APPENDIX D

PANEL MEMBER DETAILED PIRT SUBMITTALS FOR TRISO FUEL REACTIVITY ACCIDENT

The INEEL submittal is provided in Appendix D.1 (pages D-2 through D-47).

The ORNL submittal is provided in Appendix D.2 (pages D-48 through D-93).

The SNL submittal is provided in Appendix D.3 (pages D-94 through D-140).

Appendix D.1

Detailed PIRT Submittal by the INEEL Panel Member

D. A. Petti

TRISO Fuel PIRT: Rapid Reactivity Accident

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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	8	Remedy:
Rationale: Fuel element matrix may provide significant hold up of fission products. However, irradiation history per se will only modestly affect hold up potential (e.g. via production of trapping sites under irradiation).	Rationale: (≤ 1600 °C) Can be easily calculated for conditions of interest	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: Transport at high temperature in the fuel element may be a combination of bulk and surface diffusion. Some holdup of fission products can be expected in pebble matrix material. However, given the short duration of the reactivity event, surface diffusion may dominate.	Rationale: (≤ 1600 °C) Effective diffusion coefficients exist for the major fission products (Cs, Sr, Ag) in the Henrian concentration regime. The effects of irradiation and corrosion on the diffusive process are also known. For future designs with new matrix material, additional data will be needed to confirm that the German data are applicable. See IAEA TECDOC 978 Appendix A.	Closure Criterion:
	Rationale (> 1600 °C) see above	

<u>Additional Discussion</u>

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: It may be important to consider during reactivity pulse portion of the transient. It should be added to any bulk diffusion that might be expected.	Rationale: (≤ 1600 °C) A limited number of effective diffusion coefficients for noble gases and iodine have been measured. See IAEA TECDOC 978 Appendix A. Little data exist on permeability of the matrix material.	Closure Criterion:
	Rationale (> 1600 °C)	

<u>Additional Discussion</u>

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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	5	Remedy:
Rationale: Important to determine sorptive behavior of fission products in fuel element matrix	Rationale: (≤ 1600 °C) Transport has been assumed to be elemental for the major fission products (Cs, Ag, I, Xe, Sr).	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: L	8	Remedy:
Rationale: Releases are expected to be dominated by failed particles from the reactivity event. Thus, the OPyC layer is failed and thus does not holdup to fission products.	Rationale: (≤ 1600 °C)	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: L	8	Remedy:
Rationale: Releases are expected to be dominated by failed particles from the reactivity event. Thus, the OPyC layer is failed, and thus does not holdup to fission products.	Rationale: (≤ 1600 °C)	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: M	6	Remedy:
Rationale: As a consequence of the reactivity event, the kernel could swell and contact the OPyC thus causing oxidation of the layer and potentially failing the layer. Since we have already assumed failure of the coating layer in the scenario, this is only ranked medium.	Rationale: (≤ 1600 °C)	Closure Criterion:
	Rationale (> 1600 °C)	

<u>Additional Discussion</u>

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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	7	Remedy:
Rationale: Rapid expansion of the kernel expected during the reactivity event could lead to interaction between the coating layers and the kernel. Knowing the overall stress state in each layer is important to calculate the structural response of the TRISO coating. However, since OPyC layer is assumed to be failed in the accident scenario, this factor is rated medium	Rationale: (≤ 1600 °C)	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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		Remedy:
Rationale: OPyC layer is assumed to be failed and not a significant holdup mechanism for fission products.	Rationale: (≤ 1600 °C)	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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		Remedy:
Rationale: OPyC layer is assumed to be failed and not a significant holdup mechanism for fission products.	Rationale: (≤ 1600 °C)	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: L		Remedy:
Rationale: Releases will be dominated by failed particles in the event. Since the SiC layer is assumed to be failed in the event, diffusion is not important.	Rationale: (≤ 1600 °C)	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: L		Remedy:
Rationale: Releases will be dominated by failed particles in the event. Since the SiC layer is assumed to be failed in the event, diffusion is not important.	Rationale: (≤ 1600 °C)	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: L		Remedy:
Rationale: A time at temperature phenomena that is important only at very high temperatures (> 1800°C). Since time at high temperature is very short in a reactivity event this is not important.	Rationale: (≤ 1600 °C)	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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		Remedy:
Rationale: Corrosion processes are driven by time at temperature. Since reactivity event is only seconds in duration, significant corrosion is not expected.	Rationale: (≤ 1600 °C)	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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	5	Remedy:
Rationale: Given short time at elevated temperature during the reactivity event, this is not expected to be a major factor.	Rationale: (≤ 1600 °C)	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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	5	Remedy:
Rationale: As a consequence of the reactivity event, the kernel could swell and contact the SiC, thus causing oxidation of the SiC layer and potentially failing the layer. Since we have already assumed failure of the coating layer in the scenario, this is only ranked medium	Rationale: (≤ 1600 °C)	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	SiC Layer Fission product release through undetected defects, 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: L	5	Remedy:
Rationale: Release in the reactivity event would be dominated by the particles that fail during the reactivity pulse and not undetected defects in intact particles.	Rationale: (≤ 1600 °C)	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	SiC Layer	Passage of fission products from the buffer region through failed regions in the SiC layer
	Fission product release through failures, e.g., cracking	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	6	Remedy:
Rationale: Release via cracks in the layers of the failed particles are assumed in the scenario	Rationale: (≤ 1600 °C)	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

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

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	5	Remedy:
Rationale: Since the SiC layer is assumed to be failed in the event, rapid transport is expected and the chemical form in the layer is not important.	Rationale: (≤ 1600 °C)	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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	5	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 during this event.	Rationale: (≤ 1600 °C)	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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	6	Remedy:
Rationale: The scenario assumes the coating layers are failed and thus, gas phase diffusion through cracks in the layer are the dominant transport mechanism.	Rationale: (≤ 1600 °C) Models exist to estimate transport rates. Uncertainties exist on details of the crack.	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: L	7	Remedy:
Rationale: The scenario assumes the coating layers are failed and thus, transport via the cracks in the layer are the dominant transport mechanism, not condensed phase diffusion.	Rationale: (≤ 1600 °C)	Closure Criterion:
	Rationale (> 1600 °C)	

<u>Additional Discussion</u>

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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	7	Remedy:
Rationale: Pressure from fission gases will increase significantly because of the reactivity event. This is why the scenario assumed the coatings on the particle have failed.	Rationale: (≤ 1600 °C) Can be calculated	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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	7	Remedy:
Rationale: Pressure from CO will increase significantly because of the reactivity event. This is why the scenario assumed the coatings on the particle have failed.	Rationale: (≤ 1600 °C)	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: M	5	Remedy:
Rationale: As a consequence of the reactivity event, the kernel could swell and contact the PyC thus causing oxidation of the layer and potentially failing the layer. Since we have already assumed failure of the coating layer in the scenario, this is only ranked medium.	Rationale: (≤ 1600 °C)	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: M	7	Remedy:
Rationale: Rapid expansion of the kernel expected during the reactivity event could lead to interaction between the coating layers and the kernel. Knowing the overall stress state in each layer is important to calculate the structural response of the TRISO coating. However, since we assume failure in the event, this is rated medium.	Rationale: (≤ 1600 °C)	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	Inner PyC Layer Intercalation	Trapping of species between the basal planes of the structure

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	5	Remedy:
Rationale: Transport through the cracks is the dominant release mechanism. However, because the IPyC layer is assumed to be failed in the scenario and not a significant holdup mechanism for fission products, this factor is rated medium.	Rationale: (≤ 1600 °C) Although cracking is an important mechanism, the actual size and number of cracks is not well known.	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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	7	Remedy:
Rationale: Dominant mechanism for gaseous fission product transport through the layer	Rationale: (≤ 1600 °C) Rapid diffusion through the porous structure of the buffer is assumed in both U.S. and German transport models. Knudsen diffusion calculations suggest rapid transport. Uncertainty exists in microscope parameters needed in the model. Sensitivity studies can be used to evaluate influence of the uncertainty.	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: H	7	Remedy:
Rationale: This is a key mechanism for transport of metallic fission products through this layer. Rapid transport of metallic fission products through the buffer has also been historically assumed in U.S. and German models.	Rationale: (≤ 1600 °C) 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:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: H	4	Remedy:
Rationale: It is important to understand the ability of the buffer layer to accommodate the rapid swelling expected during the reactivity event. This will determine if the TRISO coating will fail.	Rationale: (≤ 1600 °C) Models suggest swelling can lead to mechanical interaction which can cause fuel failure; data suggests that under non-reactivity events that the buffer accommodates the swelling. Very little data is available to evaluate the effect under reactivity conditions.	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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	4	Remedy:
Rationale: Important because it can limit the transport rate of fission products through the layer	Rationale: (≤ 1600 °C) Little is known about this under reactivity conditions	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	Buffer Layer Layer oxidation	Reaction of buffer layer with oxide material in the kernel

