APPENDIX E

PANEL MEMBER DETAILED PIRT SUBMITTALS FOR TRISO FUEL DEPRESSURIZATION ACCIDENT WITH WATER INGRESS

The INEEL submittal is provided in Appendix E.1 (pages E-2 through E-79).

The ORNL submittal is provided in Appendix E.2 (pages E-80 through E-160).

The SNL submittal is provided in Appendix E.3 (pages E-161 through E-238).

Appendix E.1

Detailed PIRT Submittal by the INEEL Panel Member

E. A. Petti

TRISO Fuel PIRT: Accident with Subsequent Water Intrusion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Fuel Element Irradiation history	The temperature, burnup and fast fluence history of the layer

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	7	Remedy:
Rationale: Irradiation history determines inventory at risk and initial conditions in particle relative to internal pressure in the particle and stress state.	Rationale:	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Fuel Element 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	6	Remedy:
Rationale: Mechanism describing the transport of fission products in matrix of the fuel element. Important to understanding source term for the reactor.	Rationale: Air or water ingress can change the microstructure of the matrix, which can influence the surface diffusion of fission products by making transport easier. At very low partial pressures, air and water oxidation rates can be determined by the number of active sites in the matrix at which the oxidation can occur. In some cases oxidation can be catalyzed by impurity elements that are trapped at adsorption sites in the graphitic matrix. Thus there can be competition between fission product adsorption and the reaction between the air or steam and the matrix. The isotherms are fairly well known. The key issue is whether the internal surface area of the matrix has been changed by the air or water oxidation event and thus the amount of material available for release. Dislocations and/or defects can act as trapping sites for fission products as they transport through the matrix. If the number of dislocations is about the same as the number of fission products then the effect may be important. If the fission product concentration is much greater than the dislocation density then the effect is probably second order. Exact values have not been measured nor has any transport behavior been directly correlated with these parameters. The influence of the oxidation event may be to provide enough energy to the matrix to release fission products from the traps. Sensitivity analysis can be performed to scope this out.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	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). Other factors include holdup, cracking, adsorption, site poisoning, permeability, sintering and annealing.

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	5	Remedy:
Rationale: Gas phase diffusion is thought to be the mechanism for gaseous fission product transport in the matrix.	Rationale: Air or water ingress can change the microstructure and porosity of the matrix, which can influence the gas diffusion of fission products by making transport easier. The interconnected porosity can be a transport path for the air or water intrusion. The reaction of air or water with the matrix can change the microstructure, porosity, tortuosity, and permeability, and hence affect gaseous fission product transport in the matrix.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Fuel Element: Transport of metallic FPs through fuel element	Chemical stoichiometry of the chemical species that includes the radioisotope of interest
	Chemical form	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	7	Remedy:
Rationale: Transport has been assumed to be elemental for the major fission products (Cs, Ag, I, Xe, Sr). Potential changes in chemical form due to the presence of air or water can be calculated.	Rationale:	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Fuel Element: Chemical attack by water Kinetics	Rate of reaction per unit surface area as a function of temperature and partial pressure of steam

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	6	Remedy:
Rationale: Very important to determining the overall course of the oxidation transient.	Rationale: Some reaction rate data exists and sensitivity analysis can be used to address uncertainties.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Fuel Element: Chemical attack by water Catalysis	Modification of the reaction rate by fission products or impurities

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	5	Remedy:
Rationale: Impurities can alter reaction rate and thus behavior expected in the reactor.	Rationale: Oxidation rate data have been determined for actual pebbles and compacts and thus implicitly include the effects of impurities. The effects of fission products have not been included because oxidation testing has not been performed on irradiated material. In principle sensitivity calculations can be performed with variations in the oxidation rate to bound this effect.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Fuel Element: Chemical attack by water	Changes in chemical form resulting from oxidizing or reducing fission products
	Changes in chemical form of fission products	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	7	Remedy:
Rationale: This can be important because the transport behavior is dependent on the chemical form.	Rationale: This can also be calculated for a range of oxygen potentials to determine if any of the key fission products change in chemical form during the air or water ingress accident.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Fuel Element: Chemical attack by water Changes in graphite properties	Changes in diffusivity, porosity, adsorptivity, etc.

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	6	Remedy:
Rationale: The oxidation can change the microstructure of the graphite by creating tunnels or pathways in the matrix. Thus, because the microstructure changes, the porosity, adsorptivity, etc. can also change.	Rationale: No measurements have been made on this effect. Conservative assumptions on such changes may allow sensitivity studies in this area.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Fuel Element: Chemical attack by water	Release of graphite FP inventory
	Holdup reversals	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	6	Remedy:
Rationale: As the oxidation process continues, any fission products trapped at sites in the matrix may be released because of the thermal energy associated with the oxidation.	Rationale: This can be accounted for in a very simplistic, yet conservative manner if details are not well known or more sophisticated models with detrapping can be used if the fundamental data needed for such models exist.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Fuel Element: Chemical attack by water	Impact of graphite oxidation on temperature distribution through material
	Temperature distribution	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	8	Remedy:
Rationale: Very important in doing an oxidation calculation is to make sure the temperature response of the material, as a result of the energy generation, is properly calculated.	Rationale: This is well known and can be done in most of the safety codes used by NRC (e.g. MELCOR). The degree of fine detail in the model may be an open question but can be handled with sensitivity studies.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer 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: M	6	Remedy:
Rationale: Release from intact particles is less important than from particles with exposed kernels in the presence of water.	Rationale: Effective diffusion coefficients for noble gases through PyC exist for both German and U.S. PyC. The Knudsen diffusion formalism has not been historically used in the modeling. The effect of oxidation on changes in the transport behavior has not been studied. Sensitivity studies can be performed to bound potential changes to determine the impact on the overall source term.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer Condensed-phase diffusion	Inter-granular diffusion an/or intra-grannular solid state diffusion.

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	6	Remedy:
Rationale: Release from intact particles is less important than from particles with exposed kernels in the presence of water.	Rationale: Data exist on the effective diffusivity of Cs, Ag, and Sr through the PyC layer. The mechanism responsible for the transport has not been definitively identified. The effect of oxidation on transport properties has not been studied. Sensitivity studies can be performed to bound potential changes to determine the impact on the overall source term.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer Layer oxidation	Uptake of oxygen by the layer through a chemical reaction

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	7	Remedy:
Rationale: Oxidation of OPyC is needed to understand thermal response of the particles in the fuel element.	Rationale: Reaction rates for PyC are known at these temperatures.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer Stress state (compression/tension)	The state of the forces induced by external forces that are acting across the layer to resist movement

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	8	Remedy:
Rationale: The stress state is judged to be of low importance for a chemical oxidation event.	Rationale: Stress state is easily calculated using current finite element models for coated particles.	Closure Criterion:

<u>Additional Discussion</u>

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer Intercalation	Trapping of species between crystallite planes of the graphite structure

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	4	Remedy:
Rationale: In an intact particle, little diffusion of fission products is expected. If the level of adsorption or defect sites is high in the OPyC due to neutron irradiation, for example, then these sites may be effective in holding up fission products if they are not annealed out during the oxidation event. In a failed particle, the number of fission product atoms is so large that such a mechanism is very small. This is based on diffusion and trapping modeling performed for tritium under the NPR program in the early 1990s. The oxidation event if severe enough could probably liberate any adsorbed or trapped fission products. Sensitivity studies with a diffusion and trapping model can study this in more detail to determine overall significance in the core for the oxidation event.	Rationale:	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer Trapping	Adsorption of fission products on defects

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	4	Remedy:
Rationale: In an intact particle, little diffusion of fission products is expected. If the level of adsorption or defect sites is high in the OPyC due to neutron irradiation, for example, then these sites may be effective in holding up fission products if they are not annealed out during the oxidation event. In a failed particle, the number of fission product atoms is so large that such a mechanism is very small. This is based on diffusion and trapping modeling performed for tritium under the NPR program in the early 1990s. The oxidation event if severe enough could probably liberate any adsorbed or trapped fission products. Sensitivity studies with a diffusion and trapping model can study this in more detail to determine overall significance in the core for the oxidation event.	Rationale:	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer Cracking	Lengths, widths and numbers of cracks produced in layer during operation or an accident

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	6	Remedy:
Rationale: A cracked OPyC will not retain fission gases and would act as a fast transport path for oxidation of the SiC.	Rationale: Models can be used to calculate the stress state in the OPyC layer.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer: Chemical attack by water	Rate of reaction per unit surface area as a function of temperature and partial pressure of steam
	Kinetics	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	7	Remedy:
Rationale: Oxidation of OPyC is needed to understand thermal response of the particles in the fuel element.	Rationale: Reaction rates for PyC are known at these temperatures.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer: Chemical attack by water Catalysis	Modification of the reaction rate by fission products or impurities

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	4	Remedy:
Rationale: Impurities can change reaction rates and thus influence course of the ingress event.	Rationale: Reaction rate testing of PyC would implicitly include the effects of any impurities on the overall oxidation. No chemical reaction rate measurements have been performed using irradiated PyC where fission products may be in the layer. In principle sensitivity calculations can be performed with variations in the oxidation rate to bound this effect.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer: Chemical attack by water	Changes in chemical form resulting from oxidizing or reducing fission products
	Changes in chemical form of fission products	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	7	Remedy:
Rationale: This can be important because the transport behavior is dependent on the chemical form.	Rationale: This can be calculated for a range of oxygen potentials to determine if any of the key fission products change in chemical form during the air or water ingress accident.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer: Chemical attack by water	Changes in diffusivity, porosity, adsorptivity, etc.
	Changes in graphite properties	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	6	Remedy:
Rationale: The oxidation can change the microstructure of the PyC by creating tunnels or pathways in the matrix. Thus, because the microstructure changes, the porosity, adsorptivity, etc. can also change.	Rationale: No measurements have been made on this effect. Conservative assumptions on such changes may allow sensitivity studies in this area.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer: Chemical attack by water	Release of graphite FP inventory
	Holdup reversal	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	6	Remedy:
Rationale: As the oxidation process continues any fission products trapped at sites in the PyC may be released because of the thermal energy associated with the oxidation.	Rationale: This can be accounted for in a very simplistic yet conservative manner if details are not well known or more sophisticated models with detrapping can be used if the fundamental data needed for such models exist.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer: Chemical attack by water Temperature distribution	Impact of graphite oxidation on temperature distribution through material

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	8	Remedy:
Rationale: Very important in doing an oxidation calculation is to make sure the temperature response of the material as a result of the chemical reaction is properly calculated.	Rationale: This is well known and can be done in most of the safety codes used by NRC (e.g. MELCOR). The high conductivity of the PyC should make the gradient quite small in general. The degree of fine detail in the model may be an open question but can be handled with sensitivity studies.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	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	7	Remedy:
Rationale: As the primary fission product barrier understanding the transport is very important.	Rationale: Effective diffusion coefficients exist in both the U.S. and Germany for the fission gases through the SiC. They are probably a combination of bulk diffusion and Knudsen diffusion at these high temperatures but the two mechanisms have never been individually sorted out in any experiment. The parameters needed for such detailed models and the changes in microstructure of the SiC particle to particle and/or across the layer and/or as a result of the oxidation make such an effort very expensive and time consuming. The use of effective diffusion coefficients although less scientifically satisfying is more pragmatic and may be completely acceptable in system safety analysis when accompanied by proper sensitivity studies.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	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	7	Remedy:
Rationale: As the primary fission product barrier understanding the transport is very important.	Rationale: Effective diffusion coefficients exist in both the U.S. and Germany for the metallic fission products through the SiC. They are probably a combination of bulk diffusion and grain boundary diffusion at these high temperatures but the two mechanisms have never been individually sorted out in any experiment. The parameters needed for such detailed models and the changes in microstructure of the SiC particle to particle and/or across the layer and/or as a result of the oxidation process make such an effort very expensive and time consuming. The use of effective diffusion coefficients although less scientifically satisfying is more pragmatic and may be completely acceptable in system safety analysis when accompanied by proper sensitivity studies.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer Thermal deterioration/decomposition	Decline in the quality of the layer due to thermal loading

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	8	Remedy:
Rationale: Less important in oxidation events than in the longer term traditional heatup event. (See similar factor in heatup PIRT table for more information).	Rationale:	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	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: M	7	Remedy:
Rationale: The deterioration of the SiC layer via Pd attack has been postulated as a key failure mechanism because Pd forms silicides based on phase diagram and experimental measurements. This is very important for the high burnup fuel being proposed in new reactor designs since the Pd yield from Pu fission is much greater (~ 25 x) that from U fission. Overall, it is judged to be of less importance in the oxidation event since it is assumed that the chemical energy associated with the oxidation event would dominate the subsequent fission product behavior in the particle.	Rationale: Various research institutions have performed many measurements. The kinetics of this mechanism is not known with enough certainty since extrapolations from the database are required. More testing would help develop a better understanding of the phenomena and its impact above 1600°C. Synergistic effects between oxidation and Pd attack (e.g., increase in temperature due to oxidation and its impact on greater Pd corrosion) have never been studied experimentally, but can be examined use computer models with appropriate sensitivity studies.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer Heavy metal diffusion	Diffusion of heavy metals through the intact layer

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	3	Remedy:
Rationale: Although higher oxides of uranium (UO_{2+x}) can be volatile, this factor is judged to be of low importance in air or water ingress events since the ability of air or water to get to the kernel to mobilize the uranium is quite small given the large amount of carbon in the system available to react with air or steam.	Rationale: Heavy metal diffusion has never been observed in German accident heating tests.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer Layer oxidation	Uptake of oxygen by the layer through a chemical reaction

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	5	Remedy:
Rationale: Oxidation by air or water is important to understand the response of the fuel.	Rationale: Some data exist, but the database is incomplete.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer Fission product release through undetected defects	Passage of fission products from the buffer region through defects in the SiC layer

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	5	Remedy:
Rationale: As the primary fission product barrier understanding the transport is very important.	Rationale: Effective diffusion coefficients exist in both the U.S. and Germany for the fission gases through the SiC. Release via defects has never been individually sorted out from the other transport mechanisms in any experiment. The parameters needed to model release via defects and the presence or absence of defects in the SiC layer particle to particle, and/or across the layer, and/or changes in the defect structure as a result of oxidation makes such an effort very expensive and time consuming. The use of effective diffusion coefficients although less scientifically satisfying is more pragmatic and may be completely acceptable in system safety analysis when accompanied by proper sensitivity studies that assume some percentage of defective SiC layers present in the core.	Closure Criterion:

Additional Discussion

Life Cycle Phase	**Factor, Characteristic or Phenomenon**	**Definition**
Accident With Subsequent Water Intrusion	SiC Layer Fission product release through failures, e.g., cracking	Passage of fission products from the buffer region through regions in the SiC layer that fail during operation or an accident

Importance Rank and Rationale	**Knowledge Level and Rationale**	**Remedy for Inadequate Knowledge/Issue Closure Criteria**
Rank: H	7	Remedy:
Rationale: A particle with a failed SiC layer, but intact PyC layers, will not release fission gas. The PyC layers must fail in order to have fission gas release. A failed layer sometimes is modeled as having no fission product retention characteristics in fuel performance models. This conservative assumption is reasonable assuming that the code can adequately calculate when an SiC layer can fail. The oxidation event may cause failure of the layer, which would then result in fission product release.	Rationale: Such a causal relationship can be modeled and sensitivity studies performed to determine the overall impact in an oxidation event.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer Thermodynamics of the SiC-fission product system	Chemical form of fission products including the effects of solubility, intermetallics, and chemical activity.

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	7	Remedy:
Rationale: Critical to understanding transport behavior of fission products	Rationale: Thermodynamic calculations have been performed for both the UO_2 and UCO systems over a broad temperature, burnup and enrichment range to establish the chemical forms of the fission products. Similar calculations can be performed in the presence of steam or air to determine the changes in chemical form of the fission products.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer Sintering	Change of SiC microstructure as a function of temperature

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	2	Remedy:
Rationale: The CVD SiC is very high density almost theoretical, so it is difficult to see that there would be much of a role for sintering to change the microstructure. Chemical effects from the oxidation event are much more important.	Rationale:	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer: Chemical attack by water	Rate of reaction per unit surface area as a function of temperature and partial pressure of steam
	Kinetics	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	6	Remedy:
Rationale: Oxidation by air or water is important to understand the response of the fuel.	Rationale: Some data exist, but the database is incomplete.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer: Chemical attack by water Catalysis	Modification of the reaction rate by fission products or impurities

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	5	Remedy:
Rationale: Impurities can modify the reaction rate and thus impact the course of the event.	Rationale: Some air oxidation rate data have been determined for SiC and thus implicitly include the effects of impurities. The effects of fission products have not been included because oxidation testing has not been performed on irradiated SiC material with fission products. In principle sensitivity calculations can be performed with variations in the oxidation rate to bound this effect.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer: Chemical attack by water	Changes in chemical form resulting from oxidizing or reducing fission products
	Changes in chemical form of fission products	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	7	Remedy:
Rationale: This can be important because the transport behavior is dependent on the chemical form.	Rationale: This can also be calculated for a range of oxygen potentials to determine if any of the key fission products change in chemical form during the air or water ingress accident.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer: Chemical attack by water	Changes in diffusivity, porosity, adsorptivity, etc.
	Changes in SiC properties	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	2	Remedy:
Rationale: The oxidation can change the microstructure of the SiC by creating tunnels or pathways in the matrix. Thus, because the microstructure changes, the porosity, adsorptivity, etc. can also change.	Rationale: No measurements have been made on this effect. Conservative assumptions on such changes may allow sensitivity studies in this area.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer: Chemical attack by water	Release of SiC FP inventory
	Holdup reversals	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	6	Remedy:
Rationale: As the oxidation process continues, any fission products trapped at sites in the SiC may be released because of the thermal energy associated with the oxidation.	Rationale: This can be accounted for in a very simplistic yet conservative manner if details are not well known or more sophisticated models with detrapping can be used if the fundamental data needed for such models exist.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer: Chemical attack by water	Impact of SiC oxidation on temperature distribution through material
	Temperature distributions	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	8	Remedy:
Rationale: Very important in doing an oxidation calculation is to make sure the temperature response of the material, as a result of the chemical reaction, is properly calculated.	Rationale: This is well known and can be done in most of the safety codes used by NRC (e.g. MELCOR). The degree of fine detail in the model may be an open question but can be handled with sensitivity studies.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	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: M	6	Remedy:
Rationale: Transport through intact particles is less important than those with exposed kernels in ingress events.	Rationale: PyC effectively retain fission gases. Effective diffusion coefficients for noble gases through PyC exist for both German and U.S. PyC. The Knudsen diffusion formalism has not been historically used in the modeling. The effect of oxidation on changes in the transport behavior has not been studied. Sensitivity studies can be performed to bound potential changes to determine the impact on the overall source term.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	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: M	6	Remedy:
Rationale: Transport through intact particles is less important than those with exposed kernels in ingress events.	Rationale: Data exist on the effective diffusivity of Cs, Ag, and Sr through the PyC layer. The mechanism responsible for the transport has not been definitively identified. The effect of oxidation on transport properties has not been studied. Sensitivity studies can be performed to bound potential changes to determine the impact on the overall source term.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer Pressure loading (Fission products)	Stress loading of the layer by increased pressure from fission products

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	8	Remedy:
Rationale: A key parameter to determine stress in coating layer	Rationale: Noble gases contribute to the pressure loading in the particle. The effect of temperature due to the oxidation event on the pressure is easily calculated.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer Pressure loading (Carbon monoxide)	Stress loading of the layer by carbon monoxide by increased pressure

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H for UO_2 and L for UCO	8	Remedy:
Rationale: A key parameter to determine stress in coating layer	Rationale: Co (for UO_2 only) contributes to the pressure loading in the particle. The effect of temperature due to the oxidation event on the pressure is easily calculated.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer Layer oxidation	Reaction of pyrolytic graphite with oxygen released from the kernel

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	3	Remedy:
Rationale: At high temperatures, oxygen release from kernel increases over that in normal operations because of instability of some oxidic fission products at high temperatures.	Rationale: Known at these temperatures	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer Stress state (compression/tension)	The state of the forces induced by external forces that are acting across the layer to resist movement

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	8	Remedy:
Rationale: The stress state is judged to be of low importance for a chemical oxidation event.	Rationale: Stress state is easily calculated using current finite element models for coated particles.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer Cracking	Lengths, widths and numbers of cracks produced in layer during accident

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	5	Remedy:
Rationale: A cracked IPyC will not retain fission gases and would act as a fast transport path for metallic fission products to the SiC layer. Furthermore, a cracked IPyC will allow CO to attack the SiC layer.	Rationale:	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer Intercalation	Trapping of species between sheets of the graphite structure

