NUREG/CR-6844, Vol. 2

# TRISO-Coated Particle Fuel Phenomenon Identification and Ranking Tables (PIRTs) for Fission Product Transport Due to Manufacturing, Operations, and Accidents

## Appendices A through D

U.S. Nuclear Regulatory Commission
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NUREG/CR-6844, Vol. 2

# TRISO-Coated Particle Fuel Phenomenon Identification and Ranking Tables (PIRTs) for Fission Product Transport Due to Manufacturing, Operations, and Accidents

## Appendices A through D

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## ABSTRACT

TRISO-coated particle fuel is to be used in the next generation of gas-cooled reactors. In anticipation of future licensing applications for gas-cooled reactors, the United States Nuclear Regulatory Commission (NRC) seeks to fully understand the significant features of TRISO-coated particle fuel design, manufacture, and operation, as well as behavior during accidents. The objectives of the TRISO Phenomena Identification and Ranking Table (PIRT) program are to (1) identify key attributes of gas-cooled reactor fuel manufacture which may require regulatory oversight, (2) provide a valuable reference for the review of vendor fuel qualification plans, (3) provide insights for developing plans for fuel safety margin testing, (4) assist in defining test data needs for the development of fuel performance and fission product transport models, (5) inform decisions regarding the development of NRC's independent reactor fuel performance code and fission product transport models, (6) support the development of NRC's independent models for source term calculations, and (7) provide insights for the review of vendor fuel safety analyses. To support these objectives, the NRC commissioned a PIRT panel to identify and rank the factors, characteristics, and phenomena associated with TRISO-coated particle fuel. PIRTs were developed for (1) Manufacturing, (2) Operations, (3) a Depressurized Heatup Accident, (4) a Reactivity Accident, (5) a Depressurization Accident with Water Ingress, and (6) a Depressurization Accident with Air Ingress.

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## FOREWORD

In anticipation of future licensing applications for gas-cooled reactors, the United States Nuclear Regulatory Commission (NRC) seeks to fully understand the significant features of TRISO-coated particle fuel design, manufacture, and operation, as well as behavior during accidents.

To address this objective, the NRC convened the formation of a panel of experts to identify and rank the factors, characteristics, and phenomena associated with the life-cycle phases of TRISO-coated particle fuel. The products of the panel are Phenomena Identification and Ranking Tables (PIRTs) and the associated documentation.

Six phenomena identification and ranking tables (PIRTs) were developed by the panel and are presented in this report. They are: (1) Manufacturing, (2) Operations, (3) Depressurized Heatup Accident, (4) Reactivity Accident, (5) Depressurization Accident with Water Ingress, and (6) Depressurization Accident with Air Ingress.

Analyses and summaries for each of the six PIRTs are presented. A total of 327 factors, characteristics and phenomena are identified in the six PIRT tables. The importance of each factor, characteristic, process or phenomenon was assessed relative to the magnitude of its influence on fission product release or in a more accident consequence-related term, the source term. One hundred-ten (110) factors, characteristics and phenomena were assigned an importance rank of "High" by each panel member. The panel concluded that these 110 factors, characteristics and phenomena had the most significant impact on fission product release. Each panel member prepared a written rationale supporting the importance rank assigned to each highly ranked factor, characteristic or phenomenon. These rationales are included in this report. The level of knowledge for each factor, characteristic or phenomenon was also assessed and documented. Of particular interest to the agency are those factors, characteristics or phenomena assessed by the panel as being of high importance but not yet adequately understood.

The PIRT results will be used by the agency to (1) identify key attributes of gas-cooled reactor fuel manufacture, (2) provide a valuable reference for the review of vendor gas-cooled reactor fuel qualification plans, (3) provide insights for developing plans for fuel safety margin testing, (4) assist in defining test data needs for the development of fuel performance and fission product transport models, (5) inform decisions regarding the development of NRC's independent gas-cooled reactor fuel performance code and fission product transport models, (6) support the development of NRC's independent models for source term calculations, and (7) provide insights for the review of vendor gas-cooled fuel safety analyses.

This report is consistent with the NRC strategic performance goals (NUREG-1614, Vol. 2)

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# APPENDIX A

## PANEL MEMBER DETAILED PIRT SUBMITTALS FOR MANUFACTURING

The INEEL submittal is provided in Appendix A.1 (pages A-2 through A-37)

The ORNL submittal is provided in Appendix A.2 (pages A-38 through A-75)

# Appendix A.1

## Detailed PIRT Submittal by the INEEL Panel Member

D. A. Petti

## TRISO Fuel PIRT: Manufacturing

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing<br><br>Process Variables (Current process; process may change) | Layer coating process specifications (Buffer, IPyC, SiC, OPyC)<br><br>Gases (levitation gas and coating gas) | Gases used to levitate and coat to create layer |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: M | Level: 8 | Remedy: |
| Rationale: Both German and U.S. processes use a mixture of argon, hydrogen and $C_2H_2$ and $C_3H_6$ for the PyC and buffer layers. For the SiC layer, MTS is used with hydrogen. The use of hydrogen is used primarily as a diluent, to control the concentration of the coating gases and to prevent/ suppress the formation of other chemicals that would inhibit the CVD process. (See refs. 1,2) | Rationale: There is a lot of experience with the use of these gases. | Closure Criterion: |

**Additional Discussion**


1. Petti, D. A. et al., "Key Differences in the Fabrication, Irradiation, and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance," INEEL/EXT-02-00300, June 2002.

2. NP-MHTGR Fuel Product Specification Basis Report, CEGA-000396, June 1992.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing<br><br>Process Variables (Current process; process may change) | Layer coating process specifications (Buffer, IPyC, SiC, OPyC)<br>Ratio of gases | Ratio of active gas to total gas, including concentration |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 7 | Remedy: |
| Rationale: For the PyC layers, the ratio of the active hydrocarbon gas to the total gas determines the concentration of the hydrocarbons in the gas phase. This directly affects the nature of the CVD layer that is produced. This parameter together with temperature and time determine the coating rate for the layer, which determines its structure and isotropy. The U.S. has different specifications for the OPyC and IPyC for this ratio ($<0.25$ for IPyC and $>0.25$ for OPyC). See references 1, 2, and 3 for details about PyC coating behavior and the technical basis for U.S. fuel. For the SiC layer, there is an optimum ratio of $H_2$/MTS. (Typical ratio is $>20$ and can be as high as 70). The hydrogen is used to suppress the formation of volatile silicon chlorides. | Rationale: Coated particle fuel needs very isotropic pyrocarbon. This is achieved at relatively high ratios of active gas to total gas so that the carbon is nucleated in the gas phase and then deposits on the particle instead of nucleating on the surface of the particle, which will lead to anisotropy. The difference in the structure of the pyrocarbon produced via these two methods can be thought of as the difference between snow that falls on a surface and frost that forms on a surface. (See ref. 4). It should be pointed out that the irradiation performance of U.S. PyC has not been acceptable which calls into question the technical merit of the active gas to total gas ratio specification for the pyrocarbon layers. By contrast the German fuel has performed much better. For the SiC layer, the knowledge of the critical ratio is fairly well known (see ref. 4). | Closure Criterion: |

**Additional Discussion**


1. Petti, D. A. et al., "Key Differences in the Fabrication, Irradiation, and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance," INEEL/EXT-02-00300, June 2002.
2. Martin, D.G., April 2000, *Pyrocarbon in High Temperature Nuclear Reactor in Irradiation Damage in Graphite due to Fast Neutrons in Fission and Fusion Systems*, Report IAEA-TECDOC-1154.
3. NP-MHTGR Fuel Product Specification Basis Report, CEGA-000396, June 1992.
4. Bourrat, X. "Pyrocarbon and SiC in HTR Fuel Particles," Lecture at Eurocourse on HTR Technology, Cadarache France, Nov. 2002.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing<br><br>Process Variables (Current process; process may change) | Layer coating process specifications (Buffer, IPyC, SiC, OPyC)<br>Temperature | Temperature of coater |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 8 | Remedy: |
| Rationale: Temperature of the coater is also a critical variable for the production of each layer. The buffer layer is deposited at between 1250 and 1300 C. The PyC layers are deposited between 1200 and 1300 C. Temperatures outside this range result in the wrong structure of the PyC layers. The SiC layers are deposited generally between 1500 and 1650 C to ensure the proper density and structure. See references 1, 2, and 3 for details of the U.S. and German process and the technical specification for the U.S. process. | Rationale: Temperature is known to be critical, especially for the SiC layer. In fact, U.S. fuel has been coated over the range of 1500 to 1650°C. The SiC coated at the higher end of this range is very dense and has larger columnar grains while that coated near 1500° C results is smaller grains that appear to result in better fission product retention. Coating below 1500°C results in low density SiC, with the potential for porosity and/or some elemental silicon in the layer. The trend is to coat near 1500°C. It is also important to note that the temperature measured in one coater may not necessarily be directly related to that in another coater and hence comparisons between U.S. and German coaters can be problematic. There are some data on the effect of coating temperatures on silver release (ref.4). | Closure Criterion: |