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	5	Remedy:
Rationale: Low importance in the reactivity event because of the limited time available for interaction between the buffer and kernel	Rationale: (≤ 1600 °C) Absolute magnitude of reaction is determined kinetically. No known data under reactivity conditions	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: M	7	Remedy:
Rationale: During the reactivity event, the excessive power generation and the inability to conduct that extra heat out of the kernel could lead to large thermal gradients that could drive thermal diffusion. The short time at temperature suggests that this effect will not be dominant. It should be investigated analytically.	Rationale: (≤ 1600 °C) The thermal response should be able to be calculated fairly well given the reactivity pulse. Values of the heat of solution needed to model the thermal diffusion of fission products are sorely lacking. May be able to use models and sensitivity studies to bound the effect	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: L	7	Remedy:
Rationale: Shrinkage will largely occur very early in life and will be an initial condition for the reactivity event. Judged not to be very important for the reactivity event	Rationale: (≤ 1600 °C) Can be calculated.	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: Fission product transport is dominated by time at temperature. Thus, temperature is important.	Rationale: (≤ 1600 °C) Should be able to be calculated during the reactivity event fairly accurately	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: Exact time/temperature response will determine fission product release during the reactivity event.	Rationale: (≤ 1600 °C) Should be able to be calculated during the reactivity event fairly accurately	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	Kernel Energy deposition (total)	Amount of fission energy generated in kernel during reactivity event (j/gm heavy metal because of Pu)

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	7	Remedy:
Rationale: Energy deposition determines the thermal response of the particle, which is important to fission product transport, and the rate of fission product and CO generation, which is important to mechanical integrity.	Rationale: (≤ 1600 °C) Should be able to be calculated during the reactivity event fairly accurately	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	Kernel Energy deposition (rate)	Rate at which fission energy is generated in kernel

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	7	Remedy:
Rationale: Energy deposition determines the thermal response of the particle, which is important to fission product transport, and the rate of fission product and CO generation, which is important to mechanical integrity.	Rationale: (≤ 1600 °C) Should be able to be calculated during the reactivity event fairly accurately	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

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

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	7	Remedy:
Rationale: Needed to understand thermal response of the particle as input to mechanical integrity evaluation and fission product transport calculations	Rationale: (≤ 1600 °C) Conductivity is reasonably well known and sensitivity analysis can be used to bound any uncertainty.	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: (≤ 1600 °C) 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.	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	Kernel: 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	5	Remedy:
Rationale: Important to determine release of fission gases that exist on surface of grains or in grain boundaries	Rationale: (≤ 1600 °C) Current models are based on Booth diffusion to describe fission gas release from kernels. The models ignore details of microstructure and instead use effective diffusivities in the Booth model that implicitly includes all of these phenomena. However, none of these have ever been individually sorted out in the detail required for a first principles based model. Based on LWR work, the parameters needed for such detailed models 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. Unclear if other mechanisms are needed to describe releases due to the reactivity pulse	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	Kernel 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	5	Remedy:
Rationale: Mechanism responsible for transport of fission products in the kernel grains to the grain boundaries and ultimately to the connected porosity in the kernel to the buffer layer.	Rationale: (≤ 1600 °C) Booth diffusion model is used to describe fission gas and metallic fission product release from kernels. The exact mechanism is probably a mixture of bulk and surface diffusion for metallic fission products and bulk and Knudsen diffusion for fission gases. The models ignore these details and instead use effective diffusivities in the Booth model that implicitly includes all of these phenomena. However, none of these have ever been individually sorted out in the detail required for a first principles based model. Based on LWR work, the parameters needed for such detailed models 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. Unclear if other mechanisms are needed to describe releases due to the reactivity pulse	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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		Remedy:
Rationale: The short time at temperature for the reactivity event makes oxygen redistribution and hence kernel migration overall less important in the reactivity scenario.	Rationale: (≤ 1600 °C)	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: M	5	Remedy:
Rationale: Some grain growth might occur during the reactivity event because of the rapid energy deposition. Overall influence could be to enhance sweeping of fission products to the grain boundaries.	Rationale: (≤ 1600 °C)	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

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

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	6	Remedy:
Rationale: As a consequence of the reactivity event, the kernel could swell and contact the buffer thus causing oxidation of the layer. Low importance from an oxidation standpoint in the reactivity event because of the limited time available for interaction between the buffer and kernel.	Rationale: (≤ 1600 °C) Absolute magnitude of reaction is determined kinetically. No known data under reactivity conditions	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Appendix D.2

Detailed PIRT Submittal by the ORNL Panel Member

R. Morris

TRISO Fuel PIRT: Rapid Reactivity Accident

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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. 1600°C has been the accepted long term (100's of hours) accident limit for SiC coated fuels. Normal (test) operating temperatures are generally considerably lower (800° - 1200 °C)	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)) Less testing has been done on this fuel at the higher temperatures, but a reasonable amount has been done at 1800°C and ramp tests to well over 2000°C have been done.	Verification that the fuel can meet any new operating condition. Closer examination of the 1600 to 1800°C region may allow an increase of accident temperatures.

Additional Discussion

This characterization is more a TRISO performance vs. overall fuel element performance issue. 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
Rapid Reactivity Accident	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: 6	Remedy: Defer to fission product transport area.
	> 1600 °C: N/A	Remedy: N/A.
Rationale: After the event breaks a significant amount of fuel, the matrix material will be an important barrier.	Rationale: (≤ 1600 °C) A fair amount of work shows that the matrix sorbs some of the released fission products (metals), but it is not a major barrier to the release of fission products. It provides some attenuation of the metal releases.	Closure Criterion: Diffusion and trapping coefficients for the material of interest as a function of temperature.
	Rationale (> 1600 °C) Under accident conditions the fission products may become mobile again. The element matrix will hold up some fraction of the less volatile fission products.	Diffusion and trapping coefficients for the material of interest as a function of temperature

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. 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)

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.

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
Rapid Reactivity Accident	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 gas migration through the fuel element matrix after escape from the particle is rapid compared to other processes and is usually assumed to be instantaneous. This fact is used to monitor fuel behavior via R/B.	Rationale: (≤ 1600 °C) The gases are assumed to escape rapidly and quickly enter the coolant. Testing has not shown much holdup in the matrix	Closure Criterion: None
	Rationale (> 1600 °C) The gases are assumed to escape rapidly and quickly enter the coolant.	None

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.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: M	≤ 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 reactor system quite reducing, thus the chemical form of the fission product may change as it leaves the fuel.	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) Thermochemical calculations can give plausible chemical forms, but this author is not aware of any measurements confirming the chemical states.	If necessary, collect or calculate the compounds.

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. 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.

The diffusion coefficients will depend on the matrix material used for the fuel elements. The exact material has not been selected for the GT-MHR yet. 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

This PIRT concern and response is essentially identical to that in the “Heatup Accident” PIRT Table because the considerations for the fuel are the same.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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	≤ 1600 °C: 7	Remedy: Insure that proper PyC is manufactured
	> 1600 °C: N/A	Remedy: N/A
Rationale: Significant coating damage has occurred so that diffusion is less important – transport is through crack.	Rationale: (≤ 1600 °C) A great deal of testing has been conduced on PyC at the temperatures of interest. Cracks would negate the value of this barrier.	Closure Criterion: Test fuel performs as expected
	Rationale (> 1600 °C) A great deal of testing has been conduced on PyC at the temperatures of interest. Cracks would negate the value of this barrier.	Test fuel performs as expected

Additional Discussion

Extensive testing has been done of the PyC for BISO and TRISO fuels 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
Rapid Reactivity Accident	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: L	≤ 1600 °C: 7	Remedy: None
	> 1600 °C: N/A	Remedy: N/A
Rationale Significant coating damage has occurred so that diffusion is less important.	Rationale: (≤ 1600 °C) The OpyC offers little holdup to metallics. Cracks would negate the value of this barrier.	Closure Criterion: None
	Rationale (> 1600 °C) The OpyC offers little holdup to metallics at accident temperatures. Cracks would negate the value of this barrier.	None

Additional Discussion

Extensive testing has been done of the PyC for BISO and TRISO fuels 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
Rapid Reactivity Accident	Outer PyC Layer	Uptake of oxygen by the layer through a chemical reaction
	Layer oxidation	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	≤ 1600 °C: 6	Remedy: None for helium heatup
	> 1600 °C: N/A	Remedy: N/A
Rationale: This issue is not important for the heatup under helium. It is more important for the water and air ingress cases.	Rationale: (≤ 1600 °C) Little oxygen is available under these conditions.	Closure Criterion: None
	Rationale (> 1600 °C) Little oxygen is available under these conditions.	None

Additional Discussion

This accident scenario does not expose the fuel to an oxygen source.

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

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	≤ 1600 °C: 6	Remedy: Review and collect new data for the codes if necessary. Define the energy and rate.
	> 1600 °C: N/A	Remedy: N/A
Rationale: Significant coating damage has occurred so that diffusion is less important.	Rationale: (≤ 1600 °C) The fuel design codes include these calculations. (Assumes the PyC is irradiation stable) Cracks would negate the value of this layer.	Closure Criterion: Adequate test fuel performance.
	Rationale (> 1600 °C) The fuel design codes includes these calculations. (Assumes the PyC is irradiation stable) Cracks would negate the value of this layer.	Adequate test fuel performance.