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	6	Remedy:
Rationale: Surface and bulk diffusion with intercalation of Cs and Sr (trapping) is probably the underlying mechanism of transport through the PyC. Given the large number of Cs atoms, the trapping may be somewhat less important in the IPyC than in the OPyC where fewer Cs atoms are expected and their concentration may be more on the order of the number of trapping sites.	Rationale: Transport models do not consider intercalation. Effective diffusion coefficients exist in both the U.S. and Germany for the Cs and Sr through IPyC. The data are probably a combination of diffusion and trapping via intercalation at these high temperatures but the two mechanisms have never been individually sorted out in any experiment. Furthermore, the models do not consider effects that oxidation could have on changing the microstucture and the intercalation behavior. The parameters needed for such detailed models and the changes in microstructure of the IPyC particle to particle and/or sometimes across the layer and/or as a result of oxidation make such an effort very expensive and time consuming. The use of effective diffusion coefficients although less scientifically satisfying is more pragmatic and may be completely acceptable in system safety analysis when accompanied by proper sensitivity studies.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer: Chemical attack by water Kinetics	Rate of reaction per unit surface area as a function of temperature and partial pressure of steam

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	7	Remedy:
Rationale: Oxidation of IPyC is needed to understand thermal response of the particles in the fuel element.	Rationale: Reaction rates for PyC are known at these temperatures.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer: Chemical attack by water Catalysis	Modification of the reaction rate by fission products or impurities

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	4	Remedy:
Rationale: Impurities can alter reaction rates and change course of the ingress event.	Rationale: Reaction rate testing of PyC would implicitly include the effects of any impurities on the overall oxidation. No chemical reaction rate measurements have been performed using irradiated PyC where fission products may be in the layer. In principle, sensitivity calculations can be performed with variations in the oxidation rate to bound this effect.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer: Chemical attack by water	Changes in chemical form resulting from oxidizing or reducing fission products
	Changes in chemical form of fission products	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	7	Remedy:
Rationale: This can be important because the transport behavior is dependent on the chemical form.	Rationale: This can also be calculated for a range of oxygen potentials to determine if any of the key fission products change in chemical form during the air or water ingress accident.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer: Chemical attack by water	Changes in diffusivity, porosity, adsorptivity, etc.
	Changes in graphite properties	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	6	Remedy:
Rationale: The oxidation can change the microstructure of the PyC by creating tunnels or pathways in the matrix. Thus, because the microstructure changes, the porosity, adsorptivity, etc., can also change.	Rationale: No measurements have been made on this effect. Conservative assumptions on such changes may allow sensitivity studies in this area.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer: Chemical attack by water	Release of graphite FP inventory
	Holdup reversal	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	6	Remedy:
Rationale: As the oxidation process continues, any fission products trapped at sites in the PyC may be released because of the thermal energy associated with the oxidation.	Rationale: This can be accounted for in a very simplistic yet conservative manner if details are not well known or more sophisticated models with detrapping can be used if the fundamental data needed for such models exist.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer: Chemical attack by water Temperature distribution	Impact of graphite oxidation on temperature distribution through material

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	8	Remedy:
Rationale: Very important in doing an oxidation calculation is to make sure the temperature response of the material as a result of the chemical reaction is properly calculated.	Rationale: This is well known and can be done in most of the safety codes used by NRC (e.g. MELCOR). The high conductivity of the PyC should make the gradient quite small in general. The degree of fine detail in the model may be an open question but can be handled with sensitivity studies.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	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: L	7	Remedy:
Rationale: The transport is fairly rapid and thus oxidation is not expected to affect the transport in this layer significantly.	Rationale: Rapid diffusion through the porous structure of the buffer is assumed in both U.S. and German transport models. Knudsen diffusion calculations confirm rapid gas phase transport.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer 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: L	7	Remedy:
Rationale: The transport is fairly rapid and thus oxidation is not expected to affect the transport in this layer significantly.	Rationale: Rapid transport of metallic fission products through the buffer has also been historically assumed in U.S. and German models. Key measurements needed to develop grain boundary diffusion models along the edges of the crystallite plans have never been obtained. Instead effective diffusion coefficients are used.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer Response to kernel swelling	Mechanical reaction of the layer to the growth of the kernel via swelling

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	4	Remedy:
Rationale: Not expected to be important in oxidation events	Rationale: Has been predicted by EU fuel modelers to be important at high burnup where swelling is large. Usually this is accommodated by appropriate changes in the buffer thickness to ensure that the kernel does not come in contact with the TRISO coated and cause large mechanical stresses. Has not been shown to be a problem in current irradiation database at relatively low burnup.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer Maximum fuel gaseous fission product uptake	Maximum loading of fission products that can deposit from the gas phase onto surfaces of materials surrounding the fuel kernel

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	2	Remedy:
Rationale: Not important in oxidation events; probably more important in reactivity related events	Rationale:	Closure Criterion:

<u>Additional Discussion</u>

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer Layer oxidation	Reaction of buffer layer with oxide materials in the kernel

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	5	Remedy:
Rationale: Some oxide materials in the kernel become less stable resulting in additional oxygen that can react with the buffer causing additional CO formation.	Rationale: In UO_2 excess oxygen from fission reacts with fission products and then carbon from the buffer. This is well known and can be calculated and has been measured at low burnups. In UCO fuel no oxidation is expected.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer Thermal gradient	Change in temperature with distance

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	6	Remedy:
Rationale: In pebble cores, the temperature gradients are generally low because of the lower power per particle in the core. Thus, Soret effects are much less important. Thus, this effect is important as an initial condition for the accident. Under oxidation events the gradients are much smaller and thus much less important during the accident.	Rationale: Temperature gradients can drive thermal diffusion (Soret effect). Temperature gradients under normal operation are very high in prismatic cores (up to 10000 K/cm) which can cause Soret effects in fission product transport. Values of the heat of solution needed to model the fission product transport are sorely lacking.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer Irradiation and thermal shrinkage	Dimension changes in the buffer layer or changes in its porosity produced by irradiation or by exposure to elevated temperatures

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	7	Remedy:
Rationale: Rapid densification can occur in the buffer under exposure to neutrons. The state of the buffer is an important initial condition in fission product modeling. Thermal densification is not expected to be important at these temperatures.	Rationale: This is fairly well known and can be calculated.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer: Chemical attack by water Kinetics	Rate of reaction per unit surface area as a function of temperature and partial pressure of steam

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	7	Remedy:
Rationale: Overall considered to be of lower importance than the other layers in the particle	Rationale: Oxidation rates for PyC can be adjusted to estimate rates for the buffer.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer: Chemical attack by water Catalysis	Modification of the reaction rate by fission products or impurities

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	3	Remedy:
Rationale: In general, the effect is felt to be less important for this layer than other layers since rapid fission product transport through the layer is already assumed.	Rationale: Reaction rate testing of low-density carbon would implicitly include the effects of any impurities on the overall oxidation. No chemical reaction rate measurements have been performed using irradiated buffer material where fission products may be in the layer. In principle, sensitivity calculations can be performed with variations in the oxidation rate to bound this effect.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer: Chemical attack by water	Changes in chemical form resulting from oxidizing or reducing fission products
	Changes in chemical form of fission products	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	7	Remedy:
Rationale: This can be important because the transport behavior is dependent on the chemical form.	Rationale: This can also be calculated for a range of oxygen potentials to determine if any of the key fission products change in chemical form during the air or water ingress accident.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer: Chemical attack by water	Changes in diffusivity, porosity, adsorptivity, etc.
	Changes in graphite properties	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	3	Remedy:
Rationale: The oxidation can change the microstructure of the buffer by creating tunnels or pathways in the matrix. Thus, because the microstructure changes, the porosity, adsorptivity, etc., can also change. Given the high porosity in the buffer and the rapid fission product transport in this layer, these effects are not considered important.	Rationale: No measurements have been made on this effect.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer: Chemical attack by water	Release of graphite FP inventory
	Holdup reversal	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	3	Remedy:
Rationale: Given the rapid transport expected in the buffer, this effect is not expected to change the transport properties significantly.	Rationale: As the oxidation process continues, any fission products trapped at sites in the buffer may be released because of the thermal energy associated with the oxidation. This can be accounted for in a very simplistic yet conservative matter if details are not well known or more sophisticated models with detrapping can be used if the fundamental data needed for such models exist.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer: Chemical attack by water Temperature distribution	Impact of graphite oxidation on temperature distribution through material

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	8	Remedy:
Rationale: Very important in doing an oxidation calculation is to make sure the temperature response of the material as a result of the chemical reaction is properly calculated. It is rated medium because the reaction is endothermic.	Rationale: This is well known and can be done in most of the safety codes used by NRC (e.g. MELCOR). The degree of fine detail in the model may be any open question but can be handled with sensitivity studies.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel Maximum fuel temperature	Maximum fuel temperature attained by the fuel kernel during the accident

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	7	Remedy:
Rationale: Temperature is the key parameter that drives fission product migration in the coated particle fuel.	Rationale: This can be calculated and sensitivity studies can determine its overall importance in any accident scenario.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel Temperature vs. time transient conditions	The time-dependent variation of fuel temperature with time

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	7	Remedy:
Rationale: Similar to temperature and time at temperature, the thermal response of the particle is important to calculating fission product behavior in the particle.	Rationale: Sensitivity studies can be easily performed to determine the impact of this factor on the overall progression of the accident.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel Energy Transport: Conduction within kernel	Flow of heat within a medium from a region of high temperature to a region of low temperature

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	6	Remedy:
Rationale: Needed to calculate thermal response of kernel	Rationale: Thermal conductivity of UO_2 is fairly high and reasonably well known. Conductivity of UCO is assumed to be that of UO_2. Can be varied easily in sensitivity studies to determine impact.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel Thermodynamic state of fission products	Chemical and physical state of fission products

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	7	Remedy:
Rationale: Thermodynamic state of fission products can determine volatility and mobility of the species.	Rationale: Thermodynamic studies have been performed for UO_2, UCO and UC_2 systems and chemical states of major fission products have been identified as a function of burnup and temperature. The impact of air and/or water can be evaluated.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel Oxygen flux	Mass transport of oxygen per unit surface area per unit time

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	6	Remedy:
Rationale: Less important in air and water ingress events than in traditional heatup events	Rationale:	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel Grain growth	Enlargement of grains as a result of diffusion

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	4	Remedy:
Rationale: Not important for air or water ingress events	Rationale:	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel Buffer carbon-kernel interaction	Chemical reaction between carbon and the fuel (UO_2) to form UC_2 and CO (gas)

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	6	Remedy:
Rationale: The reaction of the kernel and the buffer is known to form a "rind" of UC_2 at the interface between the two layers. Photomicrographs show a different phase that is easily distinguished optically. Such interaction can result in release of fission products.	Rationale:	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel: Chemical attack by water Kinetics	Rate of reaction per unit surface area as a function of temperature and partial pressure of steam

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	7	Remedy:
Rationale: Kinetics determine changes in physio-chemical behavior of the kernel and associated fission product release. Especially important for exposed kernels assumed in this scenario.	Rationale: Data exist on the steam oxidation of UO_2 with lesser information available for UCO.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel: Chemical attack by water	Modification of the reaction rate by fission products or impurities
	Catalysis	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	5	Remedy:
Rationale: Impurities can affect reaction rates, but influence of oxygen potential is more important.	Rationale: Implicitly built into the data on hydrolysis of irradiated UO_2 and UCO kernels.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel: Chemical attack by water	Changes in chemical form resulting from oxidizing or reducing fission products
	Changes in chemical form of fission products	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	7	Remedy:
Rationale: The oxygen potential in the system (which is directly related to the oxygen partial pressure for air and the hydrogen to steam ratio of water) determines the chemical states of the fission products which affects their mobility.	Rationale: Can be calculated using thermodynamic tools	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel: Chemical attack by water	Changes in diffusivity, porosity, adsorptivity, etc.
	Changes in kernel properties	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	5	Remedy:
Rationale: The oxidation can change the microstructure of the kernel and the resultant transport properties. Hyperstoichiometric uranium dioxide will behave differently than UO_2. In UCO, the oxygen will react with the carbide phase to produce more UO_2. The O/U ratio is a function of the hydrogen to steam pressure ratio. These are very important effects to determine fission product mobility in the kernel.	Rationale: Influence of water vapor on release from exposed kernels has been studied in in-pile tests.	Closure Criterion:

Additional Discussion

Appendix E.2

Detailed PIRT Submittal by the ORNL Panel Member

R. Morris

TRISO Fuel PIRT: Accident With Subsequent Water Intrusion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Fuel Element Irradiation history	The temperature, burnup and fast fluence history of the layer

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 7	Remedy: None if the operating envelope remains the same, otherwise additional testing is necessary
	> 1600 °C: N/A	Remedy: N/A
Rationale: The fuel behavior is strongly related to its irradiation history. Increasing burnup and fluence beyond established limits generally degrades performance. The fraction of particles failed during normal operation is important as well as they will release first.	Rationale: (≤ 1600 °C) The Germans have collected a large database for their fuel under their specific operating conditions. Deviations from these conditions warrant additional testing. Note that the proven fuel envelope is less demanding than that required for the turbine concepts.	Closure Criterion: Verification that the fuel can meet any new operating condition.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

For a discussion of the best performing fuel see:

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

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

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	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	≤ 1600 °C: 4	Remedy: Defer to fission product transport area.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The major barriers to fission product release are the particle coating layers. The diffusion through the fuel element matrix is considered to be relatively high, although it does sorb and trap some fission products. When this material is oxidized, these fission products can be released, so the inventory is important.	Rationale: (≤ 1600 °C) The fuel element matrix sorbs some of the released fission products (metals); data exist to estimate the inventory, however, chemical attack may alter things.	Closure Criterion: Diffusion and trapping coefficients for the material of interest as a function of temperature
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

Diffusion through the fuel element matrix is fairly rapid compared to the particle coating layers. Gases are not held up, but there is significant sorption of the released metals. Overall, the reactor core components can provide an attenuation factor of 10-1000 for the metallics; oxidation could release this inventory. The GT-MHR may change its matrix composition from the historical resins; if so, additional investigations may be necessary.

For examples of diffusion and sorption behavior in different HTGR materials see:

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

For general interest in the transport of volatile fission products through the reactor system see:

Plateout Phenomena in Direct-Cycle High Temperature Gas-Cooled Reactors, EPRI, Palo Alto, CA: 2002. 1003387.
An analytical Study of Volatile Metallic Fission Product Release From Very High Temperature Gas-Cooled Reactor Fuel and Core, S. Mitake, et. al., Nuclear Technology, 81 (1988), pages 7-12.
Fission Product Plateout and Liftoff in the MHTGR Primary System: A Review, NUREG/CR-5647

There are several codes for examining fission product transport in a HTGR core. The US, Germans, and Japanese all have models.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	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). Other factors include holdup, cracking, adsorption, site poisoning, permeability, sintering, and annealing.

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 7	Remedy: None
	> 1600 °C: N/A	Remedy: N/A
Rationale: The fission gases migrate rapidly through the fuel element matrix after they escape from the particle. This fact is used to monitor fuel behavior via R/B. Any damaged particles will release fission gases. Water will react in these regions.	Rationale: (≤ 1600 °C) Data shows that the gases move rapidly through the matrix material and quickly enter the coolant and/or fuel element.	Closure Criterion: None
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

Fission gases move rapidly to the coolant once they exit the particle. In a reactor they are removed by the coolant purification system so the circulating inventory is low. Transport of volatile metallics is determined by the sorption isotherms and dust. Gases released by damaged particles will rapidly move through the reactor core system.

The actual reaction of water with the core materials is more complex. For a discussion of water ingress accidents and their effect on fuel see:

Fuel Performance and Fission Product Behavior in Gas Cooled Reactors, IAEA-TECDOC-978 (1997)
Source Term Estimation for Small-Sized HTRs: Status and Further Needs, Extracted From German Safety Analysis, R. Moormann, et. al., Nuclear Technology, 135, (2001), pages 183-193
Methods and Data for HTGR Fuel Performance and Radionuclide Release Modeling during Normal Operational and Accidents for Safety Analysis, K. Verfondern, et. al., Jul-2721

For examples of the type of modeling that has been done for transport see:

Fission Product Plateout and Liftoff in the MHTGR Primary System: A Review, NUREG/CR-5647

For fuel accident models see: *Compilation of Fuel Performance and Fission Product Transport Models and Database for MHTGR Design*, Martin, R.C., ORNL/NPR-91/6

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Fuel Element: Transport of metallic FPs through fuel element	Chemical stoichiometry of the chemical species that includes the radioisotope of interest
	Chemical form	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 5	Remedy: Determine the need for this detailed knowledge.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The chemical form of the fission product will determine how it interacts with the reactor system materials. The chemical environment of the kernel and the reactor system can be quite different and depend on the kernel composition and the coolant impurities. The kernel is expected to be somewhat oxidizing and the normal reactor system quite reducing, thus the chemical form of the fission product may change as it leaves the fuel. Once the accident starts, the environment may become oxidizing again.	Rationale: (≤ 1600 °C) Thermochemical calculations can give plausible chemical forms, but this author is not aware of any measurements confirming the chemical states.	Closure Criterion: If necessary, collect or calculate the compounds.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

This issue of chemical forms probably should be covered under fission product transport since the reactor system has a difference chemical potential than the fuel. It will change again with the accident. Water will oxidize any carbides. See:

Fission Product Plateout and Liftoff in the MHTGR Primary System: A Review, NUREG/CR-5647
Chemical Behavior of Fission Products in Core Heatup Accidents in High-Temperature Gas-Cooled Reactors, R. Moormann, Nuclear Technology, 94 (1991), pages 56-67.
Source Term Estimation for Small-Sized HTRs: Status and Further Needs, Extracted From German Safety Analysis, R. Moormann, et. al., Nuclear Technology, 135, (2001), pages 183-193
Methods and Data for HTGR Fuel Performance and Radionuclide Release Modeling during Normal Operational and Accidents for Safety Analysis, K. Verfondern, et. al., Jul-2721

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Fuel Element: Chemical attack by water Kinetics	Rate of reaction per unit surface area as a function of temperature and partial pressure of steam

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 4	Remedy: Review data and perform tests to fill in gaps.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The kinetics are necessary in order to determine the reaction rates.	Rationale: (≤ 1600 °C) Some testing has been done on the reaction of steam with matrix material and graphite.	Closure Criterion: Sufficient data to resolve gaps.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

<u>Additional Discussion</u>

The reactor design should be accessed for the water ingress potential before proceeding with this testing, as it is expensive. Some testing has been done in this area. See:

Source Term Estimation for Small-Sized HTRs: Status and Further Needs, Extracted From German Safety Analysis, R. Moormann, et. al., Nuclear Technology, 135, (2001), pages 183-193

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

Compilation of Fuel Performance and Fission Product Transport Models and Database for MHTGR Design, R. Martin, ORNL/NPR-91/6

Methods and Data for HTGR Fuel Performance and Radionuclide Release Modeling during Normal Operational and Accidents for Safety Analysis, K. Verfondern, et. al., Jul-2721

The Reaction of Steam with Large Specimens of Graphite For The Experimental Gas-Cooled Reactor, R.E. Helms, R.E. MacPherson, ORNL-TM-984, March 1965

Reactivity of Graphite and Fueled Graphite Spheres with Oxidizing Gases, J.P. Blakely, ORNL-TM-751, February 1964

Oxidation of Unfueled and Fueled Graphite Spheres by Steam, J.L. Rutherford, J.P. Blakely, L.G. Overholser, ORNL-3947, May 1966

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Fuel Element: Chemical attack by water Catalysis	Modification of the reaction rate by fission products or impurities

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	≤ 1600 °C: 4	Remedy: Determine the need for this information and whether the issue is important.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The presence of catalysis can greatly increase local reaction rates. However, this is an endothermic reaction, so the consequences are much less severe that for air.	Rationale: (≤ 1600 °C) Some work has been done in this area. This is the water-gas reaction and it has been investigated for similar materials.	Closure Criterion: Sufficient data to resolve the data need.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

The steam carbon reaction has some industrial importance and has been investigated. It remains to be seen how much of this work can be applied to nuclear grade materials.