**Additional Discussion**


1. Petti, D.A. et al., "Key Differences in the Fabrication, Irradiation, and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance," INEEL/EXT-02-00300, June 2002.
2. Martin, D.G., April 2000, *Pyrocarbon in High Temperature Nuclear Reactor in Irradiation Damage in Graphite due to Fast Neutrons in Fission and Fusion Systems*, Report IAEA-TECDOC-1154.
3. NP-MHTGR Fuel Product Specification Basis Report, CEGA-000396, June 1992.
4. Forthmann, R. et al., "Influences of Material Properties on the Retention of Fission Products by Silicon Carbide Coatings," High- Temperatures-High Pressures, Vol. 14, p. 477-485, 1982.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing<br><br>Process Variables (Current process; process may change) | Layer coating process specifications (Buffer, IPyC, SiC, OPyC)<br>Coating Rate | The average deposition rate over space and time of the layer |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 8 | Remedy: |
| Rationale: This is a macroscopic parameter that can be used to judge the "goodness" of the layers. PyC that behavior well under irradiation is coated at coating rates between 4 and 6 microns/minute. Slower coating rates result in greater anisotropy in the layer, which can lead to cracking of the IPyC under irradiation. Higher coating rates lead to very low-density coatings (which is acceptable for the buffer layer only and not the PyC layers) For the SiC layer, coating rates between 0.2 and 0.33 microns/min are acceptable. Outside of this range results in some alpha SiC being produced or improper grain structure. See references 1, 2, and 3 for details. | Rationale: A significant amount of work has been done to study the coating behavior of both PyC and SiC in the early days of the gas reactor programs in Europe and the U.S. | Closure Criterion: |

**Additional Discussion**


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

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing<br><br>Process Variables (Current process; process may change) | Layer coating process specifications (Buffer, IPyC, SiC, OPyC)<br>Pressure | Pressure inside coater |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: L | Level: 3 | Remedy: |
| Rationale: Most of the coating is done at atmospheric pressure (ignoring pressure losses in the coating equipment) most likely for ease of coating and cost. There is very little data on the effect of pressure on the coating process. However, since diffusion coefficients in the gas phase scale with the inverse of pressure, higher pressure will decrease reaction rates relative to atmospheric pressure. Increasing pressure can increase the concentration of the gases in the coater but this can probably be more easily obtained by varying the gas flow rates into the coater. | Rationale: The effect is unknown since I am unaware of any particles coated at a pressure different than atmospheric. | Closure Criterion: |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing<br><br>Process Variables (Current process; process may change) | Layer coating process specifications (Buffer, IPyC, SiC, OPyC)<br>Coater Size | Size is measured by the diameter of the coater |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 6 | Remedy: Irradiate particles from both lab scale and production scale coaters |
| Rationale: The size of the coater is felt to be important in determining the uniformity of the coating properties of the layers that are obtained. Much work has been done on lab scale coaters (~ 2 inch) in the U.S. post-Ft. St. Vrain. By contrast the German work on high quality coated particle fuel has been performed on large scale (~ 10 inch) coaters. It is difficult to trace quantitatively the poor performance of U.S. fuel over the past 25 years solely to the coater size but discussions with experts in Germany and GA suggest that coater size is important to produce high quality fuel. Excessive fluidization where particles hit walls has been identified as a mechanism to pick up carbon soot, which can lead to defective SiC layers. (See ref. 1) The excessive fluidization is a bigger problem in smaller coaters because of the hydrodynamics relative to a large coater. | Rationale: No quantitative side by side irradiations of fuel from both small and large-scale coaters have ever been performed. Anecdotal evidence and discussion with experts in Germany and the U.S. suggest that there is an effect of scale on the quality of the fuel. The DOE Advanced Gas Reactor Fuel Qualification (ref. 2) will make fuel using different scale coaters and will examine the resultant attributes as measured by QA/QC. If deemed important, irradiations may also be conducted. | Closure Criterion: |

**Additional Discussion**


1. Minato, K., et al., 1994, "Internal Flaws in The Silicon Carbide Coating of Fuel Particles for High-Temperature Gas-Cooled Reactors," *Nuclear Technology*, Vol. 106, pp. 342-349.
2. Technical Program Plan for the Advanced Gas Reactor Fuel Development and Qualification Program, ORNL/TM-2002/262, Nov. 2002.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing<br><br>Process Variables (Current process; process may change) | Layer coating process | Continuous vapor deposition (CVD) TRISO coating without unloading of particles |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 6 | Remedy: Irradiate particles produced by both continuous and interrupted methods and compare results |
| Rationale: The coating of the TRISO layers in an uninterrupted manner is a hallmark of the German fuel manufacturing process. By contrast in the U.S. process, the particles are unloaded at each step to perform QC measurements. This difference is felt by many experts to be important in the overall performance of fuel, but one cannot be completely quantitative here. See reference 1 for a discussion of the two coating methods | Rationale: The effect is not definitively known but experts in Germany suspect that this is an important difference between the U.S. and German fuel manufacturing approaches. The DOE Advanced Gas Reactor Fuel Qualification (ref. 2) will make fuel using both the continuous and interrupted methods and will examine the resultant attributes as measured by QA/QC. If deemed important, irradiations may also be conducted. | Closure Criterion: |

**Additional Discussion**


1. Petti, D.A. et al., "Key Differences in the Fabrication, Irradiation, and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance," INEEL/EXT-02-00300, June 2002.
2. Technical Program Plan for the Advanced Gas Reactor Fuel Development and Qualification Program, ORNL/TM-2002/262, Nov. 2002.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Process control | Correlation between measured process parameters and irradiation performance |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 6 | Remedy: |
| Rationale: Certain key aspects of the fuel fabrication process must be controlled to get good irradiation and safety performance of the fuel. Coating rates for example are critical to getting proper microstructures and isotropies of the layer, which in turn correlate to good performance of the fuel. | Rationale: We know a fair amount about what coating rates are required to get "good" fuel, however, there are come uncertainties that will be examined in the DOE AGR Fuel Development & Qualification Program | Closure Criterion: |

**Additional Discussion**


1. Petti, D.A., et al., "Key Differences in the Fabrication, Irradiation, and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance, " INEEL/EXT-02-00300, June 2002.
2. NP-MHTGR Fuel Product Specification Basis Report, CEGA-000396, June 1992.
3. Bryan, M.F., 1992, *Evolution of NP-MHTGR Performance Test Fuel Quality Control Data,* INEEL.Report EGG-NPR-10130.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Product control | Correlation between measured product parameters and irradiation performance |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: M | Level: 6 | Remedy: |
| Rationale: These physical attributes of the coated fuel particle (densities, kernel diameter, layer thicknesses) are all measured during fabrication. The CVD processes have been optimized so that each of these attributes falls within the required specifications. Performance modeling (ref.1) and anomalous fuel performance data from the past (see ref.2) suggest that these physical characteristics are of somewhat less importance than the harder to measure attributes such as anisotropy of the PyC layer, material properties of the layers, microstructure of the SiC layer, potential flaws, defects or porosity of the layers, the nature of the interface between the SiC and IPyC layers, and kernel stoichiometry. Once the fabricator assures that these harder to measure attributes are satisfactorily achieved, then the more easily measured physical characteristics become important. | Rationale: Such parameters are routinely measured in fabrication runs and fall within specified ranges. See references 1-3 for examples and rationales behind the values. | Closure Criterion: |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Fuel element | Layer on outside of outer PyC added after coating |
| | Particle overcoating (fuel form dependent) | |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 8 | Remedy: |
| Rationale: Used historically only in pebble fuel. The overcoating protects the particle during the creation of the pebble. The soft carbonaceous material helps cushion the particles during molding. This helps reduce the number of initially defective particles that would release fission products under normal and off-normal conditions | Rationale: The use of the overcoat reduces the number of particles that would be broken during the manufacturing process. Germans and Chinese have used it successfully. | Closure Criterion: |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Fuel element<br>Matrix and Binder | Filler mixed with resin |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 6 | Remedy: Irradiations needed to qualify the filler material. |
| Rationale: A specification exists to ensure that an adequate amount of matrix material is homogeneously distributed throughout the fuel body to ensure uniform mechanical integrity and thermal conductivity. | Rationale: Specific type of filler material has been specified in the past. It is not clear that such filler material is available today. If not, a new filler material will need to be qualified. | Closure Criterion: |