<u>Additional Discussion</u>

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
Rapid Reactivity Accident	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: 1	Remedy: Determine if relevant
	> 1600 °C: N/A	Remedy: N/A
Rationale: Significant coating damage has occurred so that diffusion issues are less important.	Rationale: (≤ 1600 °C) At present, this level of detail has not been explored. It is an area of study. Plus, cracks would negate the value of this barrier.	Closure Criterion: None
	Rationale (> 1600 °C) At present, this level of detail has not been explored. It is an area of study.	None

Additional Discussion

If the fuel is broken, this effect is not important.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: 2	Remedy: None
	> 1600 °C: N/A	Remedy: N/A
Rationale: Significant coating damage has occurred so that diffusion issues are less important.	Rationale: (≤ 1600 °C) Some work in this area has been done. Cracks would negate the value of this barrier.	Closure Criterion: None
	Rationale (> 1600 °C) Some work in this area has been done. Cracks would negate the value of this barrier.	None

Additional Discussion

If the fuel is broken, this effect is not important.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: L	≤ 1600 °C: 7	Remedy: None unless the fuel operation envelope is different. In that case, additional testing may be necessary.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The pulse is assumed to have broken a significant number of particles, so diffusion is no longer important	Rationale: (≤ 1600 °C) Extensive testing by the Germans on their fuel has generated a database. Cracks negate any value of this barrier.	Closure Criterion: Adequate test fuel performance, particularly at higher burnups.
	Rationale (> 1600 °C) Less, but similar testing has been done at the higher temperature. Cracks negate any value of this barrier.	Adequate test fuel performance.

Additional Discussion

Most of the high quality fuel testing results have come from the German program. For a summary 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
Rapid Reactivity Accident	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: L	≤ 1600 °C: 7	Remedy: None unless the fuel operation envelope is different. In that case, additional testing may be necessary.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The pulse is assumed to have broken a significant number of particles, so diffusion is no longer important	Rationale: (≤ 1600 °C) Extensive testing by the Germans on their fuel has generated a database. Note that GT-MHR fuel will operate at higher burnup and temperatures. Cracks negate any value of this barrier.	Closure Criterion: Adequate test fuel performance, particularly at higher burnups.
	Rationale (> 1600 °C) Less, but similar testing has been done at the higher temperature. Cracks negate any value of this barrier.	Adequate test fuel performance.

Additional Discussion

The German fuel design performance is summarized in:

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)

The primary challenge is to duplicate the SiC that performed so well. Materials characterization is the difficult part of this fuel. See the other PIRT Tables for more details.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: L	≤ 1600 °C: 7	Remedy: If 1600°C and the irradiation envelope are adequate then okay; otherwise testing may be necessary.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The pulse is assumed to have broken a significant number of particles, so decomposition is less important. However, high temperatures could increase the failure rate	Rationale: (≤ 1600 °C) Extensive testing at 1600°C has shown it to be a "safe" limit. Cracks negate any value of this barrier, however.	Closure Criterion: Satisfactory fuel performance.
	Rationale (> 1600 °C) Significant, but much less testing has been done above 1600°C. Cracks negate any value of this barrier, however.	Satisfactory fuel performance, particularly at higher burnups.

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. Greater resolution in the data between 1600 and 1800°C would be necessary to raise the acceptable limit. See the other PIRT Tables for more details. Large amounts of damaged fuel represent a significant source of releases even without the decomposition.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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	≤ 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: The pulse is assumed to have broken a significant number of particles, so corrosion is no longer important, but it may preconditions the SiC for cracking.	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, including consideration of fuel type and fission product concentration histories.
	Rationale (> 1600 °C) Above 1600 °C, decomposition becomes more important.	None, thermal effects become important

Additional Discussion

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

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

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

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

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

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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	≤ 1600 °C: 5	Remedy: Examine the particle behavior at the pulses and energies of interest.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The pulse is assumed to have broken a significant number of particles, so diffusion is no longer important, but some U could be expelled during the event.	Rationale: (≤ 1600 °C) To this author's knowledge, heavy metal diffusion through the SiC is not a problem, but some U could be expelled by the event through cracks.	Closure Criterion: Acceptable performance
	Rationale (> 1600 °C) To this author's knowledge, heavy metal diffusion through the SiC is not a problem at the accident temperatures of interest, but some U could be expelled by the event through cracks.	Acceptable performance

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

Actual destruction of the particle by a large pulse could eject material from the particle. The pulse energy and duration needs to be defined to determine the relevance of this issue.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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	≤ 1600 °C: 5	Remedy: None, as long as the integrity of the IPyC layer is good.
	> 1600 °C: N/A	Remedy: N/A
Rationale: Not important for this short event, but it could precondition the SiC if a problem existed under normal conditions.	Rationale: (≤ 1600 °C) A reasonable amount is known about CO corrosion and controlling the properties of the IPyC layer to prevent failure will limit the expose.	Closure Criterion: Demonstrated good fuel performance.
	Rationale (> 1600 °C) Same	Demonstrated good fuel performance.

Additional Discussion

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:

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
Rapid Reactivity Accident	SiC Layer Fission product release through undetected defects, 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: L	≤ 1600 °C: 7	Remedy: Defer to fuel fabrication
	> 1600 °C: N/A	Remedy: N/A
Rationale: Defective SiC is very small compared to the event damage.	Rationale: (≤ 1600 °C) This is a manufacturing issue that shows up during accident conditions. This event should damage far more fuel.	Closure Criterion: None
	Rationale (> 1600 °C) Same, thermal decomposition effects begin to dominate. This event should damage far more fuel.	None

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.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	SiC Layer Fission product release through failures, e.g. cracking	Passage of fission gas from the buffer region through failed regions in the SiC layer

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 5	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 in tact, the gas will not be released, if not, the gas will be released. Metallics will be released in both cases. See previous entry.	Rationale: (≤ 1600 °C) Accident models have been compared to experiments to approximately model the situation. If material properties are consistent, useful predictions can be made. However, this accident stresses the particle to a greater extent.	Closure Criterion: Acceptable performance
	Rationale (> 1600 °C) Above this temperature the decomposition is important. However, this accident stresses the particle to a greater extent.	Acceptable performance

<u>Additional Discussion</u>

Most SiC failure models are based on pressure vessel failure. More recent models are considering cracking. 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

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)

If large amounts of damaged SiC are present, then this mechanism may dominate.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	SiC Layer	Chemical form of fission products including the effect of solubility, intermetallics, and chemical activity
	Thermodynamics of the SiC-fission product system	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	≤ 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, thus preconditioning it for failure from the pulse. This corrosion process is a function of temperature. See the entry on corrosion.	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) Above 1600 °C, decomposition becomes more important.	None, thermal effects become important

Additional Discussion

See entries on corrosion. 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.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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.
	> 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) SiC begins to decompose above this temperature.	Acceptable performance at the slightly higher temperature.

Additional Discussion

The major challenge is to reproduce the SiC that performed so well in past testing. The pulse is short and is not likely to matter.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: 7	Remedy: None at present
	> 1600 °C: N/A	Remedy: N/A
Rationale: Significant amounts of fuel are broken, so diffusion is of less importance – transport is through crack.	Rationale: (≤ 1600 °C) Extensive testing has been done on BISO and TRISO fuels. Gas diffusion through this layer is low. The principal concern is irradiation stability. Cracks would negate the value of this layer.	Closure Criterion: Acceptable test fuel behavior
	Rationale (> 1600 °C) Significant, but less testing has been done above this temperature. Cracks would negate the value of this layer.	Acceptable test fuel behavior

Additional Discussion

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

However**,** for large amounts of damaged fuel, diffusion through layers may not be very important.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: L	≤ 1600 °C: 7	Remedy: None, nothing can be done
	> 1600 °C: N/A	Remedy: N/A
Rationale: The particle is assumed broken, so diffusion is less important.	Rationale: (≤ 1600 °C) Testing has shown that the PyCs generally have limited retention of metallic fission products at accident temperatures. Cracks would negate the value of this layer.	Closure Criterion: None
	Rationale (> 1600 °C) Same	None

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

However**,** for large amounts of damaged fuel, diffusion through layers may not be very important.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: 4	Remedy: Proper design and fabrication. Determine the impact of the pulse loading.
	> 1600 °C: N/A	Remedy: N/A
Rationale: High pressures during the event will challenge the coating.	Rationale: (≤ 1600 °C) Pressure can be controlled by particle design, burnup, and kernel composition. However, the pulse will probably results in much higher pressures and perhaps impulse loads.	Closure Criterion: Acceptable fuel performance
	Rationale (> 1600 °C) Same.	Acceptable fuel performance

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.

The graph at the right (from Yuri Degalsev, RF code GOLT) shows how the stress in the SiC varies as the PyC fails.