An industrial report is: *Catalytic Gasification of Graphite or Carbon*, H. Heinemann, LBL-21702, April 1986
Also see chemical textbooks.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Fuel Element: Chemical attack by water	Changes in chemical form resulting from oxidizing or reducing fission products
	Changes in chemical form of fission products	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 4	Remedy: Determine the need for this knowledge, collect as necessary.
	> 1600 °C: N/A	Remedy: N/A
Rationale: Changes in the chemical form of the fission products can greatly change their transport properties.	Rationale: (≤ 1600 °C) Thermochemical codes can calculate the possible chemical compounds. Little confirmation work is available.	Closure Criterion: Collect data to resolve uncertainties
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

The forms and migration of the fission products can be complex. For some information on the chemical forms see:

Fission Product Plateout and Liftoff in the MHTGR Primary System: A Review, NUREG/CR-5647

Chemical Behavior of Fission Products in Core Heatup Accidents in High-Temperature Gas-Cooled Reactors, R. Moormann, Nuclear Technology, 94 (1991), pages 56-67.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Fuel Element: Chemical attack by water	Changes in diffusivity, porosity, adsorptivity, etc.
	Changes in graphite properties	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 4	Remedy: Determine the data needs and new materials and see if the existing data base is useful
	> 1600 °C: N/A	Remedy: N/A
Rationale: Changes in graphite properties may changes the rate at which the graphite reacts.	Rationale: (≤ 1600 °C) Steam corrosion of graphite has been investigated for HTGRs	Closure Criterion: Sufficient information to resolve the issue.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

Some investigations are contained in:

The Reaction of Steam with Large Specimens of Graphite For The Experimental Gas-Cooled Reactor, R.E. Helms, R.E. MacPherson, ORNL-TM-984, March 1965

Reactivity of Graphite and Fueled Graphite Spheres with Oxidizing Gases, J.P. Blakely, ORNL-TM-751, February 1964

The particular material under relevant conditions needs to be examined, as there can be considerable variation in results.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Fuel Element: Chemical attack by water	Release of graphite FP inventory
	Holdup reversal	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 4	Remedy: Determine the fission product inventories likely to be released and their impact on the safety case. Collect data as necessary to resolve the issue.
	> 1600 °C: N/A	Remedy: N/A
Rationale: One concern of chemical attack is the release of fission products deposited on reactor core materials.	Rationale: (≤ 1600 °C) Some work has been done in this area.	Closure Criterion: Determination of the safety case and/or data to access the impact.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

<u>Additional Discussion</u>

The importance of this issue depends on the amount of fission products outside of sound particles. If the fuel quality is very high, then the amount of material available for release will be very low. If this is the case, then detailed analysis may be unnecessary. See:

Methods and Data for HTGR Fuel Performance and Radionuclide Release Modeling during Normal Operational and Accidents for Safety Analysis, K. Verfondern, et. al., Jul-2721

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Fuel Element: Chemical attack by water	Impact of graphite oxidation on temperature distribution through material
	Temperature distribution	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 4	Remedy: Review the ability to calculate temperature distributions and determine if the situation warrants more work.
	> 1600 °C: N/A	Remedy: N/A
Rationale: Reaction rates are generally strong functions of temperature.	Rationale: (≤ 1600 °C) General modeling has been done for graphite and fuel oxidation. The specific case needs to be accessed.	Closure Criterion: Resolution of the calculational and data needs.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

Some investigations are contained in:

The Reaction of Steam with Large Specimens of Graphite For The Experimental Gas-Cooled Reactor, R.E. Helms, R.E. MacPherson, ORNL-TM-984, March 1965

Reactivity of Graphite and Fueled Graphite Spheres with Oxidizing Gases, J.P. Blakely, ORNL-TM-751, February 1964

The particular material under relevant conditions needs to be examined, as there can be considerable variation in results.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer 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: M	≤ 1600 °C: 5	Remedy: Insure that proper PyC is manufactured. Material properties are difficult to characterize.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The PyC layers hold gases well. The diffusion coefficients are generally quite low. The biggest concern is the rupture of the layer and the release of gases. This layer may be attacked by air/steam.	Rationale: (≤ 1600 °C) A great deal of testing has been conduced on PyC at the temperatures of interest. The primary concern is fabricating the proper material and its loss during the accident.	Closure Criterion: Test fuel performs as expected
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

Extensive testing has been done of the PyC for BISO and TRISO fuels under helium conditions, less so under air/steam see:

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

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

Nuclear Technology, 35, Number 2 (entire issue devoted to coated particle fuels)

If the OpyC is unbreached, the helium heatup issues generally apply. If the layer is damaged or burned away, then the loss of OPyC issues would apply.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer 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: M	≤ 1600 °C: 7	Remedy: None
	> 1600 °C: N/A	Remedy: N/A
Rationale: Metallic fission products generally diffuse through the layer rapidly at high temperatures. Its loss would make some difference, but the primary issue would be exposing the SiC to the steam.	Rationale: (≤ 1600 °C) The OpyC offers little holdup to metallics at accident temperatures.	Closure Criterion: None
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

Extensive testing has been done of the PyC for in helium BISO and TRISO fuels; less has been done for air/steam. See:

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

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

Nuclear Technology, 35, Number 2 (entire issue devoted to coated particle fuels)

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer Layer oxidation	Uptake of oxygen by the layer through a chemical reaction

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 4	Remedy: Determine the conditions of interest and collect the necessary data.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The oxidation rate determines the life of this layer under steam ingress. Generally, a bulk rate is assumed rather than detailed behavior.	Rationale: (≤ 1600 °C) Testing has been done, but it is of a more integral nature.	Closure Criterion: Resolution of the data gaps.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

For information on fuel exposure in steam see:

Source Term Estimation for Small-Sized HTRs: Status and Further Needs, Extracted From German Safety Analysis, R. Moormann, et. al., Nuclear Technology, 135, (2001), pages 183-193

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

Compilation of Fuel Performance and Fission Product Transport Models and Database for MHTGR Design, R. Martin, ORNL/NPR-91/6

Methods and Data for HTGR Fuel Performance and Radionuclide Release Modeling during Normal Operational and Accidents for Safety Analysis, K. Verfondern, et. al., Jul-2721

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer Stress state (compression/tension)	The state of the forces induced by external forces that are acting across the layer to resist movement

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	≤ 1600 °C: 6	Remedy: Review and collect new data for the codes if necessary. Material properties are the major issue.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The stress state of the OPyC helps keep a compression force on the SiC. Failure of the OpyC by oxidation increases the likelihood of SiC failure.	Rationale: (≤ 1600 °C) The fuel design codes include these calculations. (Assumes the PyC is irradiation stable)	Closure Criterion: Adequate test fuel performance.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

See the PIRT Design Table for references on fuel design. Also see the accident models. The most common accident model is pressure vessel failure. See:

Revised MHTGR High-Temperature Fuel Performance Models, R.C. Martin, ORNL/NPR-92/16

Methods and Data for HTGR Fuel Performance and Radionuclide Release Modeling during Normal Operational and Accidents for Safety Analysis, K. Verfondern, et. al., Jul-2721

Compilation of Fuel Performance and Fission Product Transport Models and Database for MHTGR Design, Martin, R.C., ORNL/NPR-91/6

Revised MHTGR High-Temperature Fuel Performance Models, R.C. Martin, ORNL/NPR-92/16

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

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer Intercalation	Trapping of species between sheets of the graphite structure

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	≤ 1600 °C: 2	Remedy: Review data to determine if it is important.
	> 1600 °C: N/A	Remedy: N/A
Rationale: Small amounts of material may be trapped in the layer, but the material sorbed in the matrix is expected to be much larger.	Rationale: (≤ 1600 °C) Some work has been done in this area, but it has not been an important driver.	Closure Criterion: None
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

With good SiC, the fission product transport to the OPyC is very low. Some new modeling efforts are determining if this is an important factor.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer Trapping	Adsorption of fission products on defects

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	≤ 1600 °C: 3	Remedy: Review data to determine if it is important.
	> 1600 °C: N/A	Remedy: N/A
Rationale: Some trapping is used in the modeling and it may play a role in the transport, but the FPs in the matrix appears to be the major concern.	Rationale: (≤ 1600 °C) Some modeling has looked at this	Closure Criterion: None
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

With good SiC, the fission product transport to the OPyC is very low. Current modeling efforts are investigating this effect. Even if it is a real effect, it may be consumed up by general data uncertainties.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer Cracking	Lengths, widths and numbers of cracks produced in layer during operation or an accident

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 5 (models determine failure rather than cracks)	Remedy: Better data and model for fuel performance, especially PyC behavior.
	> 1600 °C: N/A	Remedy: N/A
Rationale: Failure of the OpyC affects the likelihood of SiC failure and exposes it to air/steam. Cracking of particle layers can result in particle failure. One intact PyC can retain gases, but metallic release will be high. Modeling often assumes that particles fail by overpressure rather than a small crack. A crack is assumed to equal failure.	Rationale: (≤ 1600 °C) Fuel models have been developed to model normal and accident behavior. Particles are assumed to fail when they meet some weakness criteria based on a layer stress. Details of cracks are not modeled (yet). Agreement has been good for high quality fuel	Closure Criterion: Models that predict fuel behavior under normal and accident conditions. Does one need cracks or just failure? This adds a lot of complexity.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

<u>Additional Discussion</u>

For some work on examining the effects of cracks on fuel performance and general models 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.

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*Compilation of Fuel Performance and Fission Product Transport Models and Database for MHTGR Design*, Martin, R.C., ORNL/NPR-91/6

Methods and Data for HTGR Fuel Performance and Radionuclide Release Modeling during Normal Operational and Accidents for Safety Analysis, K. Verfondern, et. al., Jul-2721

Compilation of Fuel Performance and Fission Product Transport Models and Database for MHTGR Design, Martin, R.C., ORNL/NPR-91/6

Revised MHTGR High-Temperature Fuel Performance Models, R.C. Martin, ORNL/NPR-92/16

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

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer: Chemical attack by water Kinetics	Rate of reaction per unit surface area as a function of temperature and partial pressure of steam

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 3	Remedy: Determine the relevance of the event and collect the necessary data.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The kinetics determine the reaction rate and duration of the accident.	Rationale: (≤ 1600 °C) Some work has been done in this area. The rate is sensitive to the specific material.	Closure Criterion: The need and the required data.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

See:

Compilation of Fuel Performance and Fission Product Transport Models and Database for MHTGR Design, Martin, R.C., ORNL/NPR-91/6

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

Oxidation of Unfueled and Fueled Graphite Spheres by Steam, J.L. Rutherford, J.P. Blakely, L.G. Overholser, ORNL-3947, May 1966

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer: Chemical attack by water Catalysis	Modification of the reaction rate by fission products or impurities

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	≤ 1600 °C: 4	Remedy: Review the literature and determine if it is relevant or important
	> 1600 °C: N/A	Remedy: N/A
Rationale: A catalysis can increase the reaction rate in the layer and hasten its failure.	Rationale: (≤ 1600 °C) The carbon steam reaction has been studied in some detail. It needs to be applied to the fuel.	Closure Criterion: Collect the effects of catalysis if necessary.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

If the fission product inventory in the PyC is low and its loss does not significantly increase the SiC failure probably, then this issue may be unimportant. The industrial literature needs to be consulted, as this is an important commercial reaction.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer: Chemical attack by water	Changes in chemical form resulting from oxidizing or reducing fission products
	Changes in chemical form of fission products	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 4	Remedy: Determine the need for this knowledge, collect as necessary.
	> 1600 °C: N/A	Remedy: N/A
Rationale: Changes in the chemical form of the fission products can greatly change their transport properties.	Rationale: (≤ 1600 °C) Thermochemical codes can calculate the possible chemical compounds. Little confirmation work is available.	Closure Criterion: Collect data to resolve uncertainties
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

<u>Additional Discussion</u>

If the inventory of the layer is low, this issue may be of little practical importance. The forms and migration of the fission products can be complex. For some information on the chemical forms see:

Fission Product Plateout and Liftoff in the MHTGR Primary System: A Review, NUREG/CR-5647

Chemical Behavior of Fission Products in Core Heatup Accidents in High-Temperature Gas-Cooled Reactors, R. Moormann, Nuclear Technology, 94 (1991), pages 56-67.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer: Chemical attack by water	Changes in diffusivity, porosity, adsorptivity, etc.
	Changes in graphite properties	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	≤ 1600 °C: 1	Remedy: Determine if this item is relevant.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The modeling is not performed at this level; generally, the layer is assumed to disappear at some rate.	Rationale: (≤ 1600 °C) Not examined in this detail.	Closure Criterion: Collect relevant detail.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

This level of detail may not be necessary if all one needs is time to significant fuel releases as the failure of the SiC may dominate.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer: Chemical attack by water	Release of graphite FP inventory
	Holdup reversal	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	≤ 1600 °C: 3	Remedy: Determine the conditions of interest and collect the necessary data.
	> 1600 °C: N/A	Remedy: N/A
Rationale: As the OPyC is removed; any inventory of fission products will be released. The inventory of this layer is low for high quality fuel.	Rationale: (≤ 1600 °C) Some steam ingress experiments have been done.	Closure Criterion: Determine the relevance of this need and collect data.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

<u>Additional Discussion</u>

If the fuel performs as expected, the inventory of this layer will be very low. Thus, the actual details of its release may not be important. The greater problem will be that its loss exposes the SiC to water. See:

Compilation of Fuel Performance and Fission Product Transport Models and Database for MHTGR Design, Martin, R.C., ORNL/NPR-91/6

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

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer: Chemical attack by water	Impact of graphite oxidation on temperature distribution through material
	Temperature distribution	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 5	Remedy: Determine if the uncertainty in the temperatures is acceptable. Refine models and collect data as necessary.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The temperature determines the reaction rates and thus how fast the layer is attacked.	Rationale: (≤ 1600 °C) Enough modeling has been done to reasonably estimate the temperatures.	Closure Criterion: Adequate data for calculations.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	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	≤ 1600 °C: 4	Remedy: Determine relevance of this issue and collect data if necessary.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The SiC is an important barrier to fission products. Its damage will allow fission product to migrate. It is assumed that the OPyC has been destroyed so that air/steam can reach the layer. Also, note that the IPyC must also fail for gas release.	Rationale: (≤ 1600 °C) Germans have done extensive testing in this area with a helium atmosphere. The major problem is attack of the layer. Some work has been done in this area. Extensive work to collect diffusion coefficients has not been done.	Closure Criterion: Resolution of the uncertainties.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

Much work has been done in a helium atmosphere, but less has been done with steam. See:

Compilation of Fuel Performance and Fission Product Transport Models and Database for MHTGR Design, Martin, R.C., ORNL/NPR-91/6

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

Methods and Data for HTGR Fuel Performance and Radionuclide Release Modeling during Normal Operational and Accidents for Safety Analysis, K. Verfondern, et. al., Jul-2721

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer 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	≤ 1600 °C: 4	Remedy: Outline the course of the accident and collect the relevant data.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The SiC is the major barrier to the release of metallic fission products. It is assumed that the OPyC has been removed and team is attacking the SiC.	Rationale: (≤ 1600 °C) Integral experiments exposing a particle to air and steam have been done.	Closure Criterion: The course of the accident and the necessary data.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

Much work has been done in a helium atmosphere, but less has been done with steam. See:

Compilation of Fuel Performance and Fission Product Transport Models and Database for MHTGR Design, Martin, R.C., ORNL/NPR-91/6

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

Methods and Data for HTGR Fuel Performance and Radionuclide Release Modeling during Normal Operational and Accidents for Safety Analysis, K. Verfondern, et. al., Jul-2721

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer Thermal deterioration/decomposition	Decline in the quality of the layer due to thermal loading

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	≤ 1600 °C: 4	Remedy: If 1600°C and the irradiation envelope are adequate then okay; otherwise testing may be necessary, especially if air/steam contact layer.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The loss of the SiC will result in the release of metallics even if the PyCs are in good shape. The loss of the OPyC will probably result in accelerated failure due to loss of strength.	Rationale: (≤ 1600 °C) Extensive testing at 1600°C has shown it to be a "safe" limit, but exposure to air/steam may accelerate the process.	Closure Criterion: Accident definition and the uncertainties with air/steam resolved.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

1600°C has been used as the maximum temperature; it is conservative and some researchers feel that 1650-1700°C may be allowable, but the steam exposure my greatly change the situation. The modeling approach to this situation needs to be resolved. This is a complex issue. Some references:

Compilation of Fuel Performance and Fission Product Transport Models and Database for MHTGR Design, Martin, R.C., ORNL/NPR-91/6

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

Methods and Data for HTGR Fuel Performance and Radionuclide Release Modeling during Normal Operational and Accidents for Safety Analysis, K. Verfondern, et. al., Jul-2721

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	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: M	≤ 1600 °C: 7	Remedy: None, if the particle operating temperature/time is below an acceptable damage limit.
	> 1600 °C: N/A	Remedy: N/A
Rationale: Some fission products may migrate to the SiC layer and damage it. This corrosion process is a function of temperature. The corrosion mostly occurs during normal operation at the higher temperatures and weakens the particle for the accident. At the higher accident temperatures, thermal decomposition effects dominate.	Rationale: (≤ 1600 °C) This effect has been studied both in-pile and out of pile. Controlling the maximum operating temperature is a major factor.	Closure Criterion: Insure that the operating conditions are acceptable
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

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 the other PIRT Tables and:

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
Accident With Subsequent Water Intrusion	SiC Layer Heavy metal diffusion	Diffusion of heavy metals through layer

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	≤ 1600 °C: 5	Remedy: None
	> 1600 °C: N/A	Remedy: N/A
Rationale: Diffusion of heavy metal through the particle could result is the redistribution of fissile material.	Rationale: (≤ 1600 °C) To this author's knowledge, heavy metal diffusion through the SiC is not a problem.	Closure Criterion: None
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

Significant migration of fissile material through SiC during an accident is not an issue at the temperatures of interest. See: *Compilation of Fuel Performance and Fission Product Transport Models and Database for MHTGR Design*, Martin, R.C., ORNL/NPR-91/6

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer Layer oxidation	Uptake of oxygen by the layer through a chemical reaction

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	≤ 1600 °C: 4	Remedy: Determine chemical conditions and release time for the relevant case.
	> 1600 °C: N/A	Remedy: N/A
Rationale: Oxidation of the SiC layer will destroy its fission product retention capability. A major issue is whether SiO or SiO_2 is produced. SiO_2 will produce a layer that impedes mass transfer while SiO is volatile. Also, if the IPyC breaks, the SiC layer may be exposed to CO that could slowly corrode it. This is less of a concern for UCO fuel.	Rationale: (≤ 1600 °C) Experiments have been done with particles and spheres.	Closure Criterion: Resolution of release rates.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

This is a complex issue. Some references:

Compilation of Fuel Performance and Fission Product Transport Models and Database for MHTGR Design, Martin, R.C., ORNL/NPR-91/6

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

Methods and Data for HTGR Fuel Performance and Radionuclide Release Modeling during Normal Operational and Accidents for Safety Analysis, K. Verfondern, et. al., Jul-2721

CO corrosion can be a problem at the higher pressures and temperatures if a crack in the IPyC allows access to the SiC. Controlling the IPyC properties and controlling the CO by using UCO or gettering the fuel can mitigate this problem. See other PIRT tables and:

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
Accident With Subsequent Water Intrusion	SiC Layer Fission product release through undetected defects	Passage of fission products from the buffer region through defects in the SiC layer

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	≤ 1600 °C: 7	Remedy: Defer to fuel fabrication
	> 1600 °C: N/A	Remedy: N/A
Rationale: Defective SiC will allow gas transport if the PyCs both fail. This is more of a manufacturing issue that shows up when the fuel is stressed.	Rationale: (≤ 1600 °C) This is a manufacturing issue that shows up during accident conditions.	Closure Criterion: None
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

The SiC layer can be damaged during compact fabrication by iron impurities. The particles will still retain gases as long as one of the PyCs is good. See the PIRT on Manufacturing Design. It is not known if the chemical attack will worsen the situation.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer Fission product release through failures, e.g. cracking	Passage of fission products from the buffer region through regions in the SiC layer that fail during operation or an accident

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 4	Remedy: If the fuel is used outside of its tested region, more testing is needed.
	> 1600 °C: N/A	Remedy: N/A
Rationale: Failure of the SiC will allow fission gas to pass through it. If the PyC remains good, the gas will not be released, if not, the gas will be released. Metallics will be released in both cases. See previous SiC entries.	Rationale: (≤ 1600 °C) C Accident models have been compared to experiments to approximately model the situation. If material properties are consistent, useful predictions can be made, however chemical attack issues can change the results.	Closure Criterion: Resolution of identified concerns.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

Most SiC failure models are based on pressure vessel failure. More recent models are considering cracking. See the other PIRT Tables and:

Revised MHTGR High-Temperature Fuel Performance Models, R.C. Martin, ORNL/NPR-92/16

Methods and Data for HTGR Fuel Performance and Radionuclide Release Modeling during Normal Operational and Accidents for Safety Analysis, K. Verfondern, et. al., Jul-2721

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

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

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer Thermodynamics of the SiC-fission product system	Chemical form of fission products including the effects of solubility, intermetallics, and chemical activity

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 7	Remedy: None, if the particle operating temperature/time is below an acceptable damage limit.
	> 1600 °C: N/A	Remedy: N/A
Rationale: Some fission products may migrate to the SiC layer and damage it. This corrosion process is a function of temperature. See the entry on corrosion. If the SiC fails and steam enters, the oxidation state may increase, which may not be bad.	Rationale: (≤ 1600 °C) This effect has been studied both in-pile and out of pile. Controlling the maximum operating temperature is a major factor.	Closure Criterion: Acceptable performance.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

<u>Additional Discussion</u>

See entries on corrosion and the other PIRT Tables. Also see entries on UCO. One of the goals of kernel design is to stabilize the corrosive elements so they do not migrate to the SiC. Also, determine if steam attack kernel.

During normal or accident conditions, the SiC can crack or break due to over pressure or an interaction with cracked PyC. High temperatures increase the pressure in a particle. Above 1600 °C or so, decomposition begins to weaken the SiC and it can fail.