**Additional Discussion**

NP-MHTGR Fuel Product Specification Basis Report, CEGA-000396, June 1992.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Fuel element<br>Bonding strength (PyC to matrix) | Interfacial strength at the interface |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: L | Level: 6 | Remedy: |
| Rationale: The bonding of the PyC to the matrix has historically been different in pebble (German) and compact (U.S.) fuel because of the differences in the matrix material. In the U.S., the matrix is liquid and is infiltrated into a mold. The high pressure of the process drives some of the liquid into the porosity in the OPyC. Under irradiation, this matrix material shrinks and can rip the OPyC from the SiC layer. If the SiC layer remains intact, little impact on fission product release is expected. Detailed specifications on the microporosity of the OPyC layer have been imposed on historic U.S. fuel to minimize this effect (ref. 1). For the German pebble fuel, the matrix material is the same as the overcoat material and is a powdered graphitic material. The bonding strength is unknown but irradiation testing has not shown this interface to be a problem relative to particle failure or fission product release. | Rationale: Not studied in the level of detail from a fuel performance perspective given the lack of a problem in irradiations of German pebble fuel. For the U.S. fuel, future compacts will be made using a more German-like process without liquid matrix material so this is again less of a problem. | Closure Criterion: |

**Additional Discussion**

NP-MHTGR Fuel Product Specification Basis Report, CEGA-000396, June 1992.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Fuel element<br>Compacting | Process of forming fuel element involving molding and pressing |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 7 | Remedy: Wait and evaluate results from irradiation in HFR in Petten |
| Rationale: There are differences in the process to form a pebble versus a compact. In the U.S. process, the pressing is done at 160°C at 6.9 MPa whereas German pebbles are pressed at 25°C and 300 MPa. (See ref. 1). How important these differences are on the performance of the fuel element under irradiation is not completely known. | Rationale: The compacting process in use by the Germans has never been identified as being deleterious to the particle behavior under irradiation or accident testing. The U.S. process has been the subject of much discussion and in fact an upcoming irradiation in the HFR reactor in Petten will test the behavior of German particles compacted using the U.S. method to determine if high quality fuel particles are at risk using the U.S. compacting methods (ref. 2). | Closure Criterion: |

**Additional Discussion**

1. Petti, D.A. et al., "Key Differences in the Fabrication, Irradiation, and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance," INEEL/EXT-02-00300, June 2002.
2. Conrad, R. et al., HFR-EU2 Test Specification for Irradiation Experiment of GT-MHR Compacts in the HFR Petten within HTR-TN, Technical Memorandum HFR / 01 / 4679,Revision 2, April 2002.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Fuel element<br>Carburization | Baking full fuel element to drive off volatiles |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: L | Level: 6 | Remedy: |
| Rationale: Carbonization steps are somewhat similar in the fuel compact and fuel pebble. In the U.S., the compacts are carbonized at ~ 900°C in alumina whereas German pebbles are carbonized in inert gas at between 800 and 900°C. (See refs. 1 and 2) The effect of this step on fission product release is not well known but is judged to be small. That said, it is known that the matrix does retain metallic fission products to some extent and effective diffusivities have been established for metallic fission products in the matrix. (see ref. 3) | Rationale: Exact impact on fission product release is not known but low importance suggests less emphasis here than on other factors. | Closure Criterion: |

**Additional Discussion**


1. Petti, D.A. et al., "Key Differences in the Fabrication, Irradiation, and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance," INEEL/EXT-02-00300, June 2002.

2. NP-MHTGR Fuel Product Specification Basis Report, CEGA-000396, June 1992.
3. IAEA, November 1997, *Fuel Performance and Fission Product Behaviour in Gas Cooled Reactors*, IAEA-TECDOC-978.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Fuel element | High temperature annealing to stabilize fuel form |
| | Heat treatment | |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: L | Level: 7 | Remedy: |
| Rationale: The high temperature heat treatment step is done at ~ 1650°C in Ar for compacts and 1950°C in vacuum for pebbles (see ref. 1). The final heat treatment step is done to drive off any remaining volatiles and to provide structural stability to the final fuel form. The basis for the U.S. heat treatment is found in ref. 2 | Rationale: Irradiation testing of compacts with different heat treatment temperatures indicates that satisfactory dimensional stability was obtained for compacts fired at between 1500 and 1800°C. Thus, the impact on fission product release is judged to be low. | Closure Criterion: |

**Additional Discussion**


1. Petti, D.A. et al., "Key Differences in the Fabrication, Irradiation, and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance," INEEL/EXT-02-00300, June 2002.

2. NP-MHTGR Fuel Product Specification Basis Report, CEGA-000396, June 1992.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Fuel element | Minimization of contamination of fuel form by process equipment (e.g., iron, chrome, etc) |
| | Impurities control | |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 7 | Remedy: |
| Rationale: Metallic impurities are known to attack the SiC and can lead to particle failure and hence fission product release under irradiation. Specifications limit the level of impurities. Significant work has been performed in the U.S. to study iron attack. The levels for other elements are based more on thermodynamic arguments (see ref. 1 for details. | Rationale: The attack of the SiC by metallic impurities like Fe has been found to contribute to fuel failure in the early days of gas reactor irradiations. The fuel specifications and as-manufactured QA data suggest that fuel can be manufactured to limit this fuel failure mechanism. (see refs. 2 and 3). Iron impurities have been attributed to weak tails in the SiC strength distribution measured on U.S. fuel. (ref. 4.) | Closure Criterion: |

**Additional Discussion**


1. NP-MHTGR Fuel Product Specification Basis Report, CEGA-000396, June 1992.
2. Petti, D.A. et al., "Key Differences in the Fabrication, Irradiation, and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance," INEEL/EXT-02-00300, June 2002.
3. Bryan, M.F., 1992, *Evaluation of NP-MHTGR Performance Test Fuel Quality Control Data*, INEEL. Report EGG-NPR-10130.
4. Lessing, P. and Heaps, R.J., "Strength of Silicon Carbide Layers of Fuel Particles for High-Temperature Gas-Cooled Reactors," Nuclear Technology, Vol. 108, Nov. 1994.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Fuel element<br>Tramp Uranium | Uranium introduced by raw materials, e.g., resin |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 8 | Remedy: |
| Rationale: In high quality coated particle fuel, this is one of the major sources of fission product release (along with initially defective particles). (Recall that in high quality coated particle fuel, failures during irradiation are very rarely observed) The values derived for both U.S. and German specifications are intended to limit fission product releases so that off-site safety release limits are met. See refs. 1, 2 and 3 for further information. | Rationale: This value is easily measurable in the raw materials. In the U.S. this value and the uranium resulting from initially defective particles are tracked separately. In German fuel, the sum of these values is specified as the "free uranium limit". These values are specified at both 50% and 95% confidence. The sum of the two U.S. pieces (tramp uranium and initial exposed kernel fraction) is equal to the German value at 95% confidence. | Closure Criterion: |

**Additional Discussion**


1. NP-MHTGR Fuel Product Specification Basis Report, CEGA-000396, June 1992.
2. Petti, D.A., et al., "Key Differences in the Fabrication, Irradiation, and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance," INEEL/EXT-02-00300, June 2002.
3. Gontard, R., and H. Nabielek, 1990, *Performance Evaluation of Modern HTR TRISO Fuels*, HTA-IB-05/90.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Fuel element<br>Strength | An overall measure of fuel element resistance to stresses that might occur during operation or accidents. |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 8 | Remedy: None |
| Rationale: The fuel element must be able to withstand forces and any thermal stresses associated with fabrication and handling including it being dropped several meters. | Rationale: Specifications exist and pebbles are able to meet them. | Closure Criterion: None |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Fuel element<br>Initial particle defect fraction due to manufacture | Exposed kernel fraction |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 6 | Remedy: Ensure a common protocol is used in burn leach and compare results again on different fuels (both current and historic if possible) to get resolution on this critical value. |
| Rationale: In high quality coated particle fuel, this is one of the major sources of fission product release (along with tramp uranium in raw materials). (Recall that in high quality coated particle fuel, failures during irradiation are very rarely observed) The values derived for both U.S. and German specifications are intended to limit fission product releases so that off-site safety release limits are met. See refs. 1, 2 and 3 for further information. | Rationale: This value is measured using the burn leach method. The ability to obtain accurate measurements using burn leach has been somewhat mixed. Round robin testing in the R2-K13 experiment in which ORNL, GA and KFA participated showed a wider than expected difference on the SiC defect fraction. (see ref. 4) This may be due to differences in the details of the burn leach procedures used in each institution. In the U.S. this value and the uranium resulting from initially defective particles are tracked separately. In German fuel, the sum of these values is specified as the "free uranium limit". These values are specified at both 50% and 95% confidence. The sum of the two U.S. pieces (tramp uranium and initial exposed kernel fraction) is equal to the German value at 95% confidence. | Closure Criterion: |

