gas diffusion or by Knudsen diffusion	Rationale: We know how to model vapor transport through a void network if we know the vapor species and the structure of the network. We have some concerns over the speciation of the gas phase in the unique circumstances of high pressure CO within the SiC layer as discussed above. We have very little knowledge about the structure of the void network in the buffer layer	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Buffer layer Recoil Effects	Buffer damage arisng from capture of high-energy fission products

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level:5	Remedy:
Rationale: About 1-2% of the fission products generated in the fuel particle will escape the kernel into the buffer region by recoil. The high LET of these particles will cause displacement of atoms in the layer. But, the layer is already highly disordered by design. At most, recoil will alter some of the second order features of the buffer layer that affect fission product transport.	Rationale: We have generic knowledge about the radiation damage to graphite by high LET radiation. We do not have a great deal of detail about the specific effects on retention of fission products in the damaged graphite	Closure Criterion:

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Inner PyC layer Creep	Strain release as a result of radiation induced dimensional change

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level:4	Remedy:Analyses need to be done to see if it will be necessary to model creep in models of fission product release and transport or in fuel behavior models
Rationale: Creep is one of the mechanisms by which a material responds to stresses induced by pressure or differential thermal expansion. It seems to me quite unlikely that the displacements of atoms induced by radiation would lead to a stain reduction. Rather they would produce local stresses that would induce local creep to reduce the strain. It is not clear to me that creep rupture is a significant mechanism for the failure of layers within the fuel particles that act as barriers to fission product transport from the kernel to the ambient fuel element.	Rationale: There is a lot of data on the creep and creep rupture of graphite materials with and without irradiation. It is unclear how much of this material is applicable to the PyC inner layer	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Inner PyC layer fast fluence	Accumulated fast neutron fluence greater than 0.18 MEV

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level:5	Remedy: no remediation is necessary
Rationale: Fast fluence and the development of dislocations within the pyrolytic graphite will affect the condensed phase transport of fission products across the layer. The accumulation of this damage will also cause the material to grow, perhaps to the point of rupture. Certainly, it will strain the SiC layer	Rationale: existing database can be used to meet modeling needs for fission product release. Existing knowledge may be adequate for the prediction of structural integrity effects.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Inner PyC layer Dimensional change	Unrestrained radial and tangential changes with fast fluence

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level:4	Remedy: Analyses using estimated effects of irradiation on growth and strength to ascertain if this phenomena needs to be included in codes used to predict fuel behavior and the releases of radionuclides from fuel during normal and upset conditions
Rationale: It is clear that irradiation will produce growth of the PyC layer. Because of non-uniformity of the layer growth will not be uniform and may result in rupture of the layer. Rupture will create preferential pathways for fission product transport form the fuel kernel surface to other regions of the particle and thus facilitate at least one step in the overall process that leads to release of fission products from the fuel compacts to the reactor coolant system. I am, however, not aware of data or analyses that show the growth will be sufficient to lead to such ruptures.	Rationale: There appears to be a rather limited data base on the irradiation induced growth of the layers in fuel particles. Some estimates are possible from the existing, extensive literature on irradiation of carbon.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Inner PyC layer Anisotropy	Operation-induced (thermal + radiation) change in grain orientation along principal directions as measured by the BAF

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 3	Remedy: Analyses need to be done to see if grain orientation significantly affects fission product transport within the fuel particle
Rationale: Grain orientation may affect integrity of the fuel particle. Whether these changes in the orientation significantly affect fission product diffusion is an open question. The changes are more likely to be from preferential orientation to more random orientation that will make data on polycrystalline material more suitable for analysis of the fission product transport process	Rationale: A great deal of heat and rather little light has been generated in connection with the issue of anisotropy in the carbon of coated particle fuels. Thermal data on the evolution of this anisotropy will be largely useless since irradiation will have a profound effect. In fact, the irradiation effects on the carbon are very likely to overwhelm the more subtle effects of anisotropy.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Inner PyC layer Cracking	Lengths, widths, and numbers of cracks produced in layer during operation

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 3	Remedy: transport through cracks in layers will be an important mechanism for fission product transport from the kernel to the bulk fuel element
Rationale: Vapor transport through cracks will be a very facile way to move fission products from the fuel kernel to the bulk fuel element. The magnitude of contribution this mechanism makes will depend on the number and geometry of cracks through a layer	Rationale: I am not aware of any predictive capacity to estimate the number or size of cracks in layers. Experimental data are needed on transport through cracks since it unlikely that microscopic examination of layers will include all cracks that are capable of contributing to the transport process.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Inner PyC layer Debonding	Separation of PyC layer from SiC layer