For some work on examining the effects of cracks on fuel performance and general models see the other PIRT tables and:

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.

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., INEEL/EXT-02-00300

Revised MHTGR High-Temperature Fuel Performance Models, R.C. Martin, ORNL/NPR-92/16

Methods and Data for HTGR Fuel Performance and Radionuclide Release Modeling during Normal Operational and Accidents for Safety Analysis, K. Verfondern, et. al., Jul-2721

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

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

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer Sintering	Change of graphite microstructure as a function of temperature

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	≤ 1600 °C: 7	Remedy: None if temperatures are below 1600 °C, an steam environment may modify this.
	> 1600 °C: N/A	Remedy: N/A
Rationale: SiC doesn't appear to suffer any significant changes at normal operating conditions and survives at 1600 °C without large changes.	Rationale: (≤ 1600 °C) Extensive testing at 1600 °C for hundreds of hours has shown the good behavior of SiC.	Closure Criterion: None
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

The major challenge is to reproduce the SiC that performed so well in past testing. The exposure to steam is expected to lead to corrosion effects rather than sintering effects. The loss of the SiC integrity is the major issue.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer: Chemical attack by water Kinetics	Rate of reaction per unit surface area as a function of temperature and partial pressure of steam

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	≤ 1600 °C: 1	Remedy: Determine chemical conditions and release time for the relevant case.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The rates determine how long the SiC will last. Also, oxidation of the SiC layer will destroy its fission product retention capability. A major issue is whether SiO or SiO_2 is produced. SiO_2 will produce a layer that impedes mass transfer while SiO is volatile. This is less important for steam.	Rationale: (≤ 1600 °C) Not much is known about this rate. It is assumed to be small and most experiments look at kernel oxidation rather than SiC. SiC work has been done at lower temperatures.	Closure Criterion: Resolution of reaction rates.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

<u>**Additional Discussion**</u>

Steam is less aggressive than air and this may not be a significant problem. Some references:

Compilation of Fuel Performance and Fission Product Transport Models and Database for MHTGR Design, Martin, R.C., ORNL/NPR-91/6

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

Methods and Data for HTGR Fuel Performance and Radionuclide Release Modeling during Normal Operational and Accidents for Safety Analysis, K. Verfondern, et. al., Jul-2721

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer: Chemical attack by water	Modification of the reaction rate by fission products or impurities
	Catalysis	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	≤ 1600 °C: 1	Remedy: Determine the relevance of this issue.
	> 1600 °C: N/A	Remedy: N/A
Rationale: A catalysis could increase the reaction rate and enhance the failure of the SiC.	Rationale: (≤ 1600 °C) Unknown	Closure Criterion: Resolution of issue.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

This area is less explored for fuel. Some industrial literature may exist. Since water is less aggressive than air, this issue may be less important.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer: Chemical attack by water	Changes in chemical form resulting from oxidizing or reducing fission products
	Changes in chemical form of fission products	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 4	Remedy: Determine the need for this knowledge, collect as necessary.
	> 1600 °C: N/A	Remedy: N/A
Rationale: Changes in the chemical form of the fission products can greatly change their transport properties. Once the SiC fails, the potential for significant particle releases increase. The greatest change may come from the reaction of UC and the change in kernel structure.	Rationale: (≤ 1600 °C) Thermochemical codes can calculate the possible chemical compounds. Little confirmation work is available.	Closure Criterion: Collect data to resolve uncertainties
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

<u>Additional Discussion</u>

The forms and migration of the fission products can be complex. For some information on the chemical forms see:

Fission Product Plateout and Liftoff in the MHTGR Primary System: A Review, NUREG/CR-5647

Chemical Behavior of Fission Products in Core Heatup Accidents in High-Temperature Gas-Cooled Reactors, R. Moormann, Nuclear Technology, 94 (1991), pages 56-67.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer: Chemical attack by water	Changes in diffusivity, porosity, adsorptivity, etc.
	Changes in SiC properties	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	≤ 1600 °C: 1	Remedy: Determine if this item is relevant.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The modeling is not performed at this level; generally, the layer is assumed to disappear at some rate.	Rationale: (≤ 1600 °C) Not examined in this detail.	Closure Criterion: Collect relevant detail.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

This level of detail may not be necessary if all one needs is time to significant fuel releases as the SiC fails. An integral failure of the SiC may be sufficient without all this detail.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer: Chemical attack by water	Release of SiC FP inventory
	Holdup reversal	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	≤ 1600 °C: 3	Remedy: Determine the conditions of interest and collect the necessary data
	> 1600 °C: N/A	Remedy: N/A
Rationale: As the SiC is removed; any inventory of fission products will be released. The inventory of this layer is low for high quality fuel	Rationale: (≤ 1600 °C) Some air ingress work has been done.	Closure Criterion: Determine the relevance of this need and collect data
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

<u>Additional Discussion</u>

If the fuel performs as expected, the inventory of this layer will be very low. Thus, the actual details of its release may not be important. The greater problem is that its loss exposes the high inventory kernel. See:

Compilation of Fuel Performance and Fission Product Transport Models and Database for MHTGR Design, Martin, R.C., ORNL/NPR-91/6

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

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer: Chemical attack by water	Impact of SiC oxidation on temperature distribution through material
	Temperature distribution	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 5	Remedy: Determine if the uncertainty in the temperatures is acceptable. Refine models and collect data as necessary.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The temperature determines the reaction rates and thus how fast the layer is attacked.	Rationale: (≤ 1600 °C) Enough modeling has been done to reasonably estimate the temperatures	Closure Criterion: Adequate data for calculations.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	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	≤ 1600 °C: 4	Remedy: None at present
	> 1600 °C: N/A	Remedy: N/A.
Rationale: Gas diffusion through the PyCs is generally quite low at the temperatures of interest. The SiC layer must be breeched for the gases to get out. If the SiC layer has been damaged, the failure likelihood of the IPyC is increased. If attack of the IPyC occurs, significant release will soon follow.	Rationale: (≤ 1600 °C) Gas diffusion through the PyCs has been shown to be quite low. The issue is the layer behavior after is has been attacked. Some integral testing has been done.	Closure Criterion: Acceptable test fuel behavior
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

<u>Additional Discussion</u>

Extensive testing has been done on various fuels over a range of temperatures. The challenge is to reproduce this good material. See:

Performance Evaluation of Modern HTR TRISO Fuel, R. Gontard, H. Nabielek, HTA-1B-05/90, July 1990
Fuel Performance and Fission Product Behavior in Gas Cooled Reactors, IAEA-TECDOC-978 (1997)
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

The concern is how the chemical attack affects the layer. For accident models see:

Compilation of Fuel Performance and Fission Product Transport Models and Database for MHTGR Design, Martin, R.C., ORNL/NPR-91/6
Revised MHTGR High-Temperature Fuel Performance Models, R.C. Martin, ORNL/NPR-92/16
Methods and Data for HTGR Fuel Performance and Radionuclide Release Modeling during Normal Operational and Accidents for Safety Analysis, K. Verfondern, et. al., Jul-2721

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer 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: M	≤ 1600 °C: 4	Remedy: None, nothing can be done
	> 1600 °C: N/A	Remedy: N/A
Rationale: The diffusion of metallic fission products through the PyCs is known to be fairly high. Only modest credit can be taken for PyC as a barrier or release delay for metallics. Any chemical attack will only enhance the diffusion.	Rationale: (≤ 1600 °C) The PyCs are generally assumed to provide limited retention to metallic fission products at accident temperatures. Chemical attack may make the situation worse.	Closure Criterion: None
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

For a discussion of PyC and metallics see:

Nuclear Technology, 35, Number 2, Fission Product Release Section, pages 457-526

For the higher accident temperatures, the PyCs are assumed to have essentially no resistance to metallic transport. The PyC offers some impedance to metallic transport, but is not a major barrier. Chemical attack will worsen the situation, but the SiC layer is the important one.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer Pressure loading (Fission products)	Stress loading of the layer by increased pressure from fission products

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 7	Remedy: Proper design and fabrication
	> 1600 °C: N/A	Remedy: N/A
Rationale: Depending on the particular configuration, the PyC layers can help keep the SiC in compression. Loss of a PyC layer can increase the probability of SiC failure.	Rationale: (≤ 1600 °C) Pressure can be controlled by particle design, burnup, and kernel composition. Analysis and designs are available	Closure Criterion: Acceptable fuel performance
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

According to the fuel models, the PyC functions as an important load-bearing component of the fuel particle. See the PIRT Design Table for more information concerning the stresses. Loss of other layers due to chemical attack influences the structural stability of the entire particle.

A major concern is the proper material properties – see the Manufacturing Design PIRT

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer Pressure loading (Carbon monoxide)	Stress loading of the layer by carbon monoxide by increased pressure

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 7	Remedy: Control pressure by design
	> 1600 °C: N/A	Remedy: N/A
Rationale: High CO product will result in high particle pressures, especially at the higher accident temperatures. Changing the kernel composition can control CO production.	Rationale: (≤ 1600 °C) Pressure can be controlled by particle design, burnup, and kernel composition. Analysis and designs are available.	Closure Criterion: Proof testing of final fuel design
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

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.
See the other PIRT Tables for fuel design issues.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer Layer oxidation	Reaction of pyrolytic graphic with oxygen released from the kernel.

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 3	Remedy: Collect relevant data
	> 1600 °C: N/A	Remedy: N/A
Rationale: Defects or cracks in the OPyC and SiC can allow steam to enter the particle and oxidize the IPyC. This will release fission gases and provide a direct path to the kernel.	Rationale: (≤ 1600 °C) This behavior is similar to the burn leach tests used to determine fuel quality. The rates are assumed to be the same as for OPyC	Closure Criterion: Reasonable calculational basis.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

If both the OPyC and the SiC are breeched, then the particle is releasing.

Performance Evaluation of Modern HTR TRISO Fuel, R. Gontard, H. Nabielek, HTA-1B-05/90, July 1990
Fuel Performance and Fission Product Behavior in Gas Cooled Reactors, IAEA-TECDOC-978 (1997)
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

For accident models see:

Compilation of Fuel Performance and Fission Product Transport Models and Database for MHTGR Design, Martin, R.C., ORNL/NPR-91/6
Revised MHTGR High-Temperature Fuel Performance Models, R.C. Martin, ORNL/NPR-92/16
Methods and Data for HTGR Fuel Performance and Radionuclide Release Modeling during Normal Operational and Accidents for Safety Analysis, K. Verfondern, et. al., Jul-2721

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer Stress state (compression/tension)	The state of the forces induced by external forces that are acting across the layer to resist movement

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 7	Remedy: Control pressure by design
	> 1600 °C: N/A	Remedy: N/A
Rationale: Failure of the PyC can increase the likelihood of SiC failure. See the previous pressure loading entries.	Rationale: (≤ 1600 °C) Pressure can be controlled by particle design, burnup, and kernel composition. Analysis and designs are available	Closure Criterion: Proof testing of final fuel design
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

See the table entries about pressure loading and also the PIRT Design Tables.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer Cracking	Lengths, widths and numbers of cracks produced in layer during accident

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 4 (failure only, cracking is not calculated)	Remedy: Review and collect new data for the codes if necessary.
	> 1600 °C: N/A	Remedy: N/A
Rationale: Failure of the IPyC affects the likelihood of SiC failure. See the entry on stress state. The lengths, widths, and number of cracks don't really matter – the failure does. Many models assume the SiC layer will dominate the particle failure. Effects of chemical attack may not be included.	Rationale: (≤ 1600 °C) Fuel models have been developed to model normal and accident behavior. Particles are assumed to fail when they meet some weakness criteria rather based a layer stress.	Closure Criterion: Models that predict fuel behavior under normal and accident conditions. Does one need cracks or just failure? This adds a lot of complexity.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

Under accident conditions, a pressure vessel type failure model has been used with the particle failing when the pressure exceeds a critical value. The accident models may not include all the chemical attack effects.

For some work on examining the effects of cracks on fuel performance and general models 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.
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

Compilation of Fuel Performance and Fission Product Transport Models and Database for MHTGR Design, Martin, R.C., ORNL/NPR-91/6
Revised MHTGR High-Temperature Fuel Performance Models, R.C. Martin, ORNL/NPR-92/16
Methods and Data for HTGR Fuel Performance and Radionuclide Release Modeling during Normal Operational and Accidents for Safety Analysis, K. Verfondern, et. al., Jul-2721

Massive pyrocarbon failure In HRB-21 due to a design flaw (seal coats) resulted in cracks that appear to have compromised the SiC and resulted in releases. (ORNL)

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer Intercalation	Trapping of species between sheets of the graphite structure

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	≤ 1600 °C: 2	Remedy: None
	> 1600 °C: N/A	Remedy: N/A
Rationale: This layer is likely to be saturated with fission products and this effect may only make a minor difference.	Rationale: (≤ 1600 °C) This situation has not caused problems	Closure Criterion: None
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

Some modeling is looking at this situation.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer: Chemical attack by water Kinetics	Rate of reaction per unit surface area as a function of temperature and partial pressure of steam

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 3	Remedy: Determine the relevance of the event and collect the necessary data.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The kinetics determine the reaction rate and duration of the accident.	Rationale: (≤ 1600 °C) Some work has been done in this area. The rate is sensitive to the specific material.	Closure Criterion: The need and the required data.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

See:

Compilation of Fuel Performance and Fission Product Transport Models and Database for MHTGR Design, Martin, R.C., ORNL/NPR-91/6

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

Oxidation of Unfueled and Fueled Graphite Spheres by Steam, J.L. Rutherford, J.P. Blakely, L.G. Overholser, ORNL-3947, May 1966

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer: Chemical attack by water Catalysis	Modification of the reaction rate by fission products or impurities

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	≤ 1600 °C: 4	Remedy: Review the literature and determine if it is relevant or important
	> 1600 °C: N/A	Remedy: N/A
Rationale: A catalysis can increase the reaction rate in the layer and hasten its failure.	Rationale: (≤ 1600 °C) The carbon steam reaction has been studied in some detail. It needs to be applied to the fuel.	Closure Criterion: Collect the effects of catalysis if necessary.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

If the fission product inventory in the PyC is low and its loss does not significantly increase the SiC failure probably, then this issue may be unimportant. The industrial literature needs to be consulted, as this is an important commercial reaction.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer: Chemical attack by water	Changes in chemical form resulting from oxidizing or reducing fission products
	Changes in chemical form of fission products	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 4	Remedy: Determine the need for this knowledge, collect as necessary.
	> 1600 °C: N/A	Remedy: N/A
Rationale: Changes in the chemical form of the fission products can greatly change their transport properties. Once the SiC fails, the potential for significant particle releases increase. The greatest change may come from the reaction of UC and the change in kernel structure.	Rationale: (≤ 1600 °C) Thermochemical codes can calculate the possible chemical compounds. Little confirmation work is available.	Closure Criterion: Collect data to resolve uncertainties
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

The forms and migration of the fission products can be complex. For some information on the chemical forms see:

Fission Product Plateout and Liftoff in the MHTGR Primary System: A Review, NUREG/CR-5647

Chemical Behavior of Fission Products in Core Heatup Accidents in High-Temperature Gas-Cooled Reactors, R. Moormann, Nuclear Technology, 94 (1991), pages 56-67.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer: Chemical attack by water	Changes in diffusivity, porosity, adsorptivity, etc.
	Changes in graphite properties	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	≤ 1600 °C: 1	Remedy: Determine if this item is relevant.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The modeling is not performed at this level; generally, the layer is assumed to disappear at some rate.	Rationale: (≤ 1600 °C) Not examined in this detail.	Closure Criterion: Collect relevant detail.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

This level of detail may not be necessary if all one needs is time to significant fuel releases as the failure of the SiC may dominate.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer: Chemical attack by water	Release of graphite FP inventory
	Holdup reversal	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	≤ 1600 °C: 3	Remedy: Nothing, as the kernel release will dominate.
	> 1600 °C: N/A	Remedy: N/A
Rationale: Once the SiC fails and the IPyC is exposed, releases begin to increase rapidly. The inventory of the IPyC is irrelevant compared to the kernel, which is exposed as soon as the IPyC is damaged.	Rationale: (≤ 1600 °C) The actual inventory of the IPyC at the time the SiC is breeched is only roughly known.	Closure Criterion: None
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

Once the IPyC is exposed to chemical attack, releases will increase, as the kernel will be exposed.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer: Chemical attack by water Temperature distribution	Impact of graphite oxidation on temperature distribution through material

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 5	Remedy: Determine if the uncertainty in the temperatures is acceptable. Refine models and collect data as necessary.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The temperature determines the reaction rates and thus how fast the layer is attacked.	Rationale: (≤ 1600 °C) Enough modeling has been done to reasonably estimate the temperatures.	Closure Criterion: Adequate data for calculations.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	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	≤ 1600 °C: 7	Remedy: None
	> 1600 °C: N/A	Remedy: N/A
Rationale: The buffer layer is designed to be a void to collect the gases released from the kernel. The problem would be if it weren't porous.	Rationale: (≤ 1600 °C) The buffer layer appears to work as planned. Gases are expected to diffusive through this layer.	Closure Criterion: None
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

Once this layer is exposed, the kernel is essentially exposed.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer 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	≤ 1600 °C: 7	Remedy: None
	> 1600 °C: N/A	Remedy: N/A
Rationale: The buffer layer is essentially void volume and is not expected to offer resistance to transport. Some material may be sorbed on this layer.	Rationale: (≤ 1600 °C) The buffer layer appears to work as planned. Fission products are expected to diffusive through this layer.	Closure Criterion: None
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

Once this layer is exposed, the kernel is essentially exposed.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer Response to kernel swelling	Mechanical reaction of the layer to the growth of the kernel via swelling

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	≤ 1600 °C: 7	Remedy: None
	> 1600 °C: N/A	Remedy: N/A
Rationale: The buffer layer must be weak enough that it will deform or crush without transmitting high forces to the IPyC as the kernel distorts.	Rationale: (≤ 1600 °C) All evidence to date indicates that the buffer layer performs as expected.	Closure Criterion: None
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

In the accident fuel testing done to date, no evidence of adverse buffer reaction to kernel swelling was apparent.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer Maximum fuel gaseous fission product uptake	Maximum loading of fission products that can deposit from the gas phase onto surfaces of materials surrounding the fuel kernel

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 7	Remedy: None
	> 1600 °C: N/A	Remedy: N/A
Rationale: The buffer layer must have sufficient void volume to control the pressure from released fission gases and CO.	Rationale: (≤ 1600 °C) All evidence to date indicates that the buffer layer performs as expected.	Closure Criterion: None
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

This is really a design issue. See the PIRT Design Table.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer Layer oxidation	Reaction of buffer layer with oxide materials in the kernel.

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	≤ 1600 °C: 7	Remedy: None
	> 1600 °C: N/A	Remedy: N/A
Rationale: A small portion of the layer is oxidized by the excess oxygen released form the kernel. This is of no consequence, as the layer has no structural function. It is of no consequence if the buffer is oxidized by air/steam as the particle is already failed.	Rationale: (≤ 1600 °C) No problem ahs been observed. The basic problem is CO production that has been outlined elsewhere.	Closure Criterion: None
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

See the discussions on the use of UCO to control CO pressure.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer Thermal gradient	Change in temperature with distance

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	≤ 1600 °C: 7	Remedy: None
	> 1600 °C: N/A	Remedy: N/A
Rationale: During accident conditions, the particle gradient is low because the power production is low relative to operating conditions and heat transfer is no longer driven by strong convection	Rationale: (≤ 1600 °C) The codes can compute these temperatures.	Closure Criterion: None
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

<u>Additional Discussion</u>

It is not likely that the chemical reactions will generate thermal gradients that are comparable with normal operation.

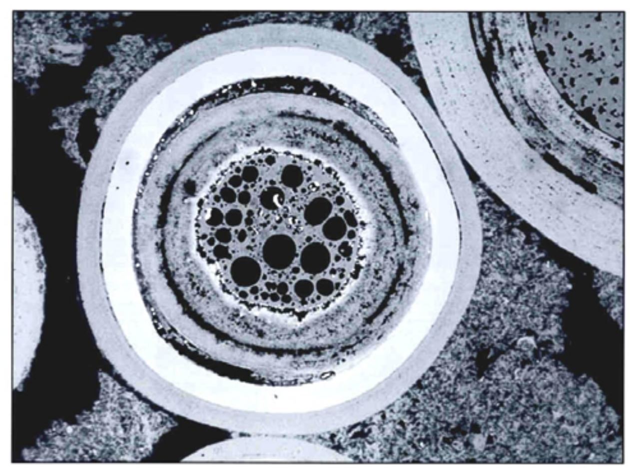
Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer	Dimension changes in the buffer layer or changes in its porosity produced by irradiation or by exposure to elevated temperatures
	Irradiation and thermal shrinkage	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	≤ 1600 °C: 6	Remedy: None
	> 1600 °C: N/A	Remedy: N/A
Rationale: Ideally, the buffer layer should isolate the kernel from the IPyC, but small cracks or limited shrinkage do not seem to cause trouble.	Rationale: (≤ 1600 °C) Modest buffer shrinkage and small cracks don't seem to result in problems	Closure Criterion: None
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

In this high burnup Pu kernel (ORNL), considerable shrinkage took place in the buffer layer and the IPyC separated from the SiC. While one would like to see less behavior of this sort, the particle performed well under irradiation.