**Additional Discussion**


1. NP-MHTGR Fuel Product Specification Basis Report, CEGA-000396, June 1992.
2. Petti, D.A. et al., "Key Differences in the Fabrication, Irradiation, and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance," INEEL/EXT-02-00300, June 2002.
3. Gontard, R., and H. Nabielek, 1990, *Performance Evaluation of Modern HTR TRISO Fuels*, HTA-IB-05/90.
4. Brodda, B. G., et al., 1985, The German-U.S. Cooperative Experiment R2-K13 Part I: Irradiation of UCO and $ThO_2$ TRISO Particles in Prismatic Block Segments, KFA-HBK-IB-09/85.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Outer PyC layer<br>Anisotropy (initial) | Difference in grain orientation along principal directions as measured by the BAF |

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

**Additional Discussion**


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

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Outer PyC layer<br>Porosity | Interconnected void accessible to the surface |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: M | Level: 8 | Remedy: |
| Rationale: Porosity in the PyC can be the dominant transport path for fission gases in that layer. Relatively high density PyC is produced (~ 1.85 - 1.9 g/cc) by both the U.S. and German processes. In the U.S., this porosity has been implicated in causing failure of the layer under irradiation because of liquid matrix infiltration and subsequent shrinkage under irradiation. However, the U.S. is going to a different matrix material (non-liquid), which will make this a non-issue. The basis for the specification on density and microporosity in U.S. fuel is found in ref. 1. | Rationale: Densities are routinely measured for the OPyC. (see refs. 2 and 3). Effective diffusivities for metallic and gaseous fission products have been measured. (see ref. 4) | Closure Criterion: |

**Additional Discussion**


1. NP-MHTGR Fuel Product Specification Basis Report, CEGA-000396, June 1992.
2. Petti, D.A. et al., "Key Differences in the Fabrication, Irradiation, and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance," INEEL/EXT-02-00300, June 2002.
3. Bryan, M.F., 1992, *Evaluation of NP-MHTGR Performance Test Fuel Quality Control Data*, INEEL. Report EGG-NPR-10130.
4. IAEA, November 1997, *Fuel Performance and Fission Product Behaviour in Gas Cooled Reactors*, IAEA-TECDOC-978.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | SiC layer<br>Grain size and microstructure, e.g. alignment | Size and orientation of the grains and the pores |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 8 | Remedy: |
| Rationale: The proper grain size and microstructure of the SiC is important to obtaining high density, high strength and good fission product retentiveness. The goal is to strive for small grained SiC. See ref.1 for technical basis for U.S. specifications. | Rationale: The conditions under which "good" SiC is made in a CVD coater is fairly well understood. The proper combination of temperature and $H_2$/MTS ratio in the coater is required. German fuel was fabricated using the proper coating parameters. In the U.S., a wide range of coating parameters was used resulting in different microstructures. (see ref. 2) Future U.S. fabrication will adopt the German grain size and microstructure as its goal. (see ref. 3) | Closure Criterion: |

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

1. NP-MHTGR Fuel Product Specification Basis Report, CEGA-000396, June 1992.
2. Petti, D.A. et al., "Key Differences in the Fabrication, Irradiation, and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance," INEEL/EXT-02-00300, June 2002.
3. Technical Program Plan for the Advanced Gas Reactor Fuel Development and Qualification Program, ORNL/TM-2002/262, Nov. 2002.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | SiC layer<br>Fracture strength | Mean tensile strength (Weibull parameter or equivalent) |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 6 | Remedy: |
| Rationale: High fracture strength is a highly desired attribute for the SiC layer to ensure the TRISO coating can maintain structural integrity and retain the fission gases and CO (UO2 only) produced during irradiation. This can be measured in a number of different ways and since the strength for a brittle ceramic like SiC is a function of the number of flaws in the volume that is tested the data on the fracture strength of SiC tends to be quite variable. German measurements suggest that irradiation reduces the strength somewhat. High fracture strength is also related to the SiC density and temperature used in the coater. The technical basis for coating parameters needed to produce high fracture strength is found in ref. 1. | Rationale: There is some variability in the measured strengths of SiC made by the Germans, U.S., Japanese etc. Also different test techniques have been used as well where different volumes of materials (and hence volumes of flaws) are stressed in the test. Examples of the strength data are found in ref. 2. Different methods are discussed in Section 3 and results from a specific method, which found a number of weak SiC particles are found in reference 4. Different strengths in the tails of the distributions were found in ref. 4 to be attributed to iron impurities, gold spots (silicon and carbon soot) in U.S. fuel. German fuel coated in a large coater did not exhibit these weak tails. Strength measurements are not specified in the fuel specification. | Closure Criterion: |

**Additional Discussion**

1. NP-MHTGR Fuel Product Specification Basis Report, CEGA-000396, June 1992.
2. Petti, D.A. et al., "Development of Improved Models and Design for Coated Particle Gas Reactor Fuels," 2002 Annual Report, INEEL/EXT-02-01493, Nov. 2002.
3. Bourrat, X.,"Pyrocarbon and SiC in HTR Fuel Particles," Lecture at Eurocourse on HTR Technology, Cadarache France, Nov. 2002.
4. Lessing, P. and R. J. Heaps, "Strength of Silicon Carbide Layers of Fuel Particles for High-Temperature Gas-Cooled Reactors," Nuclear Technology, Vol. 108, Nov. 1994.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | SiC layer | Mass per unit volume |
| | Density | |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 8 | Remedy: |
| Rationale: High density SiC contributes to its strength and good fission product retentiveness. The temperature used during coating is critical to achieving the proper density. Low-density coatings are obtained below 1450 and above 1700°C. Details of the technical basis are found in ref. 1. | Rationale: Density is easily measured and is found to be within tolerances of the specification. The specifications and actual measured values are found in refs. 2 and 3. | Closure Criterion: |

**Additional Discussion**


1. NP-MHTGR Fuel Product Specification Basis Report, CEGA-000396, June 1992.
2. Petti, D.A. et al., "Key Differences in the Fabrication, Irradiation, and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance," INEEL/EXT-02-00300, June 2002.
3. Bryan, M.F., 1992, *Evaluation of NP-MHTGR Performance Test Fuel Quality Control Data*, INEEL. Report EGG-NPR-10130.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | SiC layer | Interfacial strength at the interface |
| | Bonding strength (SiC to outer PyC) | |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: L | Level: 6 | Remedy: |
| Rationale: The actual bond strength between the SiC and OPyC is unknown. However, its impact on fuel failure and fission product release is judged to be small. Historically when the U.S. had trouble with the OPyC failing under irradiation due to matrix intrusion, photomicrographs indicated that the OPyC "peeled away" form the SiC fairly cleanly. (see ref. 1)There was no crack propagation from the OPyC to the SiC that would threaten SiC integrity and hence fission product release. Similarly, in the NP-MHTGR irradiations in which all of the OPyC failed, the cracking in the SiC was never attributed to debonding at the SiC/OPyC interface. (see ref. 2). Finite element calculations suggest that cracking and debonding of the OPyC layer does not give rise to significant stress concentrations in the SiC layer. | Rationale: Measurements of the bond strength for U.S. and German fuel are quite different. German fuel appears well bonded whereas U.S. fuel does not. (see ref. 3). Bond strength between the OPyC and SiC is not well known but does not appear to have a major impact on SiC integrity and fission product release. | Closure Criterion: |