A major concern is the proper material properties – see the Manufacturing Design PIRT
The accident could generate high particle pressures.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: 4	Remedy: Control pressure by design. Investigate the effects of the pulse on stresses.
	> 1600 °C: N/A	Remedy: N/A
Rationale: High CO product will result in high particle pressures, especially at the higher accident temperatures. The accident may result in an impulse load. Changing the kernel composition can control CO production. (see previous entry)	Rationale: (≤ 1600 °C) Initial pressure can be controlled by particle design, burnup, and kernel composition. Analysis may be help to determine accident conditions.	Closure Criterion: Proof testing of final fuel design
	Rationale (> 1600 °C) Same	Proof testing of final fuel design

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 PIRT Design Tables for fuel design issues

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: L	≤ 1600 °C: 7	Remedy: None
	> 1600 °C: N/A	Remedy: N/A
Rationale: For the accident of interest, a helium heatup, the environment is inert and reducing, rather than oxidizing. The buffer layer reacts with the oxygen released from the fuel.	Rationale: (≤ 1600 °C) Extensive testing of the fuel at 1600 °C in an inert atmosphere has shown no unusual oxygen behavior that might destroy this layer.	Closure Criterion: None
	Rationale (> 1600 °C Same	None

Additional Discussion

This is an issue for the air/water ingress if outer protective layers fail..

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

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	≤ 1600 °C: 4	Remedy: Control pressure by design; investigate accident response.
	> 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. All the layers will be challenged by this event.	Rationale: (≤ 1600 °C) Initial pressure can be controlled by particle design, burnup, and kernel composition. Analysis can help determine the accident stresses and layer behavior.	Closure Criterion: Proof testing of final fuel design
	Rationale (> 1600 °C) Same	Proof testing of final fuel design

Additional Discussion

See the table entries about pressure loading and also the PIRT Design Tables. This accident could have high particle pressures.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	Inner PyC Layer Intercalation	Trapping of species between the basal planes of the structure.

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	≤ 1600 °C: 1	Remedy: None
	> 1600 °C: N/A	Remedy: N/A
Rationale: Broken particles will make this detail unimportant.	Rationale: (≤ 1600 °C) This situation has not caused problems	Closure Criterion: None
	Rationale (> 1600 °C) This situation has not caused problems	None

Additional Discussion

The inventory of a particle far exceeds what could be trapped in the IPyC.

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

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 6	Remedy: Determine its function during the event.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The buffer layer is design to be a void to collect the gases released from the kernel. The problem would be if it weren't porous. It may be required to control the molten kernel.	Rationale: (≤ 1600 °C) The buffer layer appears to work as planned. Gases are expected to diffusive through this layer.	Closure Criterion: Acceptable performance.
	Rationale (> 1600 °C) The buffer layer appears to work as planned. Gases are expected to diffusive through this layer.	Acceptable performance.

Additional Discussion

See the design PIRT for the Buffer layer design. Because of the impulse like nature of this event, the buffer layer may be required to absorb some shock or otherwise dissipate some energy. It may also be required to control any expulsion of U.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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) The buffer layer appears to work as planned. Fission products are expected to diffusive through this layer.	None

Additional Discussion

With large amounts of damaged fuel, some absorption of fission products by the buffer could be of some significance. It may be required to control the molten kernel.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: H	≤ 1600 °C: 3	Remedy: Determine if the swelling or melting during the accident will damage the buffer.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The buffer layer is 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. Its ability to hold melted fuel is not known.	Closure Criterion: Acceptable performance.
	Rationale (> 1600 °C) All evidence to date indicates that the buffer layer performs as expected. . Its ability to hold melted fuel is not known.	Acceptable performance

Additional Discussion

The buffer layer may be required to keep the kernel melt from leaving the fuel and perhaps absorb some of the energy of the kernel expansion.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: 5	Remedy: Determine if the event places new loads or requirements on the buffer.
	> 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. However, the buffer may not be able to instantaneously handle the gases released by the kernel during the event.	Rationale: (≤ 1600 °C) All evidence to date indicates that the buffer layer performs as expected, but this accident is another challenge.	Closure Criterion: Acceptable performance
	Rationale (> 1600 °C) All evidence to date indicates that the buffer layer performs as expected, but this accident is another challenge.	Acceptable performance

Additional Discussion

This is really a design issue. See the PIRT Design Table. An issue is how the buffer would reaction to a sudden pulse of gas.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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.	Rationale: (≤ 1600 °C) No problem has been observed. The basic problem is CO production that has been outlined elsewhere.	Closure Criterion: None
	Rationale (> 1600 °C) No problem has been observed. The basic problem is CO production that has been outlined elsewhere.	None

Additional Discussion

See the discussions on the use of UCO to control CO pressure. The accident happens too quickly for other concerns.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	Buffer Layer	Change in temperature with distance
	Thermal gradient	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 2	Remedy: Determine the relevance and data need.
	> 1600 °C: N/A	Remedy: N/A
Rationale: During accident conditions, the particle gradient may be very high	Rationale: (≤ 1600 °C) There is little information about the effects of this type of accident.	Closure Criterion: Acceptable fuel performance and design.
	Rationale (> 1600 °C) There is little information about the effects of this type of accident.	Acceptable fuel performance and design.

<u>Additional Discussion</u>

The effect of high temperature pulses on the coatings have not been examined in much detail. A high thermal gradient could increase fission product migration.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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	≤ 1600 °C: 5	Remedy: Determine if the cracks matter.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The accident is too fast for this to matter. Cracks could offer a path for U and fission product expulsion.	Rationale: (≤ 1600 °C) Modest buffer shrinkage and small cracks don't seem to result in problems, however, if the kernel is molten, cracks could be a path for U expulsion.	Closure Criterion: Acceptable performance.
	Rationale (> 1600 °C) Modest buffer shrinkage and small cracks don't seem to result in problems	Acceptable performance.

Additional Discussion

Since the buffer will be the only intact layer left, its integrity may be more important than usual

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: 6	Remedy: Determine if melting is an issue.
	> 1600 °C: N/A	Remedy: N/A.
Rationale: The temperature determines the severity of the event.	Rationale: (≤ 1600 °C) Temperatures can be computed to a reasonable degree by modern codes. Uncertainties come from material properties.	Closure Criterion: Acceptable fuel performance.
	Rationale (> 1600 °C Temperatures can be computed to a reasonable degree by modern codes. Uncertainties come from material properties.	Acceptable fuel performance.

Additional Discussion

Fuel pressure and kernel melting is of concern.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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	≤ 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 and is a function of the pulse.	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) Same	Calculations within the needed uncertainties.

Additional Discussion

This is really a core design issue. Controlling the pulse will be important.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	Kernel Energy deposition (total)	Amount of fission energy generated in kernel during reactivity event (j/gm heavy metal because of Pu)

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	≤ 1600 °C: 4	Remedy: Determine if this accident is important and collect the necessary data.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The energy generated in the kernel and fuel element determines the pressure and temperature in the particle, and are of concern if the reactivity pulse is very large and rapid.	Rationale: (≤ 1600 °C) Some reactivity insertion testing has been done in Japan and Russia.	Closure Criterion: Data necessary to characterize the accident.
	Rationale (> 1600 °C) Little has been done at the extremes.	Data necessary to characterize the accident.

<u>Additional Discussion</u>

The reactivity testing done in Japan and Russia, indicate fuel failure (coatings break) in the range of 1000-2000 J/g. For details see:
Fuel Performance and Fission Product Behavior in Gas Cooled Reactors, IAEA-TECDOC-978 (1997)

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	Kernel Energy deposition (rate)	Rate at which fission energy is generated in kernel

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	≤ 1600 °C: 8	Remedy: None
	> 1600 °C: N/A	Remedy: N/A
Rationale: The temperature of the particle is determined by the heat generation in the fuel element(s) and temperature of the environment (see previous entry).	Rationale: (≤ 1600 °C) Modern codes can compute the neutronics fairly well.	Closure Criterion: None
	Rationale (> 1600 °C) Modern codes can compute the neutronics fairly well.	None

Additional Discussion

The reactivity testing done in Japan and Russia, indicate fuel failure (coatings break) in the range of 1000-2000 J/g. For details see: *Fuel Performance and Fission Product Behavior in Gas Cooled Reactors*, IAEA-TECDOC-978 (1997)

The main issue is for the designers to outline this accident and the expected pulse length and energy.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: H	≤ 1600 °C: 5	Remedy: Determine the data needed as a function of burnup.
	> 1600 °C: N/A	Remedy: N/A
Rationale: The dynamics of the accident will be affected by how the kernel acts during the event.	Rationale: (≤ 1600 °C) Data is available for normal operating conditions. Some of this may be useful for the pulse conditions.	Closure Criterion: None
	Rationale (> 1600 °C) Data is available for normal operating conditions. Some of this may be useful for the pulse conditions.	None

Additional Discussion

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

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: 6	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. Its is desirable to oxidize some fission products without producing CO.	Rationale: (≤ 1600 °C) A considerable amount of work has been done with kernel composition to limit the migration of fission products and control CO pressure. However, only UO_2 has been extensively tested in a high quality fuel.	Closure Criterion: Demonstrated performance under the conditions of interest.
	Rationale (> 1600 °C) Same	Demonstrated performance under the conditions of interest.