One concern is that cracks could offer a direct path for corrosive fission products to the SiC if the IPyC also breaks. Some current modeling is looking at this.



R71558 (C9900515-03) 200x — 20 μm

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer: Chemical attack by water Kinetics	Rate of reaction per unit surface area as a function of temperature and partial pressure of steam

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	≤ 1600 °C: 4	Remedy: Review the literature and determine if it is relevant or important
	> 1600 °C: N/A	Remedy: N/A
Rationale: A catalysis can increase the reaction rate in the layer and hasten its failure.	Rationale: (≤ 1600 °C) The carbon steam reaction has been studied in some detail. It needs to be applied to the fuel.	Closure Criterion: Collect the effects of catalysis if necessary.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

The industrial literature needs to be consulted, as this is an important commercial reaction.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer: Chemical attack by water	Modification of the reaction rate by fission products or impurities
	Catalysis	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	≤ 1600 °C: 4	Remedy: Review the literature and determine if it is relevant or important
	> 1600 °C: N/A	Remedy: N/A
Rationale: This layer is already releasing and increasing the rate may not matter much.	Rationale: (≤ 1600 °C) The carbon steam reaction has been studied in some detail. It needs to be applied to the fuel.	Closure Criterion: Collect the effects of catalysis if necessary.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

Once the buffer is exposed, additional chemical attack may not matter much.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer: Chemical attack by water Changes in chemical form of fission products	Changes in chemical form resulting from oxidizing or reducing fission products

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 4	Remedy: Determine the need for this knowledge, collect as necessary.
	> 1600 °C: N/A	Remedy: N/A
Rationale: Changes in the chemical form of the fission products can greatly change their transport properties. The greatest change may come from the reaction of UC and the change in kernel structure	Rationale: (≤ 1600 °C) Thermochemical codes can calculate the possible chemical compounds. Little confirmation work is available.	Closure Criterion: Collect data to resolve uncertainties
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

The forms and migration of the fission products can be complex. For some information on the chemical forms see:

Fission Product Plateout and Liftoff in the MHTGR Primary System: A Review, NUREG/CR-5647

Chemical Behavior of Fission Products in Core Heatup Accidents in High-Temperature Gas-Cooled Reactors, R. Moormann, Nuclear Technology, 94 (1991), pages 56-67.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer: Chemical attack by water	Changes in diffusivity, porosity, adsorptivity, etc.
	Changes in graphite properties	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	≤ 1600 °C: 1	Remedy: Determine if this item is relevant.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The modeling is not performed at this level; generally, the layer is assumed to disappear at some rate.	Rationale: (≤ 1600 °C) Not examined in this detail.	Closure Criterion: Collect relevant detail.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

This level of detail may not be necessary if all one needs is time to significant fuel releases as the failure of the SiC may dominate.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer: Chemical attack by water	Release of graphite FP inventory
	Holdup reversal	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	≤ 1600 °C: 4	Remedy: None.
	> 1600 °C: N/A	Remedy: N/A
Rationale: By the time the buffer layer is attacked, the particle has failed and is releasing. The kernel is now the dominate factor.	Rationale: (≤ 1600 °C) The buffer inventory is not well known under accident conditions.	Closure Criterion: None.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

The kernel release is now the dominate mechanism**.**

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer: Chemical attack by water Temperature distribution	Impact of graphite oxidation on temperature distribution through material

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	≤ 1600 °C: 5	Remedy: Determine if the uncertainty in the temperatures is acceptable. Refine models and collect data as necessary.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The buffer temperature is the same as the kernel, which is dominating the releases at this point since all the other layers have failed.	Rationale: (≤ 1600 °C) Enough modeling has been done to reasonably estimate the temperatures	Closure Criterion: Adequate data for calculations
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

See the reactor core models for temperature distributions.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel Maximum fuel temperature	Maximum fuel temperature attained by the fuel kernel during the accident

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 7	Remedy: Insure that core models are up to date.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The SiC layer is the primary barrier, but diffusion through the kernel does delay the release somewhat. The kernel retains a considerable amount of material and release is a function of temperature.	Rationale: (≤ 1600 °C) The core codes should be good enough to calculate the temperatures.	Closure Criterion: Acceptable uncertainties.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

For a study comparing the relative contributions of core and fuel materials and fission product retention see: *An Analytical Study of Volatile Metallic Fission Product Release From Very High Temperature Gas-Cooled Reactor Fuel and Core*, S. Mitake, et. al., Nuclear Technology, 81, 7-12.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel Temperature vs. time transient conditions	The time-dependent variation of fuel temperature with time

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 7	Remedy: None, expect to watch for hot spots
	> 1600 °C: N/A	Remedy: N/A
Rationale: The temperature history of the fuel is important. Higher temperature operation even if it is followed by lower temperature operation can result in greater corrosion problems. High temperatures also increase fission product diffusion.	Rationale: (≤ 1600 °C) Modern codes can computer the time history of the fuel. The greatest problem is material property uncertainties.	Closure Criterion: Calculations within the needed uncertainties.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

This is really a core design issue.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel Energy Transport: Conduction within kernel	Flow of heat within a medium from a region of high temperature to a region of low temperature

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	≤ 1600 °C: 7	Remedy: None
	> 1600 °C: N/A	Remedy: N/A
Rationale: The kernel conductivity determines the kernel peak temperature. The kernel is fairly small, so modest changes in conductivity won't matter much. Higher temperatures could result in greater diffusion of fission products out of the kernel.	Rationale: (≤ 1600 °C) These numbers have been measured for the fuels of interest. No major issues are associated with them.	Closure Criterion: None
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

Kernel conductivity depends on the kernel composition and changes as the kernel burns up. The small size of the kernel limits these effects in coated particle fuel.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel Thermodynamic state of fission products	Chemical and physical state of fission products

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 4	Remedy: If fuel kernels other than UO_2 are to be used, testing is required to assure that they work as expected.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The chemical state of the fission products determines how they will migrate and the temperature dependence. It is desirable to oxidize some fission products without producing CO. Steam could cause additional changes by reacting with the UCO.	Rationale: (≤ 1600 °C) A considerable amount of work has been done 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. Also, the kernel will oxide with air and water.	Closure Criterion: Demonstrated performance under the conditions of interest
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

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.

The effect of Water Vapor on the Release of Gaseous Fission Products from High-Temperature Gas-Cooled Reactor Fuel Compacts Containing Exposed Uranium Oxycarbide Fuel, B. Myers, DOE-HTGR-88486

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel Oxygen flux	Mass transport of oxygen per unit surface area per unit time

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	≤ 1600 °C: 3	Remedy: Determine if this area is of any significance
	> 1600 °C: N/A	Remedy: N/A
Rationale: The mass of oxygen from the kernel will determine the rate at which CO is formed and particle pressure. Since the particles are designed assuming maximum pressure, the rate does not seem that important, but his area is somewhat unexplored. Water will oxidize the kernel. See previous entry.	Rationale: (≤ 1600 °C) Some work has been done in this area. The full implications are not clear.	Closure Criterion: Resolution of the issue.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

Tests have shown that the oxygen does not immediately leave the kernel, leading to a somewhat lower CO pressure than normally would occur. This effect is probably more important for low burnup fuel than high burnup fuel. Upcoming tests on German fuel at higher burnups should shed more light on the oxygen issue. See:

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.

Influence of Irradiation Temperature, Burnup, and Fuel Composition on Gas Pressure (Xe, Kr, CO, CO2) in Coated Particle Fuels, G.W. Horsley, et. al., Journal of the American Ceramic Society, 59, Number 1-2, pages 1-4.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel Grain growth	Enlargement of grains as a result of diffusion

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	≤ 1600 °C: 3	Remedy: None at present
	> 1600 °C: N/A	Remedy: N/A
Rationale: Kernel grain growth has not been an issue. The higher burnups of coated particles fuels often results in the destruction of any structure. Gas release could be higher, but this issue hasn't come up.	Rationale: (≤ 1600 °C) The grain growth issue appears to be less important with coated particle fuel because the layers form the fission product boundary.	Closure Criterion: None at present
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

Unlike LWR fuel, the grain structure appears to be less important.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel Buffer carbon-kernel interaction	Chemical reaction between carbon and the fuel (UO_2) to form UC_2 and CO (gas)

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	≤ 1600 °C: 5	Remedy: None
	> 1600 °C: N/A	Remedy: N/A
Rationale: A significant problem in this area has not been observed.	Rationale: (≤ 1600 °C) Reactions of this nature can be investigated using thermochemical codes. Nothing has come up to date.	Closure Criterion: None
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

<u>Additional Discussion</u>

This issue is discussed to some extent in: *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
Accident With Subsequent Water Intrusion	Kernel: Chemical attack by water	Rate of reaction per unit surface area as a function of temperature and partial pressure of steam
	Kinetics	

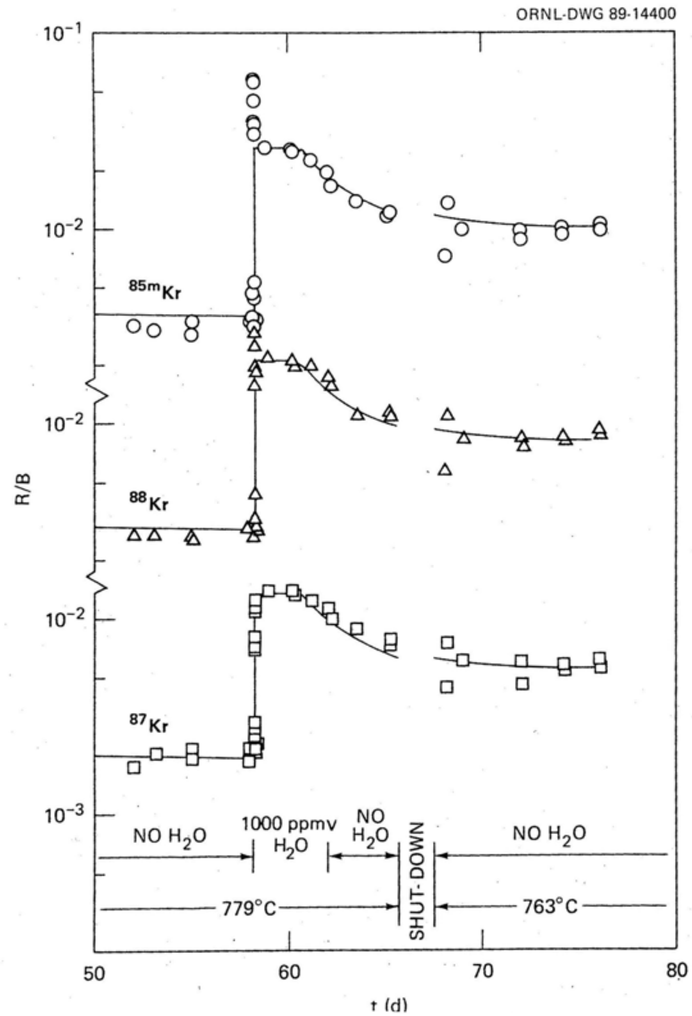
Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 4	Remedy: Determine if the existing data is good enough, collect more if necessary
	> 1600 °C: N/A	Remedy: N/A
Rationale: This determines the enhanced rate at which the fission products are released from the kernel.	Rationale: (≤ 1600 °C) Moisture ingress tests have been done on UO_2 and UCO fuel.	Closure Criterion: Enough data to bind the accident of interest.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

<u>Additional Discussion</u>

The amount of damaged fuel determines how significant this issue is. If the fuel performs as advertised, then it may not matter. See *Fuel Performance and Fission Product Behavior in Gas Cooled Reactors*, IAEA-TECDOC-978 (1997)

The effect of Water Vapor on the Release of Gaseous Fission Products from High-Temperature Gas-Cooled Reactor Fuel Compacts Containing Exposed Uranium Oxycarbide Fuel, B. Myers, DOE-HTGR-88486

Water Increases Release From Exposed UCO Kernels
A pulse of water restructures the (bare) UCO kernel and releases the stored fission gas. After the release, the R/B gradually drops back to pre injection values. (ORNL)



Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel: Chemical attack by water	Modification of the reaction rate by fission products or impurities
	Catalysis	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	≤ 1600 °C: 1	Remedy: Determine if relevant.
	> 1600 °C: N/A	Remedy: N/A
Rationale: A catalysis could increase the reaction rate and accelerate releases.	Rationale: (≤ 1600 °C) Unknown	Closure Criterion: Collection of relevant data.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

Accelerated releases from the kernel under accident conditions due to catalysis have not been explored.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel: Chemical attack by water	Changes in chemical form resulting from oxidizing or reducing fission products
	Changes in chemical form of fission products	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 4	Remedy: Determine the need for this knowledge, collect as necessary.
	> 1600 °C: N/A	Remedy: N/A
Rationale: Changes in the chemical form of the fission products can greatly change their transport properties. The greatest change may come from the reaction of UC and the change in kernel structure	Rationale: (≤ 1600 °C) Thermochemical codes can calculate the possible chemical compounds. Little confirmation work is available	Closure Criterion: Collect data to resolve uncertainties
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

The forms and migration of the fission products can be complex. For some information on the chemical forms see:

Fission Product Plateout and Liftoff in the MHTGR Primary System: A Review, NUREG/CR-5647

Chemical Behavior of Fission Products in Core Heatup Accidents in High-Temperature Gas-Cooled Reactors, R. Moormann, Nuclear Technology, 94 (1991), pages 56-67.
Fuel Performance and Fission Product Behavior in Gas Cooled Reactors, IAEA-TECDOC-978 (1997)

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel: Chemical attack by water	Changes in diffusivity, porosity, adsorptivity, etc.
	Changes graphite properties	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 5	Remedy: Determine the relevance of this situation
	> 1600 °C: N/A	Remedy: N/A
Rationale: As the kernel restructures because of oxidation, it releases some its stored inventory of fission products, mostly gases.	Rationale: (≤ 1600 °C) Moisture testing has been done and exposed kernels are the major issue, rather than good fuel.	Closure Criterion: Relevance of this situation and any data.
	Rationale (> 1600 °C) N/A	Closure Criterion: N/A

Additional Discussion

The amount of damaged fuel determines how significant this issue is. If the fuel performs as advertised, then it may not matter. See *Fuel Performance and Fission Product Behavior in Gas Cooled Reactors*, IAEA-TECDOC-978 (1997)

The effect of Water Vapor on the Release of Gaseous Fission Products from High-Temperature Gas-Cooled Reactor Fuel Compacts Containing Exposed Uranium Oxycarbide Fuel, B. Myers, DOE-HTGR-88486

Appendix E.3

Detailed PIRT Submittal by the SNL Panel Member

E. A. Powers

TRISO Fuel PIRT: Accident With Subsequent Water Intrusion

This PIRT is based more on geometry than it is on phenomenology, despite the name. The PIRT seems to be attempting to identify the critical component of the coated particle fuel structure that deserves the most attention. This is done at the expense of identifying the critical phenomena that need to be understood to anticipate the behavior of the fuel in normal and off normal circumstances. As a result questions are asked repetitively about each of the major elements of the fuel perhaps to see if one or more of the elements are more vulnerable than others. The questions do not illuminate in any detail the type of information that must be derived for coated particle fuel or the types of testing that must be done to gather the information. For instance, lumped within the simple question of gas phase diffusion are bulk and Knudsen diffusion. Though the question is repeated for each layer even when the layers are very similar, such as inner and outer PyC, there is no request for details of the materials that would be essential to estimate Knudsen versus bulk diffusion such as porosity and tortuosity. There is no indication of whether tests of permeability need to be done for layers *in situ* or such data can be obtained from macroscopic samples of analog material. We do not know from the PIRT whether phenomena such as thermal diffusion require testing to be done in prototypic gradients or just known gradients. We do not know from the PIRT whether diffusion must be considered as approximately binary diffusion or has to be viewed as a multicomponent process. This focus on the structure at the expense of phenomena limits the utility of the PIRT for the design of fuel models and experimental studies. Perhaps, the PIRT is more useful in other respects because of its focus on structure.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Fuel Element Irradiation history	The temperature, burnup and fast fluence history of the layer

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 3	Remedy: There is a need for studies of the energetics of radiation damage to the materials making up the coated particle fuel layers. (Damage to the kernel is of lesser interest). The needed information can probably be obtained by thermal analysis of specimens irradiated under prototypic conditions for varying lengths of time. There is further need for information on the kinetics of oxidant reactions and reactions of nitrogen with the materials as functions of temperature.
Rationale: The fast fluence history of the layers will dictate how much radiation damage is built into the materials. This will affect the kinetics of reaction. Also as reaction proceeds, the radiation damage energy will be released augmenting the energy of chemical reactions with the layers	Rationale: We have some knowledge of the radiation damage that can develop in carbon materials at the operating temperatures of interest for this work. We don't have such information about the specific materials involved in the coated particle fuel. Furthermore, we don't have data or models on the effects of radiation damage on the kinetics of oxidant interactions with the materials	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Fuel Element Surface 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: M	Level: 1	Remedy: The essential remedy is to wait until a specific and reproducible material is specified. Then the material has to be characterized in terms of grain size and orientation as well as in terms of the surface and grain boundary diffusion coefficients of irradiated material. Diffusion studies will have to take into account the fact that the material will not be isothermal. Rather there will be necessarily a temperature gradient across the material from the fuel particles (which are the source of the decay heat) and the coolant. A major issue to confront here is whether the release modeling should be so complete that it considers release limitations by the matrix material surrounding the fuel particles. It would not be an unreasonable conservatism to neglect this barrier to release since it appear unlikely that there will soon be useful experimental data to validate models of the barrier
Rationale: Grain boundary and surface diffusion of fission products will be faster mechanisms of mass transport of fission products from the perimeter of the fuel particles to the surfaces of the matrix material and into the reactor coolant system from where they can escape into the plant environment. Surface diffusion and grain boundary diffusion are notoriously sensitive to impurity concentrations of the material. They are also sensitive to the grain sizes and the preferential orientation of grains. Presumably they are also sensitive to the irradiation of the material though I am not familiar with definitive studies of this issue. Diffusion in the systems will be complicated by the presence of a thermal gradient across the material.	Rationale: The bulk matrix material has not been specified and certainly has not been characterized sufficiently to estimate diffusion coefficients for the fission products. There are of course no measured data because the specification of the material has not yet been made. Studies of generic material may provide some guidance.	Closure Criterion:

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Fuel Element Gas diffusion	Diffusion of gaseous fission products through layer (Knudsen and bulk diffusion through pore structure, and pressure driven permeation through structure) Other factors include holdup craking adsorption, site poisoning, permeability, sintering and annealing

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 4	Remedy: The gas phase mass transport across elements rom multi-point sources is a sufficiently complicated process that it is probably useful to set up models now and test them against models used for catalysts and the like. Detailed analyses of the issue will have to wait until there are real data on the fuel matrix materials that will be used in the reactor. A major issue to confront here is whether the release modeling should be so complete that it considers release limitations by the matrix material surrounding the fuel particles. It would not be an unreasonable conservatism to neglect this barrier to release since it appear unlikely that there will soon be useful experimental data to validate models of the barrier
Rationale: Vapor transport through pores and voids in the matrix material will be the fastest mechanism of mass transport of fission products from the fuel particle surfaces to the boundary of the fuel elements, The transport may driven by pressure differences or it may be by diffusion (either chemical or Knudsen). The presence of a thermal gradient will affect the diffusion process. It may be necessary to develop the diffusion equations to include thermal diffusion. Certainly the mass transport will have to address multicomponent effects using something like the Stefan Maxwell equations rather than Fickian diffusion equations	Rationale: The physics of the process is relative well understood and, indeed, fairly sophisticated models of this kind of mass transport have been developed by the catalyst community. What we don't know with any detail is the speciation of the fission product vapors or the pore and void structure of the matrix material. Diffusion coefficients for the vapors can be estimated with surprisingly good reliability from simple first order Chapman Enskog theory. Second order theory must be used to estimate thermal diffusion coefficients which may not be negligible if the thermal gradients are large and if there are gases that have low molecular weights relative to the fission product vapors. Application of models of this type to the issue is not possible now because we do not have data on the material such as its void and porosity structure and its permeability	A major issue to confront here is whether the release modeling should be so complete that it considers release limitations by the matrix material surrounding the fuel particles. It would not be an unreasonable conservatism to neglect this barrier to release since it appear unlikely that there will soon be useful experimental data to validate models of the barrier

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Fuel Element: Transport of metallic FPs through fuel element	Chemical stoichiometry of the chemical species that includes the radioisotope of interest
	Chemical form	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 4	Remedy:There needs to be an agreed upon thermodynamic data base for the important species arising in the analysis of fission product release at these gas-cooled reactors. Much of the data in this base could be borrowed from existing data bases. There needs also to be a search for possible species many of which have been identified in the literature but not characterized sufficiently to include in data bases now available.
Rationale: metallic fission products are going to be transported through the matrix material primarily as vapors. The effective vapor pressures of the metallic fission products depend on their gas phase speciation. There have been fairly limited investigations of the speciation of the fission products in the strongly reducing environment of the fuel element. Certainly the elemental forms will be important. What is of interest is whether there are more exotic species such as carbonyls and carbides and even cyanides that can augment the vapor pressures significantly. A reliable database on the thermodynamics of fission product species appropriate for this kind of a reducing environment (At least prior to oxidant intrusion) has not been assembled. Existing databases treat primarily elements, oxides and in some cases hydroxides. Once the oxidant (water vapor) intrudes, these other possible vapor species as well as vapor phase hydrides need to be considered to know the vapor pressures of the fission products	Rationale: Elemental vapor pressures are rather well established for most of the fission products. Databases exist for most oxides and some hydroxides. Hydride, carbonyl, carbide data are scattered in the literature and have not been systematized nor has there been a systematic survey to identify more exotic vapor species.	Closure Criterion:
	Polyatomic vapor species become less important as temperatures increase and pressures decrease.	