**Additional Discussion**


1. Petti, D.A. et al., "Key Differences in the Fabrication, Irradiation, and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance," INEEL/EXT-02-00300, June 2002.
2. Maki, J.T. et al., "NP-MHTR Fuel Development Program Results," INEEL/EXT-2002-1268, October 2002.
3. Saurwein, J., and L. Shilling, September 1993, *Final Report – Testing of As-manufactured NPR-PTF, German, and U.S. Historical Fuel*, General Atomics, Issue/Release Summary, Doc. No. 910647 N/C.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | SiC layer<br>Stoichiometry | Ratio of silicon to carbon (absence of gold spots, i.e., elemental Si) |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 6 | Remedy: |
| Rationale: Stoichiometry of the SiC is very important. The basis for the stoichiometry is found in ref 1. Under some coating conditions carbon and silicon soot can form and deposit during coating leading to "gold spots". These gold spots appear as circumferential lenticular flaws in the SiC layer and have been implicated as a reason for weak SiC in the tails of some batches of fuel particles (see ref. 2). | Rationale: When and why gold spots appear in some batches of coated particle fuel is not fully understood. Some feel that gold spots are more apt to form in small lab scale coaters, given their absence in large German coaters. Japanese researcher found that low-density circumferential SiC flaws were attributed to excess fluidization of the particles that hit the walls of their coater and picked up carbon soot. See refs. 2 and 3. | Closure Criterion: |

**Additional Discussion**


1. NP-MHTGR Fuel Product Specification Basis Report, CEGA-000396, June 1992.
2. Lessing, P. and R. J. Heaps, "Strength of Silicon Carbide Layers of Fuel Particles for High-Temperature Gas-Cooled Reactors," Nuclear Technology, Vol. 108, Nov. 1994.
3. Minato, K., et al., 1994, "Internal Flaws in The Silicon Carbide Coating of Fuel Particles for High-Temperature Gas-Cooled Reactors," *Nuclear Technology*, Vol. 106, pp. 342-349.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | SiC layer<br>Heavy metal dispersion | Amount of heavy metals dispersed in the layer present after manufacture |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: M | Level: 7 | Remedy: |
| Rationale: Heavy metal is dispersed in the SiC layer when too porous or too thin an IPyC layer is produced and the Cl produced from decomposition of the MTS attacks the kernel and uranium chloride is transported out of the kernel and is trapped in the SiC layer during the coating process. Density and thickness specifications limit the amount of heavy metal dispersion. This was once a problem in older U.S. fuel but is no longer considered a problem. Thus, its impact on fission product release is ranked low. | Rationale: Limits have been established and are met in manufacturing (see refs. 1 and 2). | Closure Criterion: |

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


1. NP-MHTGR Fuel Product Specification Basis Report, CEGA-000396, June 1992.
2. Bryan, M.F., 1992, *Evaluation of NP-MHTGR Performance Test Fuel Quality Control Data*, INEEL. Report EGG-NPR-10130.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | SiC layer<br>Defects | Initial undetected pinhole or other defects resulting from the manufacturing process |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 5 | Remedy: More work on characterization of material from the manufacturing line is needed. |
| Rationale: Defects such as porosity, flaws, gold spots, etc. have been of concern for many years in the gas reactor fuel community. Such defects can lead to premature particle failure and fission product release. The initial defect level as measured by exposed kernels is controlled during manufacture (see ref. 1). The "latent" flaws that were undetected during fabrication and could give rise to failure under normal or off-normal conditions are still not known with adequate certainty. | Rationale: The level of such flaws has varied depending on the fuel batch. The most complete comparison to date is given in ref. 2. The results suggest that small levels of flaws were observed in different coated particle fuel batches. The impact of the defects on fuel performance is not well known but may be important especially in light of the low failure rate specifications for this fuel. In many cases, it is not completely understood as to what gives rise to these defects in the coating process, however there is some empirical evidence. | Closure Criterion: |

**Additional Discussion**

1. NP-MHTGR Fuel Product Specification Basis Report, CEGA-000396, June 1992.
2. Saurwein, J., and L. Shilling, September 1993, *Final Report – Testing of As-manufactured NPR-PTF, German, and U.S. Historical Fuel*, General Atomics, Issue/Release Summary, Doc. No. 910647 N/C.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Inner PyC layer<br>Anisotropy (initial) | Difference in crystal orientation along principal directions as measured by the BAF |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 5 | Remedy: |
| Rationale: High degrees of anisotropy in the IPyC layer can lead to excessive shrinkage under irradiation. This will put the IPyC into tension and could fail the layer. The cracks in the IPyC layer can propagate into the SiC layer and cause failure as was found in the NP-MHTGR program (see refs. 1, 2, 3, 4). Controls are placed on coating conditions (gas concentration and temperature to give proper coating rate) to ensure low anisotropy in the layer. The old specification basis for U.S. fuel is clearly flawed in this area (ref. 5) and new specifications were developed (ref. 6). This is the most common failure mechanism in U.S. fuel in the past. | Rationale: The conditions needed to make isotropic PyC are well known (see refs. 2 and 7). A key uncertainty however is the measurement of anisotropy. Some false positives were obtained in U.S. fuel in the past and better methods are needed and planned in future U.S. efforts (ref. 8). It is important to note that this behavior has not been observed in German fuel. | Closure Criterion: |

**Additional Discussion**


1. Petti, D.A. et al., "Key Differences in the Fabrication, Irradiation, and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance," INEEL/EXT-02-00300, June 2002.
2. Maki, J.T. et al., "NP-MHTR Fuel Development Program Results," INEEL/EXT-2002-1268, October 2002.
3. Leikind, B.J et al., 1993, *MHTGR TRISO-P Fuel Failure Evaluation Report*, DOE-HTGR-903990.
4. Miller, G.K., et al., 2001, "Consideration of the Effects on Fuel Particle Behavior from Shrinkage Cracks in the Inner Pyrocarbon Layer," *Journal of Nuclear Materials*, Vol. 295, pp. 205-212.
5. NP-MHTGR Fuel Product Specification Basis Report, CEGA-000396, June 1992.
6. Besenbruch, G., 1993, "Improvements and Changes for Coating System," *FCT Meeting, Oak Ridge, Tennessee, September 1.*
7. Martin, D.G., April 2000, *Pyrocarbon in High Temperature Nuclear Reactor in Irradiation Damage in Graphite due to Fast Neutrons in Fission and Fusion Systems*, Report IAEA-TECDOC-1154.
8. Technical Program Plan for the Advanced Gas Reactor Fuel Development and Qualification Program, ORNL/TM-2002/262, Nov. 2002.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Inner PyC layer<br>Bonding strength (inner PyC to SiC) | Interfacial strength at the interface |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 6 | Remedy: Data forthcoming from DOE NERI and more modeling funded under DOE INERI should address this issue. |
| Rationale: The nature of the bond between the SiC and IPyC in German fuel is different than in U.S. fuel. German fuel rarely debonds, whereas in U.S. fuel debonding occurs fairly frequently but other times it does not. The difference in the bonding is a function of differences in the fabrication process (see refs. 1 and 2.) Finite element calculations suggest that debonding of the IPyC can lead to stress concentrations in the SiC that can lead to failure of that layer. (see ref. 3) | Rationale: Sensitivity calculations using finite element modeling suggest that the actual bond strength is a key parameter to model the structural behavior of the particle (see ref. 3). New measurements of the bond strength will be performed under recently funded DOE NERI funds. (see ref. 4). There are no specifications on this interface either its nature or strength | Closure Criterion: |

**Additional Discussion**


1. Petti, D.A. et al., "Key Differences in the Fabrication, Irradiation, and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance," INEEL/EXT-02-00300, June 2002.
2. Saurwein, J., and L. Shilling, September 1993, *Final Report – Testing of As-manufactured NPR-PTF, German, and U.S. Historical Fuel*, General Atomics, Issue/Release Summary, Doc. No. 910647 N/C.
3. Petti, D.A. et al., "Development of Improved Models and Design for Coated Particle Gas Reactor Fuels," 2002 Annual Report, INEEL/EXT-02-01493, Nov. 2002.
4. Snead, L.L. and D. A. Petti, "Improving the Integrity of Coated Particle Fuels: Measurements of Constituent Properties of SiC and ZrC, Effects of Irradiation and Modeling," NERI Proposal, April 2002.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Inner PyC layer<br>Porosity | Interconnected void accessible to the surface |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: M | Level: 5 | Remedy: |
| Rationale: The IPyC density is fairly high density in coated particle fuel (~ 1.85 to 1.9 g/cc). It is unclear how much of the porosity in the layer is interconnected. There is some indication of surface porosity as indicated by photomicrographs of the SiC/IPyC interface in U.S. fuel (see refs. 1 and 2). The fact that noble gases do not readily transport through the layer is an indication that there is not significant interconnected porosity in the layer. Very high coating rates can lead to unacceptable interconnected porosity. Some details are found in ref. 1. | Rationale: I am unaware of any measurements of the exact values of porosity as measured for instance by BET for either U.S. or German IPyC. | Closure Criterion: |