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level:3	Remedy: no remediation needed
Rationale: The separation of the PyC layer from SiC can affect the acceptability of fuel for use in a reactor. It is unlikely that a fission product transport model will ever be devised of sufficient sensitivity to reflect any effect of this separation on fission product transport. The only reason to be concerned with this separation is if it leads to rupture of the SiC layer which has been discussed elsewhere	Rationale: Separation has been observed in some but hardly all fuel particles tested to date. The conditions leading to separation are not understood and the subject is still being investigated by those involved in the manufacture of suitable coated particle fuel	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Inner PyC layer Condensed phase diffusion	Inter granular diffusion and/or intra-grannular solid-state diffusion

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level:1	Remedy: A transport mechanism that must be included in models of fission product release and transport from fuel
Rationale: Intergrannular diffusion of fission products is expected to be a faster mechanism of transport than intragrannular diffusion, but not as fast as vapor transport through the pores. Some evidence now available suggest that this mechanism may be especially effective for radioactive silver and even radioactive palladium	Rationale :Intergrannular diffusion depends very much on the grain structure and impurity levels of the intergrannular layers which are not known for the fuel that will finally be found acceptable for use in reactors. Intergrannular diffusion is inherently not predictable. It really has to be measured and correlated for modeling purposes.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Inner PyC layer Gas diffusion	Diffusion of gaseous fission products through layer (Knudsen and bulk diffusion through pore structure and pressure driven permeation through structure)

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level:4	Remedy: It will be important to both model the transport and the speciation of the vapor phase to account for this important mechanism of fission product transport. Data on the pores and void structures will be needed though models can be set up now using estimates of these data.
Rationale: Vapor phase transport is potentially the fastest of the mechanisms for transport across the PyC layer of the more volatile fission products. Which fission products can meaningfully avail themselves of this mechanism depends on the vapor phase speciation of the fission products. Certainly Ag, Cs I and even Te can transport readily by vapor phase processes. Other fission products normally thought to be refractory based on experience with LWR fuel may also transport this way if volatile carbonyls and carbides can form.	Rationale: I am not aware of realistic analyses of either the fission product speciation in the fuel layers or transport analysis of vapors through void and pore structures in layers. Once data on the void and pore structures were available and meaningful analyses of the fission product speciation were done, the analyses of transport even accounting for the thermal gradient can be done.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	SiC Layer	Kernel migration (amoeba effect)
	Kernel interaction with SiC layer	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level:6	Remedy: A process that will have to modeled in a fission product release model or in a fuel behavior model
Rationale: This phenomenon is discussed above it can lead to the rupture of barriers to fission product transport from the kernel to the ambient fuel elements.	Rationale: The phenomenon is understood in a qualitative way but quantitative analysis will be a challenge as discussed above. It involves gas phase processes in a nonequilibrium situation as well as heterogeneous nucleation.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	SiC Layer Fission product corrosion	Attack of layer by fission products, e.g., Pd

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level:4	Remedy: Analyses of fission product interactions with carbon need to be done to ascertain what of these interactions need to be included in fission product release models
Rationale: The interaction phenomenon involving palladium and carbon is interesting. Not a lot of other examples have been identified and Pd is not one of the fission products that is of major concern,	Rationale: Literature data can probably be used to identify other instances in which strong interactions of fission products with carbon are going to be important	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	SiC Layer Heavy metal attack	Damage to layer due to fissioning of heavy metals dispersed in the layer

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level:6	Remedy:no remedy needed
Rationale: Such fissioning is recognized as a threat to barrier integrity and manufacturers are moving to control contamination of the layer material to prevent this from becoming a major issue.	Rationale: Bounding estimates of the concentrations of heavy metals in the layer can be made since there are very tight controls on the heavy metal content of the SiC used in coated particle fuels. Useful estimates of fission damage to the layer can then be made and used to assess the impact of the phenomenon.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	SiC Layer	Lengths, widths and numbers of cracks produced in layer during operation
	Cracking	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level:1	Remedy: It will be important to include the possibility of preferential transport of fission products along cracks in the layer
Rationale: Cracks in the SiC layer will provide preferential pathways for the movement of fission products across the layer	Rationale:I am aware of no predictive capability to estimate the number, width and length of cracks in the SiC layer. Worse, I am not persuaded that there are tools to examine fuel particles capable of detecting cracks that while small may still provide a dominant pathway for fission product transport across the SiC layer	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	SiC Layer Condensed phase diffusion	Inter granular diffusion and/or intra-grannular solid state diffusion