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Fuel Element: Chemical attack by water	Rate of reaction per unit surface area as a function of temperature and partial pressure of steam
	Kinetics	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 4	Remedy:Because water is so ubiquitous in the reactor situation it will be imperative that any model of fission product release and transport account for the effects of water.
Rationale: There is one essential difference between the attack of water on graphite and the attack of air. Water attack on graphite can be endothermic rather than exothermic. Otherwise many of the points raised in connection with the attack on graphite by air are applicable for water as well. The attack can be localized. The speciation of the fission products is affected locally. Transport pathways are affected. Kinetics must be evaluated to know if the fuel particles as well as the matrix will be attacked by the oxidant. Instead of the issues of cyanogens and its effects on vapor pressure the effects of hydrogen and the formation of gas phase hydrides needs to be considered. For example CsH becomes an important vapor phase species of cesium at moderately high temperatures in the presence of hydrogen.	Rationale The databases on steam attack on the specific types of graphite used for the fuel matrix are not rich. There are data for analogous reactions of similar materials	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Fuel Element: Chemical attack by water Catalysis	Modification of the reaction rate by fission products or impurities

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 4	Remedy: This will have to be included in any model of graphite reactions with steam.
Rationale: catalysis of the steam reactions with graphite are known and the catalytic agents are the same as those that catalyze the reactions of oxygen.	Rationale: some data available on analogous materials. A suitable model does not exist	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Fuel Element: Chemical attack by water	Changes in chemical form resulting from oxidizing or reducing fission products
	Changes in chemical form of fission products	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 5	Remedy: The speciation of the fission products ill be an essential part of any model of fission product release and transport. The model will probably have to speciation as a spatially dependent calculation
Rationale: Just as for air intrusion the presence of water can affect the speciation of the fission products and consequently the vapor pressures. The presence of water raises the possibilities of gas phase hydroxides of the fission products. The presence of hydrogen as a reaction product raises the possibility of vapor phase hydrides of fission products such as CsH and RuH contributing to the vapor pressure. See also the discussion of speciation during air intrusion.	Rationale: there is a technical basis for estimating the speciation for fission products though it is not as strong as the basis for doing the speciation of fission products in light water reactors	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Fuel Element: Chemical attack by water	Changes in diffusivity, porosity, adsorptivity, etc.
	Changes in graphite properties	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 2	Remedy: This modeling of the oxidation along pathways for mass transport could be a very challenging feature of a fission product release model. Whether the development of such a model needs to be done or not depends on whether credit is taken for the barrier to fission product release provided by the matrix material
Rationale: As noted above, especially at lower temperatures, oxidant attack on graphite is localized, not uniform and the localized attack is on the regions that will facilitate gas phase mass transport of fission product vapors through the fuel matrix like cracks and pore networks, the attack opens these pathways and makes transport easier	Rationale: The prediction of the effects of oxidant attack on the pathways is challenging. There has been some work in the chemical engineering field on analogous issues that could serve as a basis for modeling this phenomenon	Closure Criterion:
	The effects of oxidant attack on cracks and pore networks becomes less important as temperature become very high	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Fuel Element: Chemical attack by water	Release of graphite FP inventory
	Holdup reversal	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 5	Remedy: It is not clear that this phenomenon needs to be included in a model. Certainly it does not need to be included if the barrier to release presented by the matrix is neglected as a conservative measure that considerably relieves the challenges in estimating releases for risk assessments
Rationale: It is known that energetic sites will adsorb fission product vapors and create some holdup of the release of radionuclides. It is not evident that there are enough of these sites to cause the holdup of a significant fraction of the radionuclide inventory. It is known that chemical reactions that destroy energetic sites or even the intrusion of polarizable gases that will compete for site occupancy can result in the release of the adsorbed fission products. But it the desorption does not involve a large fraction of the inventory of particular class of fission products the phenomenon is not significant	Rationale:) We probably do not have sufficient data on the holdup to make quantitatively defensible estimates of the holdup. We do know enough to make simple qualitative arguments about its significance	Closure Criterion:
	Holdup on the matrix surfaces is less important at high temperatures because of the high vapor pressures of the fission product species of interest. Though we certainly know less about holdup on the surfaces at high temperature than we know at low temperatures, we probably know enough to say that if the importance of the phenomenon is questionable at low temperatures, it certainly is unimportant at very high temperatures	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Fuel Element: Chemical attack by water Temperature distribution	Impact of graphite oxidation on temperature distribution through material

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 5	Remedy: Any model of fission product transport will have to have a reliable description of the temperature distributions along the flow pathway.
Rationale: Because the reactions with graphite are not iosenergetic, they will affect the temperature distribution in the fuel element. Elsewhere it has been established that this temperature distribution can affect the transport of fission products through the fuel element to the surface	Rationale: It is in principle possible to calculate the distortion of the temperature distribution to an accuracy adequate for fission product release transport analysis. It is however not trivial even if we had good models of the thermal conductivity of the material and the effects of growing pores and voids on the thermal conductivity. The essential problem is that the oxidation process does come to be localized so simple geometries are not appropriate.	Closure Criterion:
	The problem of calculating the temperature distribution actually becomes easier as reactions become more homogeneous and radiation across the pores and voids tends to even out their effects on the apparent thermal conductivity of the material.	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer 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: 6	Remedy: Any model of fission product transport within the fuel particle will have to include a gas phase mass transport model recognizing bulk diffusion, pressure driven flow and Knudsen diffusion
Rationale: These gas phase mass transport processes are the fastest ways for fission products released from the kernel to cross the Outer PyC layer.	Rationale: Given the geometry and nature of the pore and crack network in the layer it is possible to calculate the gas phase mass transport across the layer. We can estimate most of the gas phase diffusion coefficients. The mass transport is probably not modeled well by Fickian diffusion and one will have to develop a multicomponent diffusion model much like the membrane models that have been developed in the chemical engineering literature. It may be necessary to include in these models the effects of thermal diffusion especially if the gas includes both low molecular weight species such as CO (MW=28) and fission product vapor species (MW>100) and temperature gradients are significant as they surely must be to get decay heat out of the particle. The most complicated part of the modeling will be to treat the geometries of the layer as a whole and	Closure Criterion: (continued from previous column) the pore, crack and void network in the layer. We know the layers will not by spherically symmetric. Does the deviation from symmetry have a significant effect on the rate of transport? Similarly the layers will not be uniformly thick and this may create short circuits or preferred pathways for mass transport. We do not have good data on the pore and void network. We are not likely to get adequate data from microscopic analysis. The cracks pores and voids that are of interest are too small to readily identify and detect and microscopic examinations will never yield anything but a biased estimate of the concentration and sizes of the networks. Transport data are needed, but it is not readily apparent how such data are obtained for the microscopic layers of the particles.
	The situation is much the same at elevated temperatures though gas phase mass transport becomes an even more dominant mechanism simply because the gas phase concentrations are higher. The ability to estimate diffusion coefficients and thermal diffusion coefficients for polyatomic vapor species begins to degrade because inelastic collision become more important	

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer Condensed phase diffusion	Intergrannular diffusion and'or intra-grannular solid-state diffusion

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 2	Remedy: Any model of fission product transport across the Outer PyC layer will have to include these processes, though it is likely that even with only modest vapor pressures the gas phase mass transport processes will be more important mechanisms. The diffusion process has the same problems discussed above. Spherical symmetry may be an overly crude approximation as may be the assumption that the layer is uniformly thick.
Rationale: Fission products that are not volatile will be transported across the barrier posed by the outer PyC layer by the condensed phase diffusion processes. Bulk diffusion is the slowest of these a low temperatures, but it has the highest activation energy so it does eventually become the dominant process. Even if the metals have only small vapor pressures, gas phase mass transport of fission products may still be the dominant mechanism for most fission products. There do appear to be some exceptions such as the transport of Ag.	Rationale: We do not have surface and grain boundary diffusion coefficients for the fission products and materials of interest here and surface and grain boundary diffusion are likely to be the dominant condensed phase transport processes. These coefficients cannot be estimated. They have to be measured and they are notoriously sensitive to impurities accumulated on the grain surfaces and at the grain boundaries	Closure Criterion:
	At sufficiently high temperatures (and it by no means established that 1600 is sufficiently high) bulk diffusion of fission products will be dominant transport processes for nonvolatile species. We do not have useful bulk diffusion coefficients for irradiated material. The need for irradiated material is to be emphasized since it is known that radiation defects can act as traps for diffusing species	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer Layer oxidation	Reaction of pyrolytic graphite with oxygen released from the kernel

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 2	Remedy: Analysis of fission product release during air intrusion or water intrusion accidents will have to account for the effects of oxidant on the integrity of the outer PyC layer. It will have to be a kinetic analysis so that the analyst will know how much oxidant survives the interaction with the layer to attack other regions of the fuel particle.
Rationale: Oxidant can reach the Outer PyC layer either coming from oxygen evolved from the fuel kernel or oxidant intruding into the core (air or water). It is likely that the source of oxidant coming form the fuel will be sufficiently weak that most of this oxidant will be consumed by reactions with graphite etc. before it can reach the Outer PyC layer in any form other than CO. Oxidant from intrusive sources will have to survive reactions with graphitic materials along its transport path to the fuel particle. When it does survive this transport the results can be catastrophic with respect to fission product transport across the PyC layer. The oxidant will thin the layer, but more importantly localized attack on energetically preferred sites will result in widening and smoothing the cracks and pores through the layer thereby facilitating gas phase mass transport across the layer. The oxidation reactions can also heat the layer	Rationale: The oxidation reactions kinetics are enormously sensitive to impurities that can catalyze reactions. Fission products themselves may act as catalysts. Though we have some data on the oxidation reactions, we do not have data on the specific material. Without these data accurate quantitative analysis of the oxidation process at the Outer PyC layer is really not possible	Closure Criterion:
	The situation becomes a little simpler at very high temperatures where the kinetics are less affected by the catalytic processes and proceed in a more uniform process. Still we donot have validated kinetic models.	

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer Stress state (compression/tension)	The state of the forces induced by external forces that are acting across the layer to resist movement

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 2	Remedy: it isn't clear that any remedy is needed
Rationale: This is a more important issue during normal operations since it can result in rupture of the layer prior to the accident . Thermal expansion may cause some stresses on the layer and it would be of interest to know if rupture can occur.	Rationale We really don' t know much about these forces	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer Intercalation	Trapping of species between sheets of the graphite structure

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 energetic sites in the PyC layer will provide sites for fission product deposition and holdup. There can be a preference for fission products to migrate toward the basal planes of the graphite structure and be intercalated. It is not apparent that sufficient concentrations of sites will be formed to holdup a significant fraction of the radionuclide inventory of the fuel particle. Eventually oxidation or thermal annealing will eliminate these energetic sites and lead to the desorption of fission products that have been attracted to the sites. The elevated temperatures will eventually move fission products from the intercalation sites as well.	Rationale: We don't really know how much holdup can occur At sufficiently high temperatures there really will not be any holdup since the vapor pressures of the fission products will be so high	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer Trapping	Adsorption of fission products on defects

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 energetic sites in the PyC layer will provide sites for fission product deposition and holdup. There can be a preference for fission products to migrate toward the basal planes of the graphite structure and be intercalated. It is not apparent that sufficient concentrations of sites will be formed to holdup a significant fraction of the radionuclide inventory of the fuel particle. Eventually oxidation or thermal annealing will eliminate these energetic sites and lead to the desorption of fission products that have been attracted to the sites. The elevated temperatures will eventually move fission products from the intercalation sites as well.	Rationale: We don't really know how much holdup can occur At sufficiently high temperatures there really will not be any holdup since the vapor pressures of the fission products will be so high	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer Cracking	Lengths, widths and numbers of cracks produced in layer during accident

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 1	Remedy: It is clear that any model of fission product transport through the fuel particles has to recognize the possibility of cracks in the material providing a short pathway for transport. Whether the cracking has to be modeled or cracking is input to the transport model is a decision that must be made. This decision may well rest on whether cracking occurs during the accident transient or is primarily a process that occurs during normal operations.
Rationale: Cracks through the layer facilitate gas phase mass transport of fission products across the layer	Rationale: It is not apparent that we are in any position to predict the cracking of the layers under any circumstances let alone under accident circumstances. It may not be practical to predict cracking and we will have to rely on empirical evidence for cracks. This is a challenge since cracks that can affect fission product release rates may be very difficult to detect microscopically	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer: Chemical attack by water Kinetics	Rate of reaction per unit surface area as a function of temperature and partial pressure of steam

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 6	Remedy: Any model of fission product transport treating intrusion accidents will have to consider water vapor reactions with the graphite and carbon.
Rationale Water attack, while not likely to be as dramatic as attack by air will still be of considerable influence both as it affects the volatility of the fission products and as it affects flow pathways and temperature distributions	Rationale: There is a lot of information about the rates of steam reactions with carbon – though perhaps not the specific carbon of the fuel particles.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer: Chemical attack by water Catalysis	Modification of the reaction rate by fission products or impurities

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 3	Remedy models of reactions will have to recognize that catalysis including catalysis by fission products will affect the kinetics:
Rationale: steam reactions with carbon are catalyzed especially in the lower temperature range	Rationale: see discussions of catalysis of air reactions	Closure Criterion:
	catalysis is of less importance at high temperatures where reaction rates are rapid and eventually are limited by mass transport	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer: Chemical attack by water	Changes in chemical form resulting from oxidizing or reducing fission products
	Changes in chemical form of fission products	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 5	Remedy: The speciation of fission products will be an essential part of any model of fission product release and transport. This is especially the case here because of the dominant role that vapor phase mass transport is expected to play in the transport of fission products released from the kernel to the surface of the fuel particle. There will then have to be a significant model of the fission product thermochemistry in the fission product release model. In comparing predictions of release say to predictions by the applicant for certification, a key issue will be the thermodynamic data base used to make predictions of fission product speciation and vapor pressure.
Rationale: Just as for air intrusion the presence of water can affect the speciation fo the fission products and consequently their vapor pressures. The presence of water raises the possibilities of gas phase hydroxides of the fission products. The presence of hydrogen as a reaction product raises the possibility of vapor phase hydrides of fission products such CsH and RuH contributing to the vapor pressure. Se also the discussion of speciation during air intrusion	Rationale: There is a technical basis for estimating the speciation for fission products though it is not as strong as the basis for doing the speciation of fission products in light water reactors	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer: Chemical attack by water	Changes in diffusivity, porosity, adsorptivity, etc.
	Changes in graphite properties	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 3	Remedy:The modeling of oxidation along pathways for mass transport could be a very challenging feature of a fission product release model. It is important to include because gas phase mass transport of fission products is the most important mechanism to move materials from the surface of the kernel to the surface of the fuel particle. Some work has been done in the Chemical Engineering field to look at the ways chemical reactions open pathways in porous solids. This might be a useful starting point for the development of a model.
Rationale: The important effect of oxidation aside from changing the volatilities of the fission products is to facilitate the transport of fission products released from the kernel across the fuel particle by either thinning the barrier layers such as the outer PyC layer or, and more importantly, opening the void networks and cracks through the layer for gas phase mass transport.	Rationale: The calculation of the localized oxidation that leads to the opening of gas phase flow pathways is difficult to do. We don't now have the needed data on these pathways nor do we have the kinetic information on the reaction rates of steam with the particular material of interest. We do have data on some analogous materials so it might be possible now to formulate estimates whose quantitative reliability may be open to some question.	Closure Criterion:
	The situation is largely the same at the higher temperatures, however, the reactions become more rapid at elevated temperatures and consequently the material thinning becomes more important than the reactions to form more open pathways.	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer: Chemical attack by water	Release of graphite FP inventory
	Holdup reversal	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 4	Remedy: no remedy needed
Rationale: Oxidation will destroy the energetic sites that have absorbed fission products and thus release the fission products. It is not apparent that adsorption of fission products on energetic sites produces holdup of sufficient fractions of the fission products for this reactive desorption process to be risk important	Rationale: we don't have the needed data on the fractional holdup in the layer by the adsorption process. One would suspect that for the outer layer of PyC this holdup is small if the fuel has operational integrity.	Closure Criterion:
	At elevated temperatures, the vapor pressures of the important, volatile radionuclides are so high that the adsorption fraction is low. Though we don't know any more at high temperatures than we do at low temperatures there is probably less need to know a great deal for high temperatures.	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Outer PyC Layer: Chemical attack by water Temperature distribution	Impact of graphite oxidation on temperature distribution through material

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 3	Remedy: Any model of fission product release and transport will require quite a good model of the local temperature distributions in the fuel particle.
Rationale: The chemical reactions of oxidants with the carbon materials are not iso-enthalpic, so they will distort the temperature distributions in the particle. As noted elsewhere these temperature distributions can affect release both through the effect on the thermodynamic driving force for transport across the particle and from an effect on the transport processes themselves.	Rationale: We generally know the heats of reaction. We don't have as good an understanding of the rates of reaction especially of irradiated material where reaction will simultaneously involve the destruction of defects introduced by irradiation during operations.	Closure Criterion:
	The situation is largely the same at higher temperatures though the importance of irradiation defects will decrease as they are thermally annealed.	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	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)

Additional Discussion

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 6	Remedy: Any model of fission product transport within the fuel particles will have to include an gas phase mass transport model recognizing bulk diffusion, pressure driven flow and Knudsen diffusion The mechanistic detail with which a model could be constructed is probably not supported by adequate characterization of the irradiated layer. It may be necessary to adopt a more empirical modeling retaining perhaps the functional forms suggested by the theory of mass transport through porous materials.
Rationale: Gas phase mass transport across the SiC layer through cracks or through the pore and void network in the material will be by far the fastest mechanism for mass transport of fission products across this layer	Rationale: Given the geometry and nature of the pore and crack network in the layer it is possible to calculate the gas phase mass transport across the layer. We can estimate most of the gas phase diffusion coefficients about as accurately as they can be measured. The mass transport probably cannot be calculated using Fickian diffusion and neglecting temperature gradients in the material. A multicomponent model similar in nature to the models of mass transport across membranes used widely in the chemical engineering field will have to be used. It may be necessary to recognize the effects of thermal diffusion if the temperature gradients are large and there are significant differences in the molecular weights of gases. This may well be the case especially inside the SiC layer which will be pressurized with CO from the (continued next column)	Closure Criterion: (continued from previous column) reaction of carbon materials with the urania fuel kernel. Complication in the analysis come about if the deviations from spherical symmetry of the layer are significant and if the variations in the layer thickness is significant. Characterization of the pore, void or crack network in the layer is most important and quite challenging since the voids or cracks that can be effective for mass transport are not easily detected by microscopic examination. It is furthermore quite difficult to average sets of visual observations of cracks and voids to come up with a suitable ‘average’ description for the analysis of mass transport. What would really be desirable would be permeability measurements of the layer. It is of course not practical to make such measurements.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer 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: M	Level: 2	Remedy: Modeling of fission product transport will have to include the modeling of condensed phase mass transport.
Rationale: Fission products that are not volatile will transport across the layer by diffusion. At low temperatures, grain boundary diffusion and surface diffusion will be the more rapid processes. Because the activation energy for bulk diffusion is highest, it will become, eventually the dominant mechanism of mass transport as the temperature is increased. Still, even if the fission product has only a very small vapor pressure, gas phase mass transport may outstrip condensed phase diffusion processes. There are some exceptions to this. Ag seems to be capable of fast transport across the layer and this fast transport has been ascribed to condensed phase diffusion although there are not the data necessary to conclusively demonstrate this.	Rationale: We really don't have good condensed phase diffusion coefficients for fission products during bulk, surface or grain boundary diffusion for the specific material that is of interest. Bulk diffusion coefficients from analogous materials may be adequate IF the defects in the crystal lattices produced by irradiation don't act as traps for diffusing species. Grain boundary and surface diffusion coefficients depend so much on the impurity levels at surfaces and grain boundaries where these impurities accumulate, that it would be difficult to ascribe significance to data sets for anything except the actual material of the layer including the correct crystallite orientation etc.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer Thermal deterioration/decomposition	Decline in the quality of the layer due to thermal loading