**Additional Discussion**

1. Petti, D.A. et al., "Key Differences in the Fabrication, Irradiation, and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance," INEEL/EXT-02-00300, June 2002.
2. Saurwein, J., and L. Shilling, September 1993, *Final Report – Testing of As-manufactured NPR-PTF, German, and U.S. Historical Fuel*, General Atomics, Issue/Release Summary, Doc. No. 910647 N/C.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Buffer Layer | Layer thickness less than specified or missing layer |
| | Thin or missing | |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 7 | Remedy: |
| Rationale: A thin bugger means less void volume to accommodate fission gases and Co, thus increasing the internal pressure in the particle and the probability of failure. | Rationale: This is measured routinely. High standard deviations are seen in the thickness because of the very high coating rates associated with putting down the buffer. | Closure Criterion: |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Buffer Layer<br>Density and open porosity | Mass per unit volume and interconnected void accessible to the surface |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: M | Level: 8 | Remedy: |
| Rationale: The open porosity in the buffer accommodates fission gas and CO (for UO2 only) produced during irradiation. | Rationale: Values of the total porosity are easily deduced from density measurements made in fuel. The traditional assumption used in fission gas release modeling is to assume that all of the porosity is open at the beginning of life. Others have assumed that only half of the porosity is open and the other half becomes accessible to the surface as a result of the densification of the buffer fairly early in life (probably at a fluence of $10^{21}$ nvt). This is based on discussions with Germans and UK modelers but I have no reference per se. | Closure Criterion: |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Kernel<br>Density | Mass per unit volume in final form |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: M | Level: 9 | Remedy: |
| Rationale: Density of the kernel can affect fission gas release from the kernel. Very low-density kernels tested in the U.S. (so called war kernels) showed very poor behavior and poor fission product retentiveness. High densities (>95% of theoretical) are typically produced for either the oxide or oxycarbide | Rationale: Easily measured during fabrication and found to be in spec. See refs. 1, 2 and three for technical basis and actual production values. | Closure Criterion: |

**Additional Discussion**

1. Petti, D.A. et al., "Key Differences in the Fabrication, Irradiation, and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance," INEEL/EXT-02-00300, June 2002.

2. NP-MHTGR Fuel Product Specification Basis Report, CEGA-000396, June 1992.

3 Bryan, M.F., 1992, *Evaluation of NP-MHTGR Performance Test Fuel Quality Control Data*, INEEL. Report EGG-NPR-10130.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
| --- | --- | --- |
| Manufacturing | Kernel<br>Microstructure ($UO_2$) | Grain size, pore structure (interconnectivity) and orientation in kernel |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
| --- | --- | --- |
| Rank: M | Level: 8 | Remedy: |
| Rationale: $UO_2$ particles are manufactured using the solgel process. The detailed microstructure has been characterized. | Rationale: The grain size is generally between 5 and 10 microns. The porosity tends to change as a function of burnup as fission gases migrate to the grain boundary and develop interconnected porosity there. Fission gas release data during normal operation exist and most results are correlated using an equivalent Booth model (see ref. 1) where the details of the changes in microstructure are to a first order ignored and accounted for in an effective diffusivity. | Closure Criterion: |

**Additional Discussion**

1. IAEA, November 1997, *Fuel Performance and Fission Product Behaviour in Gas Cooled Reactors*, IAEA-TECDOC-978.

**Appendix A.2**

**Detailed PIRT Submittal by the ORNL Panel Member**

**R. Morris**

## TRISO Fuel PIRT: Manufacturing

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing<br><br>Process Variables (Current process; process may change) | Layer coating process specifications (Buffer, IpyC, SiC, OpyC)<br><br>Gases (levitation gas and coating gas) | Gases used to levitate and coat to create layer |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 8 | Remedy: None at present but continue to review the state of the art. |
| Rationale: The gas used in the coater directly influences the quality of the coatings and the operation of the coater. This issue may be less important if a product specification if developed, rather than the current process specification. | Rationale: A considerable amount of work has been done in this area and the best gases to use are well known. The issue appears to the coating rate and subsequent material properties. | Closure Criterion: Monitor for a consistent and reproducible product. |

**Additional Discussion**

Much work has been done in this area. A good start is:

*Nuclear Technology*, Volume 35, Number 2, 1977 (entire issue is devoted to coated particle fuels).

The impact of coating parameters on fuel performance was recently evaluated in:

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

A useful reference covering a wide range of coatings, but somewhat dated (especially on fission product release) is:

*Coated-Particle Fuels*, T.G. Godfrey, et. al., ORNL-4324, 1968

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing<br><br>Process Variables (Current process; process may change) | Layer coating process specifications (Buffer, IpyC, SiC, OpyC)<br>Ratio of gases | Ratio of active gas to total gas, including concentration |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 7 | Remedy: Investigate layer characterization methods to provide a strong link between measurable properties and irradiation performance. |
| Rationale: The gas mixtures affect the coating properties and the production rate. | Rationale: Much work has been done on this subject, but there are still concerns about the pyrocarbon layer and how to insure good irradiation properties. At present, the best way appears to be to follow the German coating formula. | Closure Criterion: A reliable understanding between measurable coating properties and irradiation performance or at least a well-specified process. |

**Additional Discussion**
See the previous references for general behavior; for information discussing the pyrocarbon situation see:

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

,

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

Methods for characterizing the pyrocarbon structure are a high priority of the current US HTGR program.

Also, there may be some proprietary information that closes some of the gaps in the open literature.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing<br><br>Process Variables (Current process; process may change) | Layer coating process specifications (Buffer, IpyC, SiC, OpyC)<br>Temperature | Temperature of coater |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 7 | Remedy: None, once the desired temperature has been determined for a specific apparatus. |
| Rationale: The deposition temperature of the coater helps determine the properties of the coatings. | Rationale: Temperature has been investigated to a large extent. While the exact temperature may be different for a specific coater, this parameter is not difficult to control. | Closure Criterion: None at present. |

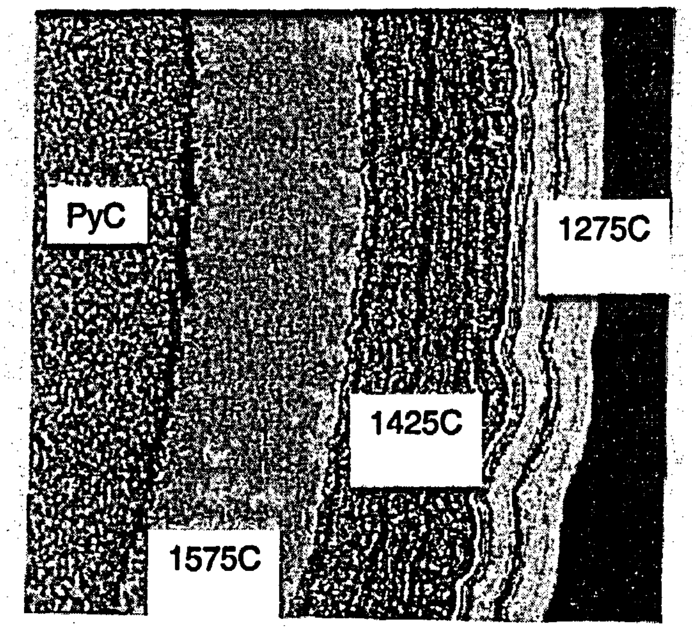
**Additional Discussion**

Considerable work has been done in this area. For a start see:

*Nuclear Technology*, Volume 35, Number 2, 1977 (entire issue is devoted to coated particle fuels).

*Coated-Particle Fuels*, T.G. Godfrey, et. al., ORNL-4324, 1968 (see coater and pyrocarbon sections, fission product release section is dated)

*Fluidized Bed Deposition and Evaluation of Silicon Carbide Coating on Microspheres*, J.I. Federer, ORNL/TM-5152




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

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing<br><br>Process Variables (Current process; process may change) | Layer coating process specifications (Buffer, IpyC, SiC, OpyC)<br>Coating Rate | The average deposition rate over space and time of the layer |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 6 | Remedy: Investigate layer characterization versus irradiation behavior. |
| Rationale: The deposition rate can strongly influence the coating behavior under irradiation. | Rationale: Especially in the case of pyrocarbon, a comprehensive understanding of coater operation and irradiation performance is not in hand. A practical formula for coater operation exists (German method), but deviations from this formula lead to poor results in some cases. | Closure Criterion: A strong link between coater operation and/or layer characterization and irradiation performance. |

**Additional Discussion**

Much work has been done in this area. A good start is:

*Nuclear Technology*, Volume 35, Number 2, 1977 (entire issue is devoted to coated particle fuels).