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level:1	Remedy: This is a transport mechanism that will have to be included in a model of fission product release and transport from fuel during normal operations and during upset conditions
Rationale: Intergrannular diffusion will be a faster mechanism of fission product transport across the SiC layer than intragrannular diffusion during operations, but not as fast as vapor transport through cracks or even vapor transport through pore and void structures.	Rationale: Intragrannular diffusion cannot be predicted a priori. It has to be measured and correlated for a specific material under specific conditions. I am aware of no pertinent studies for SiC and it is doubtful such studies exist because the precise nature of the SiC layer in the fuel has not yet been defined	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	SiC Layer Gas diffusion	Diffusion of gaseous fission products through layer (Knudsen and bulk diffusion through pore structure, and pressure driven permeation through structure)

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level:4	Remedy: This is a transport mechanism that will have to be included in a model of fission product release and transport from fuel during normal operations and during upset conditions
Rationale: Vapor transport through void and pore structures is potentially the most rapid mechanism of fission product transport across the SiC layer	Rationale: Once the nature of the void and pore structure of the SiC layer is known and the fission product vapor speciation is known, the analyses of transport by vapor across the layer can be modelled. I am not aware of meaningful data on the void and pore structure of the SiC layer. I am not aware of technically justifiable calculations of the pertinent fission product speciation.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Outer PyC layer	Strain release as a result of radiation induced dimensional change
	Radiation-induced Creep	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level:3	Remedy: This process probably does not have to be explicitly modeled in fission product release and transport codes. Because the process can lead to distortions from idealized spherical symmetry of fuel particles, models must account for the lack of symmetry in the analysis of diffusion processes.
Rationale: Creep is one of the mechanisms available to SiC to relieve stress and creep can be accentuated by irradiation. Because of Taylor instability the creep will cause the SiC layer to distort from spherical symmetry. More important than the creep in the SiC will be the effects of irradiation on the layers bounding the SiC layer and the forces these layers place on the SiC.	Rationale: There are studies of SiC creep. It is an open issue if these studies of bulk material are pertinent to the thin layers of perhaps preferentially oriented materials to be found in the fuel that eventually gets designed for gas cooled reactors.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Outer PyC layer	Unrestrained radial and tangential changes with fast fluence
	Dimensional change	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level:2	Remedy:no remedy needed
Rationale: It is known that irradiation will cause the PyC layer to grow due to the build up of defects that are not annealed significantly at the operating temperature. These changes in geometry will not greatly affect the transport of fission products except as the defects affect diffusion processes and the loss of symmetry creates pathways for accelerated transport. These effects on transport are addressed elsewhere.	Rationale :I am not aware of data or models of the growth of the PyC layer during irradiation to fluences expected for the fuel	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Outer PyC layer Anisotropy	Operation-induced (thermal + radiation) change in grain orientation along principal directions as measured by the BAF

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 7	Remedy: no remedy needed
Rationale: PyC layers are inherently anisotropic. The anisotropy can affect diffusion but these effects will be adequately reflected in diffusion coefficients measured in prototypic circumstances	Rationale: Anisotropy of the layers are measured as part of the fuel characterization.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Outer PyC layer	Solid state diffusion
	Condensed phase diffusion	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 1	Remedy: This is a transport mechanism that will have to be included in a model of fission product release and transport from fuel during normal operations and during upset conditions
Rationale: Intergrannular diffusion of fission products across the outer PyC layer will be faster than intragrannular diffusion, but not as fast as vapor transport	Rationale: Intergrannular diffusion cannot be predicted – it can only be measured and correlated. The process is very material specific and so measurements must be done on as prototypic a material as possible. Since the actual fuel has not yet been defined, it is unlikely that there are useful data on intergrannular diffusion of fission products across the outer or the inner PyC layer	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Outer PyC layer Gas diffusion	Transport through pores and void structures by vapors

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 4	Remedy: This is a transport mechanism that will have to be included in a model of fission product release and transport from fuel during normal operations and during upset conditions
Rationale: Vapor transport across the outer PyC layer can be the most rapid of the fission product transport mechanisms	Rationale: It would be possible to predict vapor transport across the PyC layer given characterization of the structure of the void and pore network and meaningful descriptions of the vapor phase speciation. Unfortunately the needed input to the analyses are not available	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Operations	Outer PyC layer Cracking	Lengths, widths and numbers of cracks produced in layer during operation

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 1	Remedy: It will be important to make allowances in any model of fission product transport through fuel particles for the existence of cracks that provide preferential transport pathways
Rationale: Vapor transport along cracks will be an exceptionally fast mechanism for fission product transport across the PyC layer	Rationale: I am not aware of any capability to predict or any database concerning the length , width or number of cracks produced in the PyC layer during normal operations or during upset conditions	Closure Criterion:

Additional Discussion