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 3	Remedy: no remedy may be needed.
Rationale: SiC is a most peculiar material. There have been reports of phase changes in the material from cubic to hexagonal at elevated temperatures. Modern phase diagrams do not reflect this phase change. It may be more important that the material is subject to polytypism based on the hexagonal structure. If the formation of the layer does not yield the thermodynamically stable product, thermal annealing during the temperature transient of an accident could cause some restructuring that will create pathways for gas phase mass transport. It might also be possible during a thermal transient for the heavily radiation damaged material to restructure to relieve the accumulation of strain energy of the irradiation defects (A sort of analogy to the formation of the rim in heavily irradiated fuel!). This restructuring could well lead to gas phase mass transport paths that will facilitate the transport of fission products released from the fuel kernel across the layer.	Rationale: To quantitatively examine this issue we would have to have considerable data on the product of the particle formation process to see if polytypism occurs and also to see if radiation restructuring can occur during an accident temperature transient. Then we would need data to see how annealing affected the permeability of the layer The situation is the same as above for lower temperatures	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	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: L	Level: 3	Remedy: AT this juncture it appears to me that holdup by chemical reaction with the SiC layer can be neglected until there is evidence that this important for more important radionuclides than Pd.
Rationale: Chemical attack on the layer by fission products will affect transport across the layer and certainly may affect the transport of the fission product doing the transporting since it will be converted to a more stable form which may be less volatile. It is however to become excessively concerned over this since the fission product inventory of the kernel is not large enough to produce massive damage to the layer that will affect the transport of all fission products. There is only one example of significant attack and that is with Pd which is not an especially important fission product from an accident consequences view point. The attack by Pd may suggest other noble metals such as Ru and Mo will produce similar attack. There would have to be substantial evidence of this to rate the process of higher significance.	RationaleWe don't have a comprehensive survey of the attack on SiC by fission products in part because SiC under reducing conditions is not an especially reactive material.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer Heavy metal diffusion	Diffusion of heavy metals through layer

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 2	Remedy: Modeling of fission product transport will have to include the modeling of condensed phase mass transport
Rationale: Fission products that are not volatile will transport across the layer by diffusion. At low temperatures, grain boundary diffusion and surface diffusion will be the more rapid processes. Because the activation energy for bulk diffusion is highest, it will become, eventually the dominant mechanism of mass transport as the temperature is increased. Still, even if the fission product has only a very small vapor pressure, gas phase mass transport may outstrip condensed phase diffusion processes. There are some exceptions to this. Ag seems to be capable of fast transport across the layer and this fast transport has been ascribed to condensed phase diffusion although there are not the data necessary to conclusively demonstrate this.	Rationale: We really don't have good condensed phase diffusion coefficients for fission products during bulk, surface or grain boundary diffusion for the specific material that is of interest. Bulk diffusion coefficients from analogous materials may be adequate IF the defects in the crystal lattices produced by irradiation don't act as traps for diffusing species. Grain boundary and surface diffusion coefficients depend so much on the impurity levels at surfaces and grain boundaries where these impurities accumulate, that it would be difficult to ascribe significance to data sets for anything except the actual material of the layer including the correct crystallite orientation etc.	Closure Criterion:

<u>Additional Discussion</u>

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer Layer oxidation	Uptake of oxygen by the layer through a chemical reaction

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 5	Remedy: No remedy needed.
Rationale: I distinguish here between the reaction of SiC with oxidant to form CO and SiO and the uptake to form nominally SiOC. This later uptake can only progress to the point of saturation. It will only be important if it causes swelling or decrepitation of the SiC layer and I can find no evidence that it does. All my experience is with higher oxygen potentials where SiO is not stable and SiO2 is the condensed product of reaction and this SiO2 does act to occlude surfaces which would interfere in gas phase mass transport at the highest temperatures. SiO, a vapor in the temperature ranges of interest could condense elsewhere in the particle and have some ramifications on the transport of fission products.	Rationale: There is a lot of information about the response of SiC to oxidizing conditions of various oxygen potentials. I don't' find information that indicates processes during uptake that would affect fission product transport (but see below when reaction is discussed)	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer Fission product release through defects	Passage of fission gas from the buffer region through defects in the SiC layer

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 1	Remedy: This mechanism probably cannot be modeled mechanistically. It will have to be treated by providing empirical evidence of the change in layer permeability as irradiation progresses.
Rationale: Defects introduced into the SiC lattice by manufacture or by irradiation will become mobile at elevated temperatures and accumulate to form dislocations that themselves will lead to the formation of porosity networks. These networks will provide a pathway for gas phase mass transport that will be the dominant mechanism for fission product transport across the layer.	Rationale: We don't have the information to assess this process now	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water intrusion	SiC Layer Fission product release through failures, e.g. craking	Passage of fission gas from the buffer region through regions in the SiC layer that fail during operations or an accident

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 4	Remedy: Mechanistic modeling of gas phase mass transport across a failed layer of SiC may not be undertaken though it can be done. A true failure of the layer may be taken somewhat but not greatly conservatively as meaning the layer no longer poses a barrier to fission product transport.
Rationale: SiC layer failure will permit the venting of accumulated fission product vapors and the ongoing releases of fission product vapors as they escape the fuel kernel and reach the SiC layer	Rationale: We don't have information that allows us to know when SiC layers fail or how massive the failures are. If we had this information it should not be difficult to model the gas phase mass transport across the layer through the failure locations.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer Thermodynamics of the SiC-fission product system	Include solubility, intermetallics, and chemical activity

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 2	Remedy: The remedy is some compatibility studies of fission products with SiC
Rationale: Fission products that dissolve in the SiC lattice will be stabilized and will be held from release at least temporarily. It does not appear, however, that this is major factor in the release of the more important, volatile fission products like I, Cs, Xe, Kr, Te etc. It may be more important for some of the transition metal fission products. Certainly Pd actually can react with SiC. Similarly Zr might react. It would also be of interest to know if other materials interacted badly with SiC, but even if we knew of some bad interactions involving materials other than fission products, we would have to have some idea of how these materials came into contact with the SiC within a fuel particle.	Rationale: There is amazingly little information about the phase relationships in the Si-C-FP systems of interest.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer Sintering	Change of graphite microstructure as a function of temperature

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 6	Remedy no remedy necessary:
Rationale: I do not find anything to suggest that changes in the microstructure of graphite will affect the SiC layer there may be some information suggesting that bonding of the graphite to the SiC affects the integrity of this layer, but it has nothing to do with microstructure issues	Rationale : there is really quite a lot of information about the sintering of SiC in the literature. It does not necessarily cover the entire region of interest nor does it address the effects of the fission product species on the sintering process. It should, however, be sufficient to estimate the magnitudes of any effects attributable to sintering on fission product transport. Far more important than simple, classic sintering will the thermal annealing of the radiation-induced defects in the SiC structure	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer: Chemical attack by water Kinetics	Rate of reaction per unit surface area as a function of temperature and partial pressure of steam

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 1	Remedy:Reaction kinetic information is required and the best information will involve dynamically prepared SiC reactions after material irradiation to produce representative defect concentrations. The data on reaction should also include data on the changes of permeability of the layer to gas phase mass transport.
Rationale: In this context water vapor is an oxidant much like air except the additional complexities of nitrogen reaction can be neglected IF one assumes pure water vapor can enter and no air can. An additional complexity that arises is the possibility that the products of reaction will include Si(OH)4 and Si(OH)2 rather than SiO. Still all these species are gases at the temperatures of real interest. The other product of reaction is hydrogen (as well as CO) and this leads to the possibility that hydrides may be formed to carry away material. Still the overall issue is whether the reaction of water vapor with SiC will facilitate fission product transport across the layer either by thinning the layer (a modest effect in light of the likely availability of oxidant) or my opening pathways for gas phase mass transport of fission products across the layer by preferential reaction with voids pores and cracks. These issues are of high importance only if the water vapor can survive transport to the SiC which is by no means established but clearly possible	Rationale: I have not been able to identify a suitable data base. I cannot find data for irradiated material of possible polytypism to address the question	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer: Chemical attack by water Catalysis	Modification of the reaction rate by fission products or impurities

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 1	Remedy see above:
Rationale: There is some evidence that impurities at the grain boundaries will accentuate the localized rate of attack on SiC. This might be of especial concern if it leads to more facile gas phase mass transport across the layer	Rationale: I can't identify suitable databases indicative of catalysis of water attack on SiC.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer: Chemical attack by water Changes in chemical form of fission products	Changes in chemical form resulting from oxidizing or reducing fission products

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 5	Remedy: Any effort to model the release and transport of fission products from coated particle fuel will have to track the fission product speciation and especially the vapor phase speciation as changes in local temperature and chemical potentials occur. To do this there will have to be a reliable thermochemical data base, again especially for the vapor species. Here mention is made of vapor phase oxides, hydroxides and hydrides.In the context of air intrusion vapor phase nitrides and cyanides are also of interest though the data bases for these are not at all well developed. Even without intrusion, vapor phase carbides and carbonyls need to be recognized and this will require development of data bases since these species have not been well explored.
Rationale: As with oxygen intrusion, the availability of water vapor can locally alter the speciation of fission products making some more volatile such as Ru, Pd, and Mo and others less volatile such as Ba, Sr, Ce, and La. Water vapor has the ancillary capability of creating vapor phase hydroxides of species such BaOH that can enhance the vapor pressure of fission products. Finally hydrogen produced by the reaction of water vapor with carbon can lead to the formation of vapor phase hydrides of fission products such as CsH and RuH that will enhance apparent fission product vapor pressures and consequently accentuate the release and transport of fission products.	Rationale We have some databases that can be used to estimate the effects of water vapor and reaction products on the vapor pressures of fission products. Best developed are the databases for elements and oxides. Bases for vapor phase hydroxides are mostly estimates obtained by considering the hydroxides to be pseudo halides somewhat intermediate in volatility between the fluorides and the chlorides of the fission product species. More spotty is the data base on hydrides of fission products The situation is largely the same at higher temperatures except that vapor phase hydrides can become more important to the overall vapor pressure	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer: Chemical attack by water	Changes in diffusivity, porosity, adsorptivity, etc.
	Changes in SiC properties	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 1	Remedy If it is concluded that there is a possibility of some water vapor reacting with the SiC layer and these reactions are to considered in the predictions of fission product transport, then there needs to be a data base on how water vapor reacting with dynamically prepared, irradiated SiC changes the permeability of the SiC:
Rationale: reaction of water vapor in the pores and networks of the SiC layer will facilitate the transport of fission products across the layer by gas phase mass transport	Rationale: I can identify no suitable data base on the reactions and the changes in the macrostructure of SiC layers with reaction	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer: Chemical attack by water	Release of SiC FP inventory
	Holdup reversal	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 1	Remedy no remedy needed:
Rationale: As discussed repeatedly above in connection with other layers, it is known that the reactions of energetic sites with adsorbed fission products will lead to the release of the fission products, but it is not clear that the layer will retain enough fission products to make this risk significant	Rationale: I can find no data on the adsorption in the layer	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	SiC Layer: Chemical attack by water Temperature distribution	Impact of SiC oxidation on temperature distribution through material

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 5	Remedy: modeling of fission product release and transport will require detailed temperatures locally.
Rationale: The chemical reactions are not iso-enthalpic so they will affect the temperature distributions in the layer and as noted elsewhere these temperatures affect both the volatilities of fission products and their transport.	Rationale We should be able to calculate the effects of reaction on the temperature distributions since we know the enthalpies of reaction. A complication arises because the reaction energies will also involve the energy release associated with the destruction of energetic radiation defects. We do need to know the kinetics of reaction well – which we do not now know.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	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: 6	Remedy: Any model of fission product transport within the fuel particle will have to include a gas phase mass transport model recognizing bulk gaseous diffusion, pressure driven flow and Knudsen diffusion
Rationale: Gas phase mass transport is the fastest mechanism to move fission products release from the fuel kernel across the barrier posed by the inner PyC layer	Rationale: Given the geometry and nature of the pore and crack network through the layer it should be possible to calculate the gas phase mass transport across the layer. We can estimate the gas phase diffusion coefficients for most of the dominant gaseous species. The diffusion process itself probably cannot be modeled as strictly Fickian diffusion. One will have develop a multicomponent diffusionmodel much like the membrane modesl that have been developed in the chemical engineering literature. It may be necessary to include in these models the effects of thermal diffusion especially since we will have low molecular weight species (CO MW=28) migrating along the same paths as the high molecular weight (>100) fission product vapor species. The importance of this will depend on the magnitude of the thermal gradients across the layer which surely must be significant given the relatively high conductivity and the need to move (Continued next column)	Closure Criterion: (Continued from previous column) the decay heat away from the fuel kernel. The most complicated part of the modeling will be a realistic portrayal of the layer geometry and the pore and crack networks. It is tempting to model the layer as a spherical shell, but this is only justified if the deviations from spherical are not sufficient to provide a short circuit pathway in some regions. Similarly, it will be tempting to treat the layer as uniform in thickness though it never will really be. We do not have meaningful data on the pore and crack network. These networks may change if there is reaction with the intruding gases. We may not be able to derive useful descriptions of the pore and crack networks through the layer from microscopic examinations of these networks. Cracks and channels to small to be readily identified in microscopic analyses can be effective in the transport of material across the layer.

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer Condensed phase diffusion)	Inter-grannular and/or intra-grannular solid-state diffusion

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 2	Remedy: Any model of fission product transport across the inner PyC layer will have to include the condensed phase mass transport process to account for mass transport of fission products when the layer does not have pore and crack networks to facilitate gas phase mass transport across the layer
Rationale: Fission products that are not volatile will be transported across the inner PyC layer by the condensed phase diffusion processes. Bulk diffusion is the slowest of these at low temperatures but it has the highest activation energy so it does eventually become the dominant process. Even if the metals have only small vapor pressures, gas phase mass transport of fission products may still be the dominant mechanism for mass transport	Rationale We do not have surface and grain boundary diffusion coefficients to model the mass transport of fission products across the layer at lower temperatures. These cannot be estimated or transferred from studies of analogous materials since they are notoriously sensitive to the precise grain structure and the nature of impurities at the grain boundaries. We don't even have a data set of bulk diffusion coefficients for the PyC layer of demonstrated reliability.	Closure Criterion:
	At sufficiently high temperatures bulk diffusion will be the dominant condensed phase mass transport process This process is very sensitive to the presence of defects produced by irradiation acting as traps for diffusing species and we don't seem to have data on this.	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer Pressure loading (Fission products)	Stress loading of the layer by fission products by increased pressure

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 2	Remedy to evaluate the pressure drop one would have to have some estimate of the permeability of the layer:
Rationale: Pressure loading will more likely be by CO pressure produced by the reaction of carbon with the fuel kernel. The loading will probably be on the SiC layer rather than the inner PyC layer though it is possible that there will be some pressure drop across the layer	Rationale: We need permeability data that seem not to exist to estimate the pressure drop across the layer. If this is significant then the layer can act at least temporarily as a barrier to fission product transport. But, if the pressure drop is significant then the layer is likely to rupture and completely lose its effectiveness as a barrier as the accident progresses and additional pressurization from both CO build up and fission product release occurs	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer Pressure loading (Carbon monoxide)	Stress loading of the layer by carbon monoxide by increased pressure

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 2	Remedy:no remedy needed
Rationale: The loading by CO should dominate that by fission products. Still it is not evident that the layer will have a substantial pressure retaining capability and the SiC layer is a more important layer for this.	Rationale: We need permeability data that seem not to exist to estimate the pressure drop across the layer. If this is significant then the layer can act at least temporarily as a barrier to fission product transport. But, if the pressure drop is significant then the layer is likely to rupture and completely lose its effectiveness as a barrier as the accident progresses and additional pressurization from both CO build up and fission product release occurs)	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer Layer oxidation	Reaction of pyrolytic graphite with oxygen released from the kernel

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 2	Remedy: Analysis of fission product transport will have to treat the effects of oxidants and ascertain if oxidants can reach the inner PyC layer. If so, the possibility of preferential and even catalyzed oxidation of the layer will have to be considered. Decent data sets on the reactions of the specific materials with oxidants are really needed.
Rationale: This high importance is assigned under the presumption that oxidant can reach the layer. The oxidant that comes is more likely to be from the fuel kernel than from the gases intruding in the accident scenario. Intruding gases will have to pass over an awful lot of reactive material before they can reach the inner PyC layer. On the other hand oxidant from the fuel will have to pass through a buffer layer of carbon to reach the inner PyC layer. If the oxidant reaches the material it can cause thinning of the layer (probably not especially important) or opening of the pathways for gas phase mass transport of fission products making the transport by gas phase processes even more rapid.	Rationale: The layer really does not take up oxidant. It reacts to form CO (and other equivalent species such as C2O and C2O3) that vaporizes. The reactions are enormously sensitive to catalysis and fission products can act as catalysts. We don't have a lot of data on which fission products will produce catalysis, We do know that Cs can catalyze the oxidation of C. We also know that irradiation makes the material more reactive. More than just rate of reaction data for the specific material, we need to know if the reaction takes place uniformly over the surface or if there is preferential reaction especially to open pathways for the gas phase transport of fission products across the layer	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer Stress state (compression/tension)	The state of the forces induced by external forces that are acting across the layer to resist movement

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 2	Remedy: Models or data to predict rupture of the layer are needed. These models may be nothing more than criteria identifying conditions for which layer integrity can no longer be assured.
Rationale: It is known that stress state can affect both condensed phase and gas phase diffusion across a layer, but this is a pretty subtle effect. More important is whether the layer stays in tact or is ruptured and allows essentially unimpeded gas phase mass transport across the layer, but this is treated in other questions	Rationale: We don't really know much about the forces and especially forces induced by the radiation caused growth of materials	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer Cracking	Lengths, widths and numbers of cracks produced in layer during accident

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 1	Remedy: Any model of the fission product transport across the inner PyC layer will have to admit to the possibility of cracks – perhaps quite narrow cracks – developing in the layer from radiation-induced growth or thermal expansion or mechanical forces on the layer including pressurization examined above.
Rationale: Any cracking of the layer will create effective pathways for gas phase mass transport across the layer	Rationale: We are not really in the position to predict cracking of the layer. Though there are data in abundance for PyC they are not for the specific material in the fuel particle and not for the material subjected to thermal transients and irradiation of the type that will be seen by the PyC layer	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer Intercalation	Trapping of species between sheets of the graphite structure

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 2	Remedy:WE need some sort of data or analyses to show whether intercalation will be an effective holdup mechanism for fission product release.
Rationale: Intercalation could act as a holdup mechanism for fission products. Intercalation usually occurs during the simultaneous condensation of vapors and graphitic material. Intercalation could occur because of the radiation displacements of materials. Intercalation is known to be an effective way to trap potassium in graphite and so it might be effective in trapping Cs in the graphite. Still, it is not evident that so much of the radionulcide inventory can be trapped in the layer that this is risk-significant issue	Rationale: I have no data on intercalation as a dynamic process either during an accident or during fuel operations	Closure Criterion:
	Intercalation will reverse at very high temperatures and not be an issue	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer: Chemical attack by water Kinetics	Rate of reaction per unit surface area as a function of temperature and partial pressure of steam

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 6	Remedy: Any model of fission product transport treating intrusion accidents will have to consider water vapor reactions with graphite and carbon. The issues include both the quantitative kinetics and the homogeneity of the attack on carbon. Uniform attack only thins the layer. Though thinning the layer certainly facilitates mass transport across the layer the effect need not be dramatic. More important will be preferential reaction in pores and cracks that opens these pathways for gas phase mass transfer across the layer.
Rationale: As with air attack the rating for this issue is conditional on the ability of oxidant to get to the layer. Reaction of water with the inner PyC layer is not as dramatic as reaction of air. Still the reaction will affect the volatilities of fission products both because of the effect on ambient oxygen potential and because of the possible formation of vapor phase hydroxides and the transport of fission products either by thinning the layer or opening pathways for gas phase mass transport. If the steam is consumed the hydrogen gas could lead to the formation of vapor phase hydrides which are also pseudo-halides and could augment the vapor pressure of the fission products via formation of vapor species like CsH and RuH.	Rationale: There is a lot of information about the rates of steam reactions with carbon though perhaps not the specific, heavily irradiated carbon of the fuel particle. Irradiation is an important issue because it will affect the rates of reaction because the defects introduced by irradiation are quite reactive.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer: Chemical attack by water Catalysis	Modification of the reaction rate by fission products or impurities

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 3	Remedy:Models of the reactions of the inner PyC layer will have to recognize the possibility of catalysis especially at lower temperatures where it is more likely that oxidant will be available to penetrate to the inner PyC layer
Rationale: steam reactions with carbon are catalyzed and catalysis leads to preferential attack and even to penetrations through the layer to facilitate gas phase mass transport of fission products across the layer.	Rationale: see discussion s of catalysis of air reactions	Closure Criterion:
	Catalysis is of less importance at high temperatures where reaction rates are high and eventually are limited by mass transport, Furthermore localized attack becomes less likely than uniform ablation of the layer material	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer: Chemical attack by water Changes in chemical form of fission products	Changes in chemical form resulting from oxidizing or reducing fission products

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 5	Remedy:The speciation of the fission products will be an essential part of any model of fission product release and transport. This is especially the case here because of the dominant role that vapor phase mass transport is expected to play in the transpor across the inner PyC layer. Significant model components will be the thermochemical data bases used to calculate speciation. It will be important to have reliable thermochemical data and estimates to compensate for the incompleteness of the experimental studies of species likely to contribute to the transport across the layer.
Rationale: Just as for air intrusion the presence of water vapor can affect the speciation of the fission products and consequently their vapor pressures. The effect is compounded by the possibility of formation of vapor phase hydroxides like BaOH and SrOH. If the steam is all reacted by the time it reaches the inner PyC layer the product hydrogen can affect fission product vaporization via the formation of vapor phase hydrides like CsH and RuH.	Rationale:There is a technical basis for estimating the oxygen potential effect on the vaporization of fission products. The database on vapor phase hydroxides consists mostly of estimated properties though some species such as CsOH, BaOH, SrOH are known well. The data base for vapor phase hydrides has not been systematically developed.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer: Chemical attack by water Changes in graphite properties	Changes in diffusivity, porosity, adsorptivity, etc.