*Coated-Particle Fuels*, T.G. Godfrey, et. al., ORNL-4324, 1968 (see coater and pyrocarbon sections, fission product release section is dated)

*Fluidized Bed Deposition and Evaluation of Silicon Carbide Coating on Microspheres*, J.I. Federer, ORNL/TM-5152

This issue has also received international examination as well.

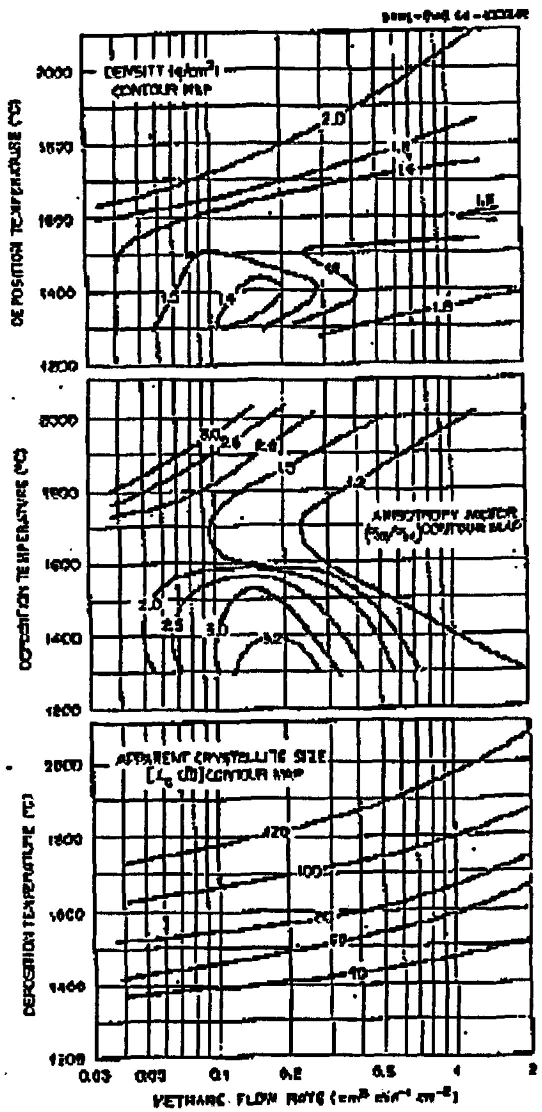
The impact of coating parameters on fuel performance was recently evaluated in:

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

.

Since this is an area of active research, consult the investigators for the latest thinking on the subject.

Difference gas flow rates and temperatures affect the properties of the pyrocarbon. (From ORNL-4324). See the references for details of coater operation.



| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing<br><br>Process Variables (Current process; process may change) | Layer coating process specifications (Buffer, IpyC, SiC, OpyC)<br>Pressure | Pressure inside coater |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: L | Level: 4 | Remedy: Document the operation of contemporary coaters to prove that their performance is reliable and predictable. |
| Rationale: Coaters are operated at relatively low pressure, usually near atmospheric pressure. | Rationale: Only modest pressures are used in the coater. A more important concern is the pressure variations during the coating process and how they might be controlled to prevent "chugging" and disruptions of the particle bed. More modern control equipment may be sufficient to control this problem. | Closure Criterion: Reliable coater operation. |

**Additional Discussion**

A reasonable approach would be to consult researchers operating contemporary coaters with modern control equipment. The coaters are generally operated near atmospheric pressure so there is not much information on operation at higher or lower pressures. There appears to be no compelling reason to operate a coater at higher or lower pressures. Safety issues would dictate operation near atmospheric pressure.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing<br><br>Process Variables (Current process; process may change) | Layer coating process specifications (Buffer, IpyC, SiC, OpyC)<br>Coater Size | Size is measured by the diameter of the coater |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 6 | Remedy: Critically assess the transition from small lab coaters to larger production coaters. |
| Rationale: It has been noted that going from one sized coater to another may not be straightforward. Since both process and product specifications are critical, the scaling is important. | Rationale: Large amounts of fuel have been made in production coaters without problems. Smaller coaters have been used for development work. The transition from small to large coaters may not be transparent, but no insurmountable problems have been encountered. | Closure Criterion: Proof of satisfactory performance. |

**Additional Discussion**

This scaling issue will be examined as the US program re-establishes its coated particle fuel capability. Data exists for the German production coaters.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing<br><br>Process Variables (Current process; process may change) | Layer coating process | Continuous vapor deposition (CVD) TRISO coating without unloading of particles |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 4 | Remedy: Either select one process or the other and stick with it or investigate the binding behavior between layers if a processing option is really necessary. |
| Rationale: All the layers may be put on a particle in a single coater run or the coater may be unloaded between runs. A continuous process may result in different bonding forces between coating layers. | Rationale: The successful German process employed a continuous process while the US process emptied the coater between runs for inspection purposes. This issue has not been examined in great detail and some speculation exists as to the best approach. | Closure Criterion: Selection of a processing method or proof than it doesn't matter. |

**Additional Discussion**

When comparing the relative performance between US and German fuels, this issue came under more critical study. This issue is discussed in:

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

The best fuel has been made with the continuous coating process and current speculation is that bonding between the layers is important. Interrupted coating may not result in as good a bonding between layers.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Process Control | Correlation between measured process parameters and irradiation performance |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 6 | Remedy: Search for a connection between the irradiation performance and the measured process parameters; Ideally one would like to connect measured properties with performance. |
| Rationale: The way the fuel is made appears to strongly influence its behavior, even it the measured parameters are within acceptable limits. | Rationale: Fuel made using the German process has performed well. Fuel made with another process has not performed as well, even though the measured properties were acceptable. The current design is empirical and a theoretical approach is desired. | Closure Criterion: Acceptable correlations |

**Additional Discussion**

The German process has resulted in a fuel that performs well; however, this fuel is a "point" design and modifying this fuel to operate under different conditions may not be easy since the understanding is limited. It is desired to understand what properties make a fuel perform well so that a general design method can be developed. In addition, this information would help with fuel QC and licensing. See:

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

A major factor appears to be the nature of the pyrocarbons, which have been best specified by process and product specifications.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Product Control | Correlation between measured product parameters and irradiation performance |
| | | |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 5 | Remedy: Investigate material properties as they effect irradiation performance. |
| Rationale: The measured parameters do not appears to be sufficient to predict fuel behavior. | Rationale: It is desired to have measurable material properties that predict fuel performance so one can better design the fuel and avoid depending on process knowledge. | Closure Criterion: A correlation between measured properties and fuel performance. |

**Additional Discussion**

Presently measured material properties do not appear to connect well with fuel performance. It desired to determine which material properties are important and to measure them, both for QA purposes and to better model the fuel. In particular, pyrocarbon performance is important. See:

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

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*An Assessment of the Methods for Determining Defect or Failure Fractions in HTGR Coated Particle Fuels and Their Relationship to Particle Microstructure*, DOE-HTGR-88260, 1989

*Influence Of Material Properties On The Retention Of Fission Products By Silicon Carbide Coatings*, R. Forthmann, et. al.. High Temperature – High Pressure, 1982, 14, pages 477-485.

This is currently an area of active research.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Fuel element | Layer on outside of outer PyC added after coating |
| | Particle overcoating (fuel form dependent) | |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 7 | Remedy: None for the German process. However, if overcoating is applied to compact type fuel elements, testing is warranted. |
| Rationale: This layer helps protect the particle during fuel element fabrication by slightly deforming, provides a spacing function, and integrates the particle into the matrix material. | Rationale: The Germans have developed an overcoating process that works very well for their pebbles. Also, other international efforts have achieved good results. US attempts to overcoat particles did not fair well. | Closure Criterion: None for the German process, but irradiation testing would be required for other fuel element types. |

**Additional Discussion**

The particle overcoating process is really a part of the admix process for making fuel elements. It has been tried in conjunction with the US injection process, but fatal design problems lead to irradiation failure. Other international programs have had success. High particle packing fractions favor the injection process.