<u>Additional Discussion</u>

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 melting point of the fuel as a function of burnup may be required to model this event. The thermochemcial state of the kernel could change if the temperature is high enough.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	Kernel 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: 5	Remedy: Determine the need to improve this data based on accident consequences.
	> 1600 °C: N/A	Remedy: N/A
Rationale: Since the major fission product barriers have been broken, retention in the kernel is now important.	Rationale: (≤ 1600 °C) Data on fission product diffusivities has been collected.	Closure Criterion: Ability to meet accident consequence goals.
	Rationale (> 1600 °C) Some data is available, but the release may be so high as not to matter.	Ability to meet accident consequence goals.

Additional Discussion

For a study comparing the relative contributions of core materials and fission product kernel 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.

The primary goal is to tie up the fission products as much as possible in the kernel without producing CO. 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.

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

If significant amounts of fuel have been broken, then diffusion may not matter much.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	Kernel 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: 6	Remedy: Determine the need to improve this data based on accident consequences.
	> 1600 °C: N/A	Remedy: N/A
Rationale: Since the major fission product barriers have been broken, retention in the kernel is now important.	Rationale: (≤ 1600 °C) Data on fission product diffusivities has been collected.	Closure Criterion: Ability to meet accident consequence goals.
	Rationale (> 1600 °C) Some data is available, but the release may be so high as not to matter.	Ability to meet accident consequence goals.

Additional Discussion

For a study comparing the relative contributions of core materials and fission product kernel 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.

The primary goal is to tie up the fission products as much as possible in the kernel without producing CO. 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.

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

If significant amounts of fuel have been broken, then diffusion may not matter much.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Rapid Reactivity Accident	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: This is too slow to matter during the event (?).	Rationale: (≤ 1600 °C) Some work has been done in this area. The full implications are not clear.	Closure Criterion Determine if this area is of any significance.
	Rationale (> 1600 °C) Little has been done. The rate is assumed to increase.	Determine if this area is of any significance.

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
Rapid Reactivity Accident	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: 5	Remedy: Determine if relevant for this type of event.
	> 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.	Rationale: (≤ 1600 °C) The grain growth issue has been studied to some extent in LWR fuel.	Closure Criterion: Acceptable kernel performance or modeling data.
	Rationale (> 1600 °C) The grain growth issue has been studied to some extent in LWR fuel.	Acceptable kernel performance or modeling data.

Additional Discussion

If the kernel breaks or melts, grain growth may not be very important. Also the accident takes place on a short time scale

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

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	≤ 1600 °C: 5	Remedy: Determine if new behavior might be expected in this accident.
	> 1600 °C: N/A	Remedy: N/A
Rationale: No significant problems in this area have been observed. Too slow to matter for this accident.	Rationale: (≤ 1600 °C) Reactions of this nature can be investigated using thermochemical codes. Nothing has come up to date.	Closure Criterion: Necessary data
	Rationale (> 1600 °C) Reactions of this nature can be investigated using thermochemical codes. Nothing has come up to date.	Necessary data

Additional Discussion

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.

Appendix D.3

Detailed PIRT Submittal by the SNL Panel Member

D. A. Powers

TRISO Fuel PIRT: Rapid Reactivity Accident

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
Reactivity Accident	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: 1	Remedy:A fuel that can be used in a reactor needs to be developed. The changes in the kernel microstructure with increasing burnup need to be measured. Experiments need to be done to see how fuel of various microstructures and burnups responds to sudden reactivity insertions.
Rationale: The temperature and burnup of the fuel will determine the amount of gas at the kernel boundaries that will be heated and will expand to cause fuel particle disruption in a reactivity accident.	Rationale: ()We don't know what the fuel will actually be. We don't know how the fuel microstructure changes as we go to high burnup. And, we don't know how fuel kernels that have experienced reasonable amounts of burnup will respond to the sudden insertion of reactivity.	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	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: L	Level: 2	Remedy: no remedy needed
Rationale: The issues here are the same as above for intragrannular diffusion. During the accident it does not matter in the least. During operations prior to the accident it has some importance in the accumulation of gas at positions in the fuel so that during a reactivity event the gas will expand and disrupt the fuel.	Rationale: Surface diffusion depends too much on the specifics of the fuel which have not been defined for this coated particle fuel to claim that knowledge is anything but quite low	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	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	Level: 2	Remedy: Get a satisfactory fuel and irradiate it to reasonable burnups. Identify the inventories of fission gases in the voids, pores and grain boundaries as functions of burnup and operating temperature.
Rationale: Again, it is difficult to interpret the question because the question does not appear to have been derived from an understanding of the physics of a reactivity insertion accident. It is the pressurization of fission gases including pressurization from the moderately volatile fission products such as Cs, I, Te, and Ag in voids and pores that drive fuel disruption in the event of a reactivity accident. Fission gases in the intragrannular microbubbles do not respond to the reactivity event in a dramatic fashion. Fission gases in voids, pores, grain boundaries do. Consequently, an understanding of the inventories of fission gases in these important locations is needed to predict fuel behavior. Presumably the ability for the gases to pass from these locations into other regions of the coated particle fuel affects the inventory in fuel kernel and is therefore important to the understanding of fuel behavior in reactivity accidents	Rationale: We know what to look for when we have an accpetable fuel taken to reasonable burnups. But, to date we do not have satisfactory fuel and we don’t have a data base on the fission product accumulations in such a fuel as burnu progresses.	Closure Criterion:

<u>Additional Discussion</u>

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	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: M	Level: 8	Remedy :no remedy necessary
Rationale: There is a fairly good understanding of the speciation of fission products in uranium oxide fuel. The speciation is not of overwhelming importance. The stoichiometry of the fuel has a real bearing on the diffusion coefficients of fission products in fuel. Diffusion is, however, too slow a process to have major impact on the course of a reactivity accident that involves the active participation of fission products that have already diffused during normal operations from within the fuel grains to the intergrannular regions and from there to voids and pores within the fuel.	Rationale: () Data on speciation of fission products accumulated for LWR fuel can be used, mutatis mutandi, to estimate the speciation in coated particle fuel. Of course, this is probably not possible to do with great confidence for UCO fuel.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	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: L	Level: 3	Remedy: no remedy necessary for reactivity accidents, but see below for longer duration accidents
Rationale: As noted above, repeatedly, diffusion processes will not be fast enough to significantly affect the short duration of reactivity accidents. Diffusion processes during normal operations may affect the inventories of gases available to actively participate in the pressurization of the fuel particles during such accidents. This issue of inventories is assumed to have been dealt with adequately in the section entitled 'operations'.	Rationale:) We have relatively little information about the diffusion of fission products through PyC that has been extensively irradiated. Gas phase diffusion can be estimated if we have reliable estimates of the gas speciation and data on the pore and microstructure of the PyC layer. Permeation by pressure driven flow can be estimated if we had data on the permeability of the layer. WE do not have such data on the permeability and it is unlikely that we can make reliable estimates of the permeability. We would expect, however, that permeation of the outer PyC layer would be small since the pressure differential of this layer, which is outside the SiC pressure boundary, would be small.	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	Outer PyC Layer Condensed-phase diffusion	Inter-grannular diffusion and/or intragrannular solid-state diffusion