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 3	Remedy:Preferential reactions of oxidant with the layer material to open pathways for mass transport will have to be considered in a model of fission product transport through coated particle fuels
Rationale: Again, IF water vapor can reach the inner PyC layer, its important effect aside from changing the volatilities of the fission products will be reaction to remove material from the layer. Thinning the layer is a modest effect. More important and more likely especially at lower temperatures is preferential reaction in pores and cracks to open pathways for gas phase mass transport of fission products across the layer.	Rationale: The calculation of the localized oxidation that leads to the opening of gas phase pathways across the layer is difficult to do. We don't now have the needed data on the pathways nor do we have the reaction kinetics information for the particular material of interest. If we had these data the calculation could be based on models of porous media reaction developed in other contexts in the chemical engineering literature)	Closure Criterion:
	The situation is somewhat the same at higher temperatures though the reactions become more rapid at elevated temperatures and the propensity for localized or preferential attack on the carbon becomes less dominant.	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer: Chemical attack by water	Release of graphite FP inventory
	Holdup reversal	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 4	Remedy:Not evident that a remedy is needed.
Rationale: Oxidation will destroy the energetic sites that have adsorbed fission products and thus release the fission products. It is not apparent, however, that the inventory of fission products absorbed on this layer will be so large that its release will be risk significant.	Rationale: We don't have the needed data on the fractional holdup in the layer fy the adsorption process. Nor do have the needed data on the concentrations of energetic sites available for adsorption	Closure Criterion:
	At elevated temperatures, the vapor pressures of the important volatile radionuclides are so high that adsorption fractions will be quite low. Though we don't know more about the adsorption/desorption processes at high temperatures than at low temperatures, we don't need to know as much to know that this will not be an important holdup process	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Inner PyC Layer: Chemical attack by water Temperature distribution	Impact of graphite oxidation on temperature distribution through material

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 3	Remedy: Any model of fission product release and transport will require auite a good model of the local temperature distributions in the fuel particle. Good data on the thermal conductivity, reaction kinetics and defect energies will be needed.
Rationale: The chemical reactions of water vapor with PyC are not iso-entahlpic so they will distort the temperature distributions in the particle. As noted elsewhere these temperature distributions do affect release both through the effect on the thermodynamic driving force for transport across the particle and the effects on the transport processes themselves	Rationale: We generally know the heats of reaction with pristine material. These heats need to be modified for the effects of defect destruction by reaction. Then, if we understood the kinetics and the thermal conductivity of the material we could, in principle calculate the effects of reactions on the temperature distributions	Closure Criterion:
	The situation is largely the same as at lower temperatures except radiation heat transfer becomes a more important factor to consider .	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	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: 4	Remedy a fairly sophisticated model of the layer porosity will be needed as will a very sophisticated model of mass transport across the layer:
Rationale: Gas phase mass transport across this layer will be the dominant transport mechanism for volatile fission products because the temperatures are high and because the material is quite porous.	Rationale Given the nature of the porosity in the layer it should be possible to calculate the gas phase mass transport quite well. We can estimate the diffusion coefficients for most vapor species. The analysis probably cannot treat the diffusion as Fickian. A multicomponent model will have to be considered because there will be a flow of CO across the layer that may be, in fact, pressure driven rather than diffusion. Diffusion may have to be augmented by consideration of thermal diffusion because of the large temperature gradient and the mixture of molecular weights of the gaseous species. Other complexities in the analysis include lack of spherical symmetry of the layer and the variations in the layer thickness	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer 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: L	Level: 1	Remedy:no remedy needed
Rationale: Fission products that reach the interface between the buffer carbon and the fuel kernel will have all escaped the kernel as some sort of a vapor species through the interconnected pore network in the urania. (The flux of fission products from the fuel via intragrannular diffusion is really quite small at temperatures that are well below the urania melting point) It does not seem likely that significant transport of even species with very modest vapor pressures would switch to a condensed phase process upon encountering the highly porous buffer region.	Rationale: Don’t have definitive condensed phase diffusion coefficients for the material Condensed phase mass transport rather than vapor phase mass transport is even less likely to be dominant at higher temperatures and the condensed phase diffusion coefficients are even less known at elevated temperatures	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer Response to kernel swelling	Mechanical reaction of the layer to the growth of the kernel via swelling

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 4	Remedy:Because integrity of the layer is not critical, it may not be necessary to develop a very detailed understanding of the mechanical properties of the buffer layer. It may not even be present in future incarnations of coated particle fuel pellets
Rationale: cracking and otherwise opening pathways for gas phase mass transport as a result of mechanical interactions could facilitate fission product transport across the buffer region, but the region is already quite porous so the incremental effects of cracking on gas phase mass transport are not likely to be as dramatic as cracking of the more compact structural barriers in the coated particle fuel.	Rationale We have been shown some evidence that in the current inadequate fuels that mechanical interactions can rupture the buffer layer. We have not been shown any indication that this process can be predicted in a quantitative way. There are data on the mechanical properties of materials analogous to materials in the buffer region, but these data may not be applicable to the thin layer that can bond to either the kernel or to the bounding PyC layer	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer Maximum fuel gaseous fission product uptake	Maximum loading of fission products that can deposit from the gas phase onto surfaces of materials surrounding the fuel kernel

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 3	Remedy no remedy needed:
Rationale: It is likely that some fission products will deposit in the buffer region at least temporarily and this effect has to be considered in developing the modeling of the fission product transport. But it does not appear likely that the fraction of the released fission product inventory that can deposit in this region will be sufficiently large to be of risk significance	Rationale We know deposition can take place. We don't have quantitative information on the density of active sites for deposition or adsorption/desorption isotherms for the fission products	Closure Criterion:
	Adsorption on active sites become even less important at elevated temperatures first because the vapor pressures at such elevated temperatures are so high and second because at elevated temperatures active adsorption sites are being thermally annealed. So it is not that we know more about the situation at high temperatures, it is that relatively we need to know less.	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer Layer oxidation	Reaction of pyrolytic graphite with oxygen released from the kernel

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 2	Remedy Easily one of the most important characteristics to understand for coated particle fuels is the reaction of carbon with the urania fuel. This may well be a heterogeneous reaction of gas phase oxidant with carbon. It may also involve a homogeneous direct reaction of two solid materials especially under conditions of irradiation. The reaction will be dependent on the ambient CO pressure. In fact leakage of the CO from the coated particle fuel may well dictate the extent of reaction
Rationale: The 'uptake' is really the reaction of oxygen from the fuel reacting with carbon in the buffer layer to form CO that pressurizes and possibly ruptures the compact barriers with the fuel particle such as the PyC layer and the SiC layer. Rupture of these layers will allow the venting of the vapor phase fission products within the particle and provide a facile pathway for the gas phase mass transport of fission products out of the fuel particle as the accident progresses. The reaction could also damage the crystal structure of urania at the surface of the kernel – converting it into UCO and eventually UCx. The crystallographic changes are sufficiently large that fission products within grains of the surface fuel will be expelled and ready to vaporize without mass transport limitations that affect release of fission products from grain surfaces within the fuel kernel.	Rationale Reactions of carbon with urania are thermodynamically possible at sufficiently low CO partial pressures even at low temperatures. They do appear to be slow. Irradiation of the carbon may create energetic sites that are more reactive than might be expected based on tests with unirradiated materials. Still the empirical evidence is that the reactions are slow in absence of some sort of catalyst. Always a concern is that the fission product species may act as catalysts under circumstances not so far encountered in the studies of coated particle fuels Reactions of carbon with urania definitely occur at more elevated temperatures. I am not aware of definitive rate data for the reactions	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer Thermal gradient	Change in temperature with distance

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 4	Remedy: Modeling of fission product transport in the coated particle fuels will require that there be a detailed model of the local temperatures and temperature gradients. To do this for the buffer layer will first require that the porosity of the layer be characterized and then some heat transfer modeling be done to develop expressions for the thermal conductivity of the material.
Rationale: Thermal gradients across the buffer layer – which could be substantial in magnitude – will affect the fission product release both by chemical diffusion of vapors and by thermal diffusion of vapors	Rationale: In principle we can calculate the mass transport across the layers given the temperature distributions. Calculations of the thermal distributions are made complicated by the poor knowledge of the material thermal conductivity and the effects of radiation defects and pores or cracks on the thermal conductivity. It is unlikely that simple corrections of material thermal conductivity using things like the Loeb correction will be adequate since the layer is so thin the bulk averaging inherent in the Loeb correction and similar corrections simply will underestimate the effects of porosity. Something much more sophisticated will have to be done.	Closure Criterion:
	The situation is largely the same at elevated temperatures except that radiation heat transfer within the layer becomes more of an issue. It is not simple to calculate because the ambient CO cannot be taken as transparent to the radiation.	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer Irradiation and thermal shrinkage of buffer	Dimension changes in the buffer layer or changes in its porosity produced by irradiation or by exposure to elevated temperatures

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 5	Remedy: The only real issue that must be borne in mind is whether the dimensional changes are sufficient to cause rupture and then this is of concern only if holdup of fission products in the buffer layer is actually credited in the transport process.
Rationale: The effects are small enough that they will probably be safely neglected in the modeling of fission product transport. Of course, if the changes open pathways for gas phase mass transport of fission products they facilitate this transport as discussed above.	Rationale: We know that the buffer layer material will grow as a result of radiation-induced defects in the material. Thermal expansion during accident transients will affect the material. While w e don't have data for the specific material, we do have data for analogous materials	Closure Criterion:

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer: Chemical attack by water	Rate of reaction per unit surface area as a function of temperature and partial pressure of steam
	Kinetics	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L – but see additional discussion below	Level: 6	Remedy: no remedy needed
Rationale: for conventional intrusion scenarios it is difficult to believe that oxidant will penetrate to the buffer layer without having reacted with other carbon materials along the way. Far more important will be the oxidation of the buffer layer by oxygen coming from the hot fuel kernel.	Rationale There is quite a lot of data on the kinetics of steam reactions with carbon but none specific to the material of interest here. The information does suggest that at low temperatures attack can be localized and the reactions can be catalyzed. Reaction rates will be very sensitive to impurity levels and the specifics of porosity and microstructure at low temperatures	Closure Criterion:
	Attack of steam on carbon is much more uniform at very high temperatures. Still information specific to the material of interest here seems not to be available.	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer: Chemical attack by water Catalysis	Modification of the reaction rate by fission products or impurities

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 4	Remedy:no remedy needed
Rationale: Catalysis of the reactions of water vapor may not be important if water vapor cannot reach the buffer layer prior to reacting with other carbon materials along the way.	Rationale We know the reactions can be catalyzed and that some fission products can act as catalysts including Cs.	Closure Criterion:
	Catalysis is less important at high temperature where heterogeneous reaction rates are intrinsically rapid.	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer: Chemical attack by water Changes in chemical form of fission products	Changes in chemical form resulting from oxidizing or reducing fission products

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 3	Remedy: Thermodynamic analyses essential in the modeling of fission product release and transport depend crucially on the identification of all the important vapor species. Not all the species that will contribute to the processes have been identified and characterized in the literature in a way that lets these species be included in the codes. NRC was advised by a panel of the National Academy of Science to estimate properties of species and include them in their fission product release models to assess possible importance and need for experimental investigations to prove the species exist and determine accurately their properties. This needs desperately to be done for the hydrides of fission product elements.
Rationale: Though the water vapor may not penetrate to the buffer layer the gaseous product of water vapor reactions with carbon – hydrogen- can penetrate to this layer and in fact will penetrate to this layer. The oxygen potential will not be affected, but there is the potential that hydrogen partial pressures will be high enough that the vapor pressures of some of the fission products will be augmented by the formation of vapor phase hydrides which are typically as volatile as the corresponding halides.	Rationale: There has not been a systematic examination of how vapor phase hydrides will affect the vapor pressures of the important fission products. We do know that CsH can be an important vapor phase form of cesium and species like RuH, BaH and the like can form. We don't really have agreed-upon thermodynamic data to assess the importance of these species. Furthermore, there has not been a systematic search for hydride species of all the fission products of interest.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer: Chemical attack by water	Changes in diffusivity, porosity, adsorptivity, etc.
	Changes in graphite properties	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 3	Remedy:no rememdy is needed
Rationale: Again, if the oxidant cannot reach this buffer layer, the effects of preferential oxidation of the buffer layer cannot be important (but note the caveat about alternative accident scenarios above)	Rationale Without a better characterization of both reaction kinetics and the nature of pore and crack structures of the buffer layer it would not be possible to calculate the effects of reaction on porosity even if it could occur	Closure Criterion:
	localized attack is less likely at higher temperatures	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer: Chemical attack by water	Release of graphite FP inventory
	Holdup reversal	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 4	Remedy: no remedy is needed
Rationale: It is not evident that intruding water vapor can reach the buffer layer to cause this release nor is it evident that holdup in the layer is so large that quantitative release of adsorbed fission products would be risk significant.	Rationale: We know reactions will release adsorbed fission products. We don't have the information on site density and isotherms to quantitatively calculate the holdup or the subsequent release in the event of reactions	Closure Criterion:
	Holdup becomes less important at elevated temperatures as active sites anneal and vapor pressures are so high that the adsorption is very small. So though we don't know more about the phenomenon at elevated temperatures than we do at low temperatures, we don't need to know as much for high temperature situations	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Buffer Layer: Chemical attack by water Temperature distribution	Impact of graphite oxidation on temperature distribution through material

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 3	Remedy: Any model of fission product transport in the fuel particle will require a detailed model of the temperature distributions in the layer. To do this for the buffer layer requires some characterization of the porosity and a way to treat it in the thermal conduction modeling.
Rationale: As discussed in the case of reaction of air, water vapor attack on the buffer layer is not going to affect temperature distributions significantly. But water vapor attack on other layers will affect the temperature distributions in the buffer layer	Rationale: The pertinent knowledge bases are those associated with water vapor reactions with other layers and the calculations of temperature distributions throughout the particle. Most pertinent to the temperature distributions in the buffer layer is the thermal conductivity of the material. The material thermal conductivity is not so much of a problem since this can be estimated with adequate accuracy from data for analogous materials. The problem is the effects of porosity on the thermal conductivity of the small layer. Usual corrections for the effects of porosity on the thermal conductivity are not applicable. The layer is just too thin to get the necessary averaging of orientations implicit in the usual correction factors. A more sophisticated treatment is needed. A roadmap for such a more sophisticated treatment exists in the literature. Input to the treatment is a better characterization of the porosity of the layer	Closure Criterion:
	The situation at very high temperatures is about the same as above but radiation heat transfer becomes an additional issue complicated by the fact that the ambient CO will not be transparent to the thermal radiation.	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel Maximum fuel temperature	Maximum fuel temperature attained by the fuel kernel during the accident

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 6	Remedy:
Rationale: Temperature is well known to be one of the dominant variables controlling the release of fission products form urania kernels	Rationale: In principle, it should be possible to calculate the maximum kernel temperature fairly accurately. Even so, errors on the order of 50 degrees are possible. Definitive, defensible calculations for credible accidents have not yet appeared.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel	The time-dependent variation of fuel temperature with time
	Temperature vs. time transient conditions	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 4	Remedy:
Rationale: Fission product release is a strong function of both time and temperature	Rationale: Though fairly reliable temperature histories are in principle possible to predict defensible calculations have not yet been produced. Most existing calculations are hopelessly optimistic about heat loss pathways.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel Energy Transport: Conduction within kernel	Flow of heat within a medium from a region of high temperature to a region of low temperature

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 3	Remedy:
Rationale: Conduction as well as decay heat generation determine the temperature history of the kernel during the event	Rationale: Conduction in moderately porous urania is known with some accuracy. But, the porosity of the urania kernels can become heroic during extended operations and the events of the accident could easily produce porosities and configurations of the kernels that are quite intractable for conduction calculations.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel Thermodynamic state of fission products	Chemical and physical state of fission products

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 5	Remedy:
Rationale: Fission product release depends on the chemical activity of the fission products. Completely diluted in the urania matrix, the fission product activities could be quite low. But, when the segregate into separate phases such as uranate phases or metallic nodules, chemical activities can be driven up substantially – orders of magnitude.	Rationale: We have a useful understanding of chemical activities of fission products in urania fuel at moderate burnups. At the higher burnups expected for some gas reactor fuels, our knowledge and predictive capabilities begin to fail us	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Air and Water Intrusion	Kernel Oxygen flux	Mass transport of oxygen per unit surface area per unit time

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 3	Remedy:
Rationale: Diffusion of fission products will occur simultaneously with the diffusion of oxygen from the kernels to the reactive graphite at the buffer-kernel interface. The release is far more a multicomponent process than we have encountered in the case of fission product release from conventional fuels. The gettering of oxygen by reaction with the carbon is not passivating as is the case with gettering of oxygen by reaction with zirconium in the case of conventional fuels. It is not evident, then, that the usual Fickian diffusion approximation can be made incaustiously to predict release from the kernels	Rationale: Release analysis recognizing the multicomponent nature of the transport within fuel grains have not been published. In multicomponent systems, remarkable things can be predicted that appear counter-intuitive when viewed within the context of binary diffusion.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel Grain growth	Enlargement of grains as a result of diffusion

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 8	Remedy:
Rationale: Grain growth is largely unimportant because of the grain boundary pinning effects of fission products and especially separated phases of fission products	Rationale: It has not been essential to consider grain growth in models of fission product release from conventional reactor fuels, though some codes include such models.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel Buffer carbon-kernel interaction	Chemical reaction between carbon and the fuel (UO2 or UOC) to form UC2 and CO (gas)

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 3	Remedy:
Rationale: The reaction of the buffer with the kernel can be responsible for the pressurization perhaps to failure of the SiC layer. The reaction can also lead to fission product release as the reactive refinement of the urania progresses	Rationale: Details of the reaction process and even the phase relations in these systems are not known well.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel: Chemical attack by water	Rate of reaction per unit surface area as a function of temperature and partial pressure of steam
	Kinetics	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 8	Remedy:
Rationale: The hypothesized scenario involves an atmosphere with only 1% water vapor. It is just not possible to imagine how such a low concentration of water vapor would persist in contact with the kernel despite opportunities to react with graphite.	Rationale: There is a wealth of information on the kinetics of low concentrations of steam reacting with urania. There is also good information on how this reaction of low concentration of steam will change the properties of the urania.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel: Chemical attack by water	Modification of the reaction rate by fission products or impurities
	Catalysis	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 8	Remedy:
Rationale: The hypothesized scenario involves an atmosphere with only 1% water vapor. It is just not possible to imagine how such a low concentration of water vapor would persist in contact with the kernel despite opportunities to react with graphite.	There is a wealth of information on the kinetics of low concentrations of steam reacting with urania. There is also good information on how this reaction of low concentration of steam will change the properties of the urania	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Accident With Subsequent Water Intrusion	Kernel: Chemical attack by water	Changes in chemical form resulting from oxidizing or reducing fission products
	Changes in chemical form of fission products	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 8	Remedy:
Rationale: The hypothesized scenario involves an atmosphere with only 1% water vapor. It is just not possible to imagine how such a low concentration of water vapor would persist in contact with the kernel despite opportunities to react with graphite.	There is a wealth of information on the kinetics of low concentrations of steam reacting with urania. There is also good information on how this reaction of low concentration of steam will change the properties of the urania	Closure Criterion:

Additional Discussion