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 2	Remedy: : no remedy necessary for reactivity accidents, but see below for longer duration accidents
Rationale: As noted above over and over again, diffusion processes are not likely to affect reactivity insertion accidents and diffusion of metallic fission products is especially unlikely to affect these accidents.	Rationale:)Diffusion of some metallic fission products across carbon layers such as the diffusion of Ag and the reactions of Pd are among the great mysteries of fission product release from coated particle fuel. There is not a useful data base for the diffusion process across these layeres though there is some research underway notably at MIT	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	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: L	Level: 3	Remedy:no remedy necessary
Rationale: During normal operations little oxygen will actually reach the Outer PyC layer from the fuel kernel. Oxygen released from the irradiated fuel will react with carbon closer to the kernel. The reactivity insertion accident scenario does not include air intrusion so there is not an additional source of oxygen,	Rationale:) The reaction of oxygen with carbon is complicated and has received substantial attention from the research community. It is not likely that the results obtained in this research will be applicable quantitatively to the unique materials being considered for the outer PyC layers of coated particle fuels.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	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: Any effort to model the effects of reactivity insertions on the coated particle fuels will have to take into account these forces that will probably ameliorate the forces induced by the internal pressurization of the fuel particles
Rationale: Rupture of the fuel particles in a reactivity insertion event is driven by the pressurization of the fuel particle. Forces that counteract this pressurization tend to limit the effects on the accident on the integrity of the fuel. It is evident that the current processes for making fuel result in a fuel matrix that can exert either compressive forces that will tend to preserve fuel integrity or tensile forces that will act with pressurization to cause fuel disruption.	Rationale: (≤ 1600 °C) There does not seem to be a reliable method for estimating even the signs let alone the magnitudes of the forces on the fuel particles exerted by the matrix. It is evident that these forces depend critically on the method of manufacture and this method is still evolving.	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	Outer PyC Layer Intercalation	Tapping 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: 3	Remedy: no remedy necessary for reactivity accidents, but see below for longer duration accidents:
Rationale: Intercalation is known to occur for element like potassium and therefore one assumes that it can occur for cesium. This may be a mechanism for the accumulation of fission products in the Outer PyC layer during normal operations that can be release during a reactivity event. It would be hoped that this accumulation will be small. The duration of a reactivity transient should be short enough that there will be little time for intercalation to affect the important release that will come from ruptured particles. Release from particles that remain intact could be further mitigated presumably by intercalation, but these releases will already be small.	Rationale:) We really don't know quantitatively how much intercalation will occur how fast for the vast majority of fission products. On the other hand it probably is not necessary to have exceptionally detailed information on this process for reactivity accidents.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	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: 3	Remedy: no remedy necessary for reactivity accidents, but see below for longer duration accidents:
Rationale: As noted above, it is known that absorption and desorption of fission products can occur on carbon such as the outer PyC layer. It is unlikely, however, that these process will operate on time scales fast enough to be issues during reactivity accidents.	Rationale:) There is some data in the literature on adsorption and desorption of species from carbon materials. It is not likely that these data can be applied directly to the outer PyC layer	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	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: L	Level: 2	Remedy: : There is a very poor understanding of fission product transport across SiC layers my any of the mechanisms.
Rationale: As noted above, the diffusion of fission products through the SiC layer during normal operations may affect the inventory of fission products that can actively participate in the pressurization of the fuel during a reactivity accident. These processes are too slow to affect the nature of the reactivity accident. The release is such reactivity accidents will depend entirely on what fraction of the particles grossly rupture.	Rationale: (As noted above, the diffusion of fission products through the SiC layer during normal operations may affect the inventory of fission products that can actively participate in the pressurization of the fuel during a reactivity accident. These processes are too slow to affect the nature of the accident	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	SiC Layer Condensed phase diffusion	Inter-grannular diffusion and/or intra-grannular solid-sate diffusion

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 2	Remedy: no remedy necessary
Rationale: As noted above, the diffusion of fission products through the SiC layer during normal operations may affect the inventory of fission products that can actively participate in the pressurization of the fuel during a reactivity accident. These processes are too slow to affect the nature of the accident	Rationale: There is a very poor understanding of fission product transport across SiC layers my any of the mechanisms.	Closure Criterion:

Additional Discussion

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

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 4	Remedy: The degradation of SiC material properties will have to be considered in modeling reactivity transients
Rationale: Any degradation of the ability of SiC to sustain the pressurization loads caused by reactivity insertion events is significant. Loss of fuel integrity as a result of the event will lead to the sudden release of some fraction of the vapor phase fission products. But these factors have been considered elsewhere. Here the issue is one of thermal loading on the layer itself. I doubt there will be sufficient time for heat generated in the kernel to penetrate to the SiC layer before the accident has been terminated.	Rationale: (There is certainly information in the literature about the temperature dependence of mechanical properties of SiC. These data are for polycrystalline materials that will not likely have microstructures at all similar to the microstructure of the SiC layer in coated particle fuels. The applicability of the literature data is, then questionable, but the literature data are certainly available for rough estimates of the ability of coated particle fuels to survive reactivity transients	Closure Criterion:

Additional Discussion

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

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 6	Remedy: degradation of the SiC layer as a result of processes during normal operations will have to be taken into account in estimating the likelihood that fuel will survive intact a reactivity insertion event
Rationale: Reaction of Pd with SiC has, apparently, been observed. It is unlikely that this attack is so rapid that its kinetics during a reactivity transient need to be considered. But the reactions of Pd with SiC during the normal operation prior to the reactivity insertion certainly need to be considered since these reactions may well degrade the ability of the SiC layer to sustain the pressure loads induced by the reactivity event	Rationale: There is some research on the kinetics of Pd attack on SiC underway at MIT. It is noteworthy that other fission products under appropriately low oxygen partial pressures can react with SiC to form stable carbides with the degradation of the mechanical properties of the SiC	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	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	Level: 2	Remedy: As noted above attack on the SiC layer during normal operations and the resulting degradation in the SiC layer mechanical properties must be considered in determining if fuel will survive intact a reactivity insertion
Rationale: Diffusion and even reaction during the reactivity event will not be extensive. Diffusion during normal operations and the formation of an inventory of heavy metals that can react with SiC and degrade its properties prior to the reactivity event is most important to consider	Rationale: There is little data on the diffusion of fission products through irradiated SiC and the chemical reactions of the diffusion species with SiC that result in a degradation of the mechanical properties	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	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 necessary for reactivity accidents but see elsewhere for other types of accidents
Rationale: Any oxygen released from the kernel during the course of irradiation will probably react either with the buffer material or with the inner PyC layer and not be available for reaction with the SiC layer. There could be some catalysis by metals that makes reaction with SiC preferential over the other carbon materials, but definitive information on this seems not available. In any event, however, the duration of the reactivity accident is sufficiently short that any incremental degradation of the SiC layer due to oxygen reaction during the accident will by negligible. More important is the protracted degradation during operations prior to the reactivity event.	Rationale: (There are data in the literature on the kinetics of oxidation of SiC. These data are for unirradiated materials and may not properly describe the kinetics of reaction with SiC in the coated particles	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Heatup Accident	SiC Layer Fission gas release through 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: L	Level: 2	Remedy: no remedy necessary for reactivity accidents but see elsewhere for other types of accidents
Rationale: As noted above transport of gases during the reactivity accident will not be sufficiently extensive to affect the accident much. Passage during normal operations that affects the inventory of gas available for pressurization of the coated fuel particle during the event is important	I am not aware of data on the passage of fission gas through defects in the SiC layer. Presumably this could be estimated if we had data on the defects in the SiC layer. Such data are not to be found.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Heatup Accident	SiC Layer Fission gas release through failures, e.g. cracking	Passage of fission products from the buffer region through regions in the SiC layer tat fail during operation or an accidnt

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 7	Remedy: This is the issue of fission product release during reactivity accidents – so it must be considered
Rationale : Rupture of the pressure boundary provided by the SiC layer is an important step in the release of safety significant quantities of radionuclides from the fuel during reactivity insertion accident. This is especially so if the rupture propagates to rupture additional layers and even affects the matrix material. In and of itself, the rupture does not imply that there will be release of safety-significant quantities of radionuclides, but it is a necessary step.	Rationale: The rupture of the SiC layer is quite uncertain, and this uncertainty is addressed in other questions. The flow of vaporized fission products through ruptures in the layer is well enough understood to allow ready calculation though, in fact, this may not be explicitly calculated. Rather it may simply be assumed that upon rupture there is venting of the pressurized bases with the region formerly bounded by the SiC layer	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	SiC Layer Thermodynamics of the SiC-fission product system	Chemical forms 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: L	Level: 4	Remedy:no remediation is needed specifically for the reactivity insertion accident. The thermodynamics of the SiC layer must, however, be understood for operations and other accidents that have a more prolonged duration
	> 1600 °C :	
Rationale: There is not evidence that thermochemistry of SiC will lead to formation of fission product species of significant volatility on the time scale of a reactivity insertion accident. The thermochemistry of the layer may affect the inventory of fission products available for release should the SiC pressure boundary rupture, but this effect has been considered in other questions	Rationale: (≤ 1600 °C) We don't have a an established understanding of the thermochemistry of SiC and fission products. There is, however, quite a lot of study of the thermodynamics of SiC in other applications and it may be possible to borrow from this base of knowledge to establish an understanding of the SiC/fission product system	Closure Criterion:
	Rationale (> 1600 °C)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	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 needed specifically for reactiviy accidents, but an understanding of how the SiC layer evolves especially with respect to its interactions with the adjacent layers of carbon will be important for operational performance of the fuel and performance of the fuel during accidents that involve substantial prolonged heatup of the fuel
Rationale: The question is not entirely clear since it addresses the sintering of SiC but the definition refers to graphite. It is interpreted here as involving the changes in the microstructure of SiC as a result of heating and interactions with the adjacent layers of carbon. None of these will be significant over the short time scale of reactivity accidents.	Rationale: There is some knowledge of the sintering of SiC and even its interactions with carbon that could be applied to address this issue for circumstances where it is important which is not during reactivity insertion accidents	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Heatup Accident	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: 2	Remedy: no remediation necessary specifically for reactivity insertion accidents
Rationale: Diffusion of fission product gases through the PyC layer will not be the most significant mechanism of fission product release from fuel during reactivity insertion accidents. Diffusion of such fission product gases during normal operations may have a bearing under some circumstances on the inventory of fission products promptly released during a reactivity accident. Also, diffusion may lead to a prolonged "tail" in the release of fission products following a reactivity insertion event. Release by recoil and by venting when particles rupture are likely to be far more important mechanisms of release than diffusion – even gas phase diffusion – but these mechanisms are not specifically called out here.	Rationale:) There is not now a well established data base on the diffusion of fission products through PyC layers	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	Inner PyC 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: 2	Remedy: no remediation needed specifically for reactivity insertion accidents
Rationale: these mass transport processes will not be especially important during a reactivity insertion event simply because the time scales will be too short for any significant transport. Metals aside from perhaps Ag are not likely to be major contributors to the release during reactivity events simply because temperatures will not be high enough or sustained over a sufficient period to produce large releases of the metallic fission products	Rationale: We do not have well developed data bases for the diffusion coefficients, gas phase speciation or pore structure needed to calculate these mass transport processes with any confidence.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	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: H	Level: 5	Remedy: phenomenon has to be considered in the analysis of fuel failure during reactivity insertion events
Rationale: Pressure loads on the layers during reactivity transients are crucial factors in determining whether fuel failure occurs. The pressurization by fission products will contribute to the loads though this pressurization may be smaller than that due to CO	Rationale: Crucial to the determination of the pressurization by fission products during reactivity transients will be knowledge of the fission product inventory that has escaped fuel grains and is able to contribute to this pressurization. We do have some knowledge of the releases from uranium dioxide fuel kernels that may be sufficient to bound the pressurization. Our knowledge for UCO fuel kernels is not so advanced, but again may be sufficient to allow some bounds on the pressurization due to fission product gases and vapors. A more refined estimate of the pressurization will require more understanding of the distribution of the fission products released from fuel during normal operations.	Closure Criterion:

Additional Discussion

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

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 3	Remedy: This is a crucial phenomena that will dictate whether fuel particles survive reactivity insertion events
Rationale: The pressure load and whether it causes rupture of the SiC pressure boundary layer leading to the venting of fission product gases is the safety significant issue of reactivity insertion accidents	Rationale: We know that carbon is fundamentally incompatible with uranium dioxide. Reaction to produce CO at the fuel kernel carbon interface (which is actually a buffer material rather than the inner PyC layer) will take place. The rates and extents of this reaction are limited by kinetic phenomena and may be quite different under conditions of irradiation than laboratory conditions that do not involve irradiation. To my knowledge the kinetics of the reaction of carbon with uranium dioxide under irradiation conditions have not been well established. We do suspect that the reaction will be catalyzed and catalysts could be fission products. It is known for instance that cesium catalyzes the reaction of carbon dioxide with graphite. Metallic species can also act as catalysts	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	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: L	Level: 4	Remedy:The uptake to form CO will not be especially important during a reactivity event simply because the duration of the event will be sufficiently short that the incremental amount of CO formed during the event will be small in comparison to that formed during normal operations
Rationale: This issue is of high safety significance because of the pressurization of the SiC layer. The uptake during reactivity events will not be especially important because of the limited duration of the event. The high temperature coefficient of reactivity of gas-cooled reactors assures that reactivity insertion will not produce prolonged periods of high temperature. The uptake and formation of CO that will be important is that taking place during operations prior to the insertion event. The CO produced during normal operations is likely to be dominated by the reaction of the buffer layer carbon rather than the inner PyC layer. The PyC layer may be involved especially if there is a strong catalytic effect for the oxidation of carbon by fission products released during operations from the fuel kernels and migrating from the fuel kernels into the inner PyC layer	Rationale: We do not have sufficiently detailed models of the reactions of carbon to predict well the catalytic effects of fission products. We do have quite a lot of information about the reactions of carbon with oxidants at low concentrations of oxidants.	Closure Criterion:

Additional Discussion

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

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 2	Remedy: These forces must be considered in any assessment of the ability of fuel particles to survive intact a reactivity insertion event
Rationale: The forces on the layer that affect the ability of the particle to survive intact a reactivity insertion event are crucial issues. These forces can ameliorate or exacerbate the effects of internal pressurization during the reactivity event	Rationale We donot know these forces now even to a sign for current fuel. They are similarly unknown for the fuel eventually found acceptable for use in power reactors.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Heatup Accident	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	Level: 4	Remedy: no remediation needed specifically for reactivity insertion accidents
Rationale: Intercalation of fission products during normal operations may reduce the inventory of fission products able to contribute to the pressurization during reactivity insertion events. The topic, however, was not raised in the questions concerning operations. Intercalation during the event itself will be of very minor significance because of the duration of the event. Release of intercalated radionulcides as a result of the temperature transient produced by the reactivity insertion event may contribute in some minor fashion to the total release – especially the low intensity 'tail' of the release following the termination of the transient.	Rationale We know that graphite will intercalate fission product species such as cesium. We have some ideas of the binding forces involved and the kinetics, so the phenomenon may be predictable for some fission products. We do not have a comprehensive base of needed information to make estimates of the intercalation of fission products generally.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	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: no remediation needed specifically for the reactivity insertion event, but these diffusive mass transfer processes do need to be understood for normal operations and for other types of accidents
Rationale: Diffusive mass transport process will be too slow to contribute significantly to the consequences of a reactivity insertion event. At best, they will contribute a low intensity 'tail' to the release following the event. The major part of the release will come from the rupture of particles by the event. This will really be a pressure driven process. It really is not helpful to lump pressure driven processes together with diffusive processes.	Rationale: We don't have sufficient data to predict diffusive mass transport of species in the region of the buffer. We certainly know how to calculate the release in the event of gross large-scale ruptures of the particles. It may be more problematical to calculate the release for smaller scale ruptures	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	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: 2	Remedy: no remediation needed specifically for the reactivity insertion event, but these diffusive mass transfer processes do need to be understood for normal operations and for other types of accidents
Rationale: Diffusive mass transport process will be too slow to contribute significantly to the consequences of a reactivity insertion event. At best they will contribute a low intensity ‘tail’ to the release following the event	Rationale: We don’t have sufficient data to predict diffusive mass transport of species in the region of the buffer. We also don’t need to make this prediction for the reactivity accident.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	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: H	Level: 7	Remedy Response forces produced by the accommodation of the expansion on the inner PyC layer and the SiC layer will need to be recognized in an assessment of the ability of fuel particles to survive reactivity events:
Rationale: The buffer layer is intended to accommodate the expansion of the kernel. This layer is intended to prevent what in normal light water reactor fuels is called pellet-clad mechanical interactions (PCMI) between the kernel and the inner PyC layer. The accommodation of the expansion by the buffer will, however , still produce forces on the inner PyC layer and on the SiC layer that will affect the abilities of these layers to sustain the pressurization produced by the transient.	Rationale: We probably have sufficient information to estimate the forrces on the PyC and SiC layer produced as the buffer layer accommodates the expansion of the fuel kernel produced during the reactivity transient.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	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: M	Level: 2	Remedy:This is a factor to take into account when estimating the pressure loads on the SiC layer during reactivity transients
Rationale: High-energy surfaces are produced in fuel particle during normal operations. We know that fission products and lots of other vapor species can absorb on these high-energy sites. To the extent this occurs it will mitigate some of the pressurization of the particle during a reactivity transient. The general suspicion is that the effect is not huge. This suspicion is, however, born of experiences with materials not exposed to the intense irradiation the surfaces with the fuel particles will sustain. The irradiation produces defects that can be prime absorption sites for vapor species	Rationale: There is, at best, a qualitative understanding of the adsorption desorption characteristics of the various materials within the fuel particle under irradiation conditions. To assess the magnitude of the effect would require there to be much more quantitative information. What are needed are adsorption/desorption isotherms taken under elevated pressures of the competitive gas CO	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Heatup Accident	Buffer Layer Layer oxidation	Reaction of the 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	Level: 4	Remedy: The inventory of CO produced by reaction of the buffer layer and other carbon layers with oxygen evolved during operations from the urania fuel is most important for estimating the pressurization of the fuel particles during reactivity accidents. This inventory is produced, however, primarily during normal operations of the fuel. The amount of reaction that can take place during a reactivity insertion event is modest.
Rationale: CO will be a major contributor to the pressurization of the fuel particle during a reactivity insertion accident. This inventory will be produced primarily during normal operations as the fuel kernel reacts with carbon primarily in the buffer layer but perhaps also other layers of carbon-bearing materials. During the reactivity insertion event there will be a temperature transient that will accentuate reaction rates, but the transient will be over so quickly because of the high temperature coefficient of the reactor that relatively little CO will be produced at the higher rates of reaction. Only under very unusual circumstance will the small amount of CO produced during the transient itself be sufficient to push the fuel particle to failure when it would not fail had there not been the incremental CO production.	Rationale: () We have some information about the rates of reaction of various types of carbon with oxidants. There is less information available concerning the kinetics of reaction of specifically the buffer layer material and uranium dioxide. We do know that the rate of oxidation of carbon is catalyzed by various materials that are fission products. Catalysis by cesium is especially noteworthy	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	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	Level: 5	Remedy: Temperatures within the various regions of the fuel particle will have to be known quite well to accurately predict the pressurization of the particle and the capacity of the various layers to sustain this pressurization
Rationale: A reactivity event will be quite dynamic and it will not be adequately accurate to assume that the particle is iso thermal. Temperatures within the the various layers will determine how much pressurization occurs and the mechanical properties of the layer to withstand the pressurization	Rationale: Thermal conductivities of the layers will not be known well but probably can be estimated with sufficient accuracy for the necessary calculations of temperature distributions	Closure Criterion:
	)	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	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 of buffer	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 7	Remedy: no remediation needed specifically for the reactivity insertion accident. The issue should receive very extensive investigation during the design of the fuel and for the assessment of fuel performance during normal operations
Rationale: The buffer layer is by intention supposed to have the ability to accommodate dimensional changes because of its relatively high porosity. Though dimensional changes of most importance are those that the fuel experiences and imposes on the buffer layer during irradiation, we know that the buffer layer will also experience growth as a result of irradiation. These dimension changes too should be accommodated by the layer	Rationale: We should have sufficient information to at least estimate the dimension changes and their effects. More difficult will be the estimation of any additional loads imposed on the SiC and inner PyC layer which it would be hoped are at worst second order increments	Closure Criterion:
	Rationale	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Heatup Accident	Kernel	Maximum fuel temperature attained by the fuel kernel during the accident
	Maximum fuel temperature during core heatup	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 8	Remedy: This is an absolutely crucial consideration in the safety analysis of fuel during reactivity insertion events
Rationale: The temperature produced in the kernel by an insertion event is the driving force both for release of fission products accumulated in pores and on grain boundaries on the fuel and for estimating the pressurization of the fuel particle during the event	Rationale: We should have the capability to predict the heat input to the fuel kernel quite well and sufficient knowledge of the heat loss processes to know temperature of the fuel and the temperatures of other regions in the particle at least well enough for safety assessment purposes	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	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: 8	Remedy The time temperature history of the fuel and the rest of the fuel particle should be taken into account to produce realistic estimates of the pressurization of the particles during the accident:
Rationale: I have interpreted this question to address not just the maximum temperature but also the whole time temperature history of the kernel and all the other regions of the fuel particle. These histories will be of some importance to more accurately calculate the pressurization of the particle and the possibility that rupture of the particle will occur		Closure Criterion:
	Rationale) WE should have sufficiently good estimates of heat transport within the fuel particle to at least obtain estimates of the time temperature histories during and after a reactivity insertion event	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	Kernel Energy deposition (total)	Amount of fission energy generated in kernel during reactivity event (j/gm heavy metal because of Pu)

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank:H	Level: 7	Remedy: no remediation needed local energy production because the necessary technology is available today. Some effort may be needed to show that the non-uniform distribution of particles within the matrix does not affect the estimates significantly or if it does affect the energy production of particles at various locations in the matrix this effect can be quantified.
Rationale: Energy production during a reactivity event is a crucial input to the calculations of temperature	Rationale: The ability to calculate the energy production locally has advanced substantially in recent years and this technology can be applied to the issues of energy production in particulate fuel. A complication arises because the fuel particles are NOT distributed uniformly within the fuel matrix and this complication needs to be assessed	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	Kernel Energy deposition (rate)	Rate at which fission energy is generated in kernel

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 6	Remedy: This is really an issue of the specification of the reactivity accident
Rationale: Reactivity insertion events can be of various intensities and durations. For the purposes of assessing fission product release, the events are nearly always fast . For the issues of assessing structural integrity particularly of the fuel kernel, slower transients can allow some of the heat input to conduct from the fuel and this reduces the maximum temperature reached by the fuel that further limits its expansion and the mechanical forces imposed by the expanding kernel on other layers in the particle	Rationale: The reactors are not now specified in sufficient detail to have precise quantification of the accident histories. Once better specifications are available, accident scenarios can be developed in detail more than adequate for source term analyses	Closure Criterion:
	Rationale)	

Additional Discussion

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

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 release will have to include a detailed model of heat transport from the through the fuel kernel into the other regions of the fuel particle especially for reactivity accidents. The challenge in developing such a model parallel in many respects the challenges associated with the analysis of fission product diffusion from the kernel to the rest of the particle. One of the issues is thermal conductivity of the materials. These are porous irradiated material. Defects introduced by irradiation reduce thermal conductivity in ways that simply have to be measured. Pores introduced by manufacture and the like reduce conductivity and probably is not adequate to treat the effects of these reductions in some average way using some approximate factor such as the Loeb correction factor. A more realistic model that takes into account orientation of the pore will have to be employed. Another approximation that is widely used but is questionable is the spherical symmetry of the particle. The particles really do not have spherical symmetry and the deviations can be enough to distort the answers. Furthermore, assuming layers are of uniform thickness may not be an adequate approximation to address the issues of reactivity insertion accidents even if the approximations are adequate for long term accidents
Rationale: Temperatures will affect pressurization, vaporization of fission products and material properties of layers to sustain forces imposed by thermal expansion and the like as well as pressurization	Rationale: The technology for doing the analyses well is available. We lack the necessary input data to implement this technology.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Heatup Accident	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: 7	Remedy: no remediation needed for reactivity insertion accidents except perhaps to investigate the literature to see if we can estimate adequately the states of fission products outside the confines of the fuel kernel
Rationale: The chemical states of the fission products determine their vaporization under the conditions of a reactivity insertion accident and consequently their abilities to contribute to the pressurization of the fuel particles and abilities to be released during the accident.	Rationale: We have quite a lot of information concerning the states of fission products in the fuel kernel, its grain boundaries and pores. We have much less information concerning the states of fission products elsewhere in the fuel particle and there can be some real surprises if the fission product is reactive toward the material or with CO at quite high pressures (~50 bar). It may be possible to estimate the conditions of fission products in these other areas based on information from the literature. It would be useful to have some sort of experimental confirmation of these estimates	Closure Criterion:

Additional Discussion

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

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank M	Level: 6	Remedy:
Rationale:.Gas phase diffusion certainly occurs within the pore structure of the kernel during a reactivity transient. It is usually not rate limiting on the release of radionuclides. Typically the rate limitations are on the vaporization of fission products accumulated at grain boundaries and in the pores as well as the transport of fission products born inside grains to reach free surfaces where they can vaporize	Rationale:. We know enough to calculate adequately the contribution gas phase transport processes within kernels will make to the radionuclide release processes during a reactivity transient.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	Kernel 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: H	Level: 6	Remedy: no remediation needed if uranium dioxide kernels are used. Significant background data are needed for UCO kernels
Rationale: Bulk diffusion during normal operations is key to knowing the inventory of fission products that can be released from the fuel. Bulk diffusion during the transient itself is simply too slow to be a factor of importance. Surface diffusion and grain boundary diffusion can contribute to the release of fission products though a more important source will be the rupture and venting of macrobubbles near the kernel perimeter.	Rationale: We know quite a lot about the diffusion of fission products from work with conventional light water reactor fuel composed of primarily uranium dioxide. Information on grain boundary diffusion may not be applicable if the method of kernel manufacture is not very similar to the method of manufacture of fuel pellets for existing reactors simply because the surface diffusion processes depend so much on impurity levels.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	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: 5	Remedy: This is important for establishing the CO inventory in the particle that will produce the particle pressurization during a reactivity insertion accident. It must be included in models of fuel performance and fission product release
Rationale: Oxygen in the fuel liberated by the fissioning of uranium atoms can be accumulated either in a buffer provided by the Mo/MoO2 system or it can migrate through the fuel to the surface where it reacts with carbon to form CO. The CO pressurization of the particle especially during a reactivity accident can lead to fuel particle rupture and the venting of fission products accumulated outside the kernel and within the pore structure of the kernel	Rationale: Oxygen diffusion through the fuel is known well –enough. We have not attempted a competitive calculation to see how much moves to a surface and how much reacts internally with metallic inclusions though there is no real reason such an analysis could not be undertaken. The challenges associated with such a calculation include: Define a model of Mo acitivity in inclusion Estimate the kinetics of reaction of Mo in the inclusions with diffusing oxygen Treat the stochastic distribution of metal inclusions at the grain boundaries in the fuel	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	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: 7	Remedy:no remediation is needed
Rationale: Grain growth during normal operations usually is unimportant because the grain boundaries are pinned by fission products . During a reactivity transients periods of elevated temperature will be of sufficiently short duration that it unlikely extensive grain growth and fission product sweeping to the grain boundaries can occur	Rationale:) We know quite a lot about grain growth in uranium dioxide fuels for temperatures in the range of normal operations of coated particle fuel.	Closure Criterion:
	Rationale	

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Reactivity Accident	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	Level: 2	Remedy: This is a major consideration for CO production during normal operations.
Rationale: carbon will attempt to reduce the ambient oxygen potential by reaction to form CO to levels that render the fuel mildly hypostoichiometric. The biggest effect is to increase the concentration of CO within the particle.	Rationale: This will be a kinetic process and the kinetics of reaction of irradiated carbon with the fuel kernels are not established	Closure Criterion:

Additional Discussion