For overcoating and fuel element fabrication see:

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

For a description of the US problems that arose from an overcoating process see:

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

It is likely that the overcoating process will not be used for injection-molded fuel (compacts). Improvements in the injection process promise to resolve the historical difficulties.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Fuel element<br>Matrix and Binder | Filler mixed with resin |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 7 | Remedy: None if the current successful process (German) and materials are used. If changes are made, testing is warranted. |
| Rationale: The resin and binder are used to combine the fuel particles into a fuel element. Complexities arise because particles may be broken or damaged during the process and the matrix material may shrink during irradiation and damage fuel particles if it binds too strongly to the particle. | Rationale: Considerable work has been done in this area and workable formulas have been found for pebbles (Germans). However, the US may change their resin from thermoplastic to thermosetting and additional irradiation testing may be required. | Closure Criterion: Proof that the fuel element fabrication process performs as expected. |

**Additional Discussion**

For a good general description of HTGR fuel element fabrication see:

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

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Fuel element | Interfacial strength at the interface |
| | Bonding strength (PyC to matrix) | |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: M | Level: 7 | Remedy: None if the current successful (German) process and materials are used. If changes are made, testing is warranted. |
| Rationale: If the bonding strength of the matrix to the fuel particle is too high, the outer pyrocarbon may be peeled away as the matrix undergoes irradiation-induced shrinkage. | Rationale: Considerable testing has been done in this area and useable formulas are available (pebbles). However, the US program may investigate alternative resins. See previous entry. | Closure Criterion: Proof that the fuel element fabrication process performs as expected. |

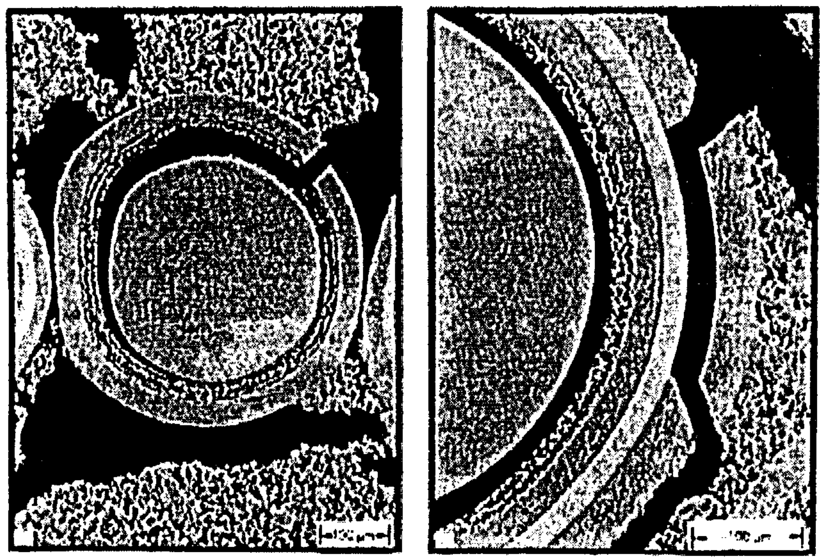
**Additional Discussion**

Again see:

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

for a discussion of these issues.

Shrinkage of matrix pulls OpyC away from BISO particle.



| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Fuel element<br>Compacting | Process of forming fuel element involving molding and pressing |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 7 | Remedy: None if the current German process and materials are used. If changes are made, testing is warranted. |
| Rationale: Forming the fuel element is critical to the final product. Many factors are present at this stage. Particles can be broken, later irradiation damage can result in matrix and particle damage, and process conditions can damage particles by force or impurities. | Rationale: This process has been investigated to a considerable extent and a large amount of high quality product has been produced through the world. However, changes could be underway for the US product so additional testing may be necessary. The US needs to integrate all the lessons learned to date. Despite past lackluster performance, the US learned a lot in the early 90's. | Closure Criterion: Proof that the fuel element fabrication process performs as expected. |

**Additional Discussion**

Again see:

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

for a discussion of these issues.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Fuel element<br>Carbonization | Baking full fuel element to drive off volatiles |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: M | Level: 7 | Remedy: None if the current process and materials are used. If changes are made, testing is warranted. |
| Rationale: Carbonization is the process of driving off the volatiles and converting the resin to char. This is the first step in processing the green fuel form and prepares the fuel element for high firing. | Rationale: Considerable work has been done in this area and processing methods are available. Changes in the process would demand that further testing be conducted to prove that they introduced no problems. | Closure Criterion: Proof that the fuel element fabrication process performs as expected. |

**Additional Discussion**

The fuel element baking coverts the resin to a carbon char; if a thermoplastic resin is used for element fabrication the element must be supported during this process to avoid slumping. Use of HCl gas to remove metallics may be part of an after treatment. Mishandling and the introduction of impurities is the primary concern at this stage.

Again see:

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

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Fuel element<br>Heat treatment | High temperature annealing to stabilize fuel form |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: M | Level: 7 | Remedy: None if the current process and materials are used. If changes are made, testing is warranted. |
| Rationale: The high firing process completes the carbonization, improves the crystallinity of the matrix, and degases the element. | Rationale: Considerable development and production work has been conducted in this area over the years and it is not expected to harbor any surprises. | Closure Criterion: Proof that the fuel element fabrication process performs as expected. |

**Additional Discussion**

The second half of the element fabrication process is the actual baking of the element at up to 1950C for an hour or two. Even though this temperature is near the decomposition temperature of SiC, no ill effects have been noted. During this baking it is very important to avoid the introduction of impurities as they can tunnel into the SiC and damage it. See *Fuel Compact Design Basis Report*, DOE-GT-MHR-100212, 1994, for a review of the element fabrication process.

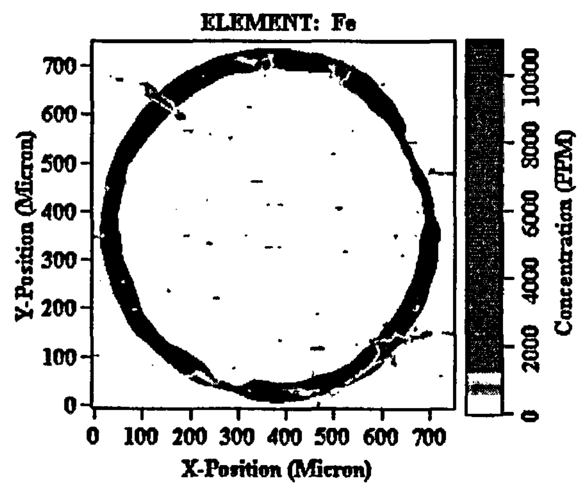
| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Fuel element | Minimization of contamination of fuel form by process equipment (e.g., iron, chrome, etc) |
| | Impurities control | |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 7 | Remedy: Nothing at present. |
| Rationale: Impurities can come from graphite, resins, handling equipment, and furnaces. These particular impurities can damage the SiC. In theory they could also act as a catalysis for graphite oxidation, but the amounts are extremely small. | Rationale: During the 1990's the affects of impurities introduced into the fuel element fabrication process was studied and the source of past problems identified. Processing options have been identified. | Closure Criterion: Monitor the situation for acceptable fuel performance. |

**Additional Discussion**

See *Fuel Compact Design Basis Report*, DOE-GT-MHR-100212, 1994, for a review of the element fabrication process and some of the particular historical problems identified. Impurities should be controlled at the source, but HCl leaching can be effective to preventing them from entering the high firing stage.

A high resolution X-Ray scan of a SiC layer showing iron impurities that have "wormed" their way into the layer. (M. Naghedolfeizi, et. al., Journal of Nuclear Materials. 312 (2003) 146-155)



| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Fuel element | Uranium introduced by raw materials, e.g., resin |
| | Tramp Uranium | |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 8 | Remedy: None |
| Rationale: Tramp uranium releases fission products in the reactor system. Since the acceptable fuel releases are so small, this material can add significantly to the released fission product fraction. | Rationale: Uranium contamination can be measured with standard techniques, so nothing new is foreseen. | Closure Criterion: None |

**Additional Discussion**

The issue surrounding this factor is the procurement of clean resins and graphites.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Fuel element<br>Strength | An overall measure of fuel element resistance to stresses that might occur during operation or accidents. |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 8 | Remedy: None |
| Rationale: At the very least, the fuel element must be able to withstand the handling forces and any thermal stresses; in the case of a pebble, it must withstand being dropped several meters. | Rationale: In the case of pebbles, a considerable amount of work to develop a high integrity element. Many years of operation have shown good results. | Closure Criterion: None |

**Additional Discussion**

See *Fuel Compact Design Basis Report*, DOE-GT-MHR-100212, 1994, for a review of the element fabrication process and some of the strength issues.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
| --- | --- | --- |
| Manufacturing | Fuel element | Exposed kernel fraction |
| | Initial particle defect fraction due to manufacture | |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
| --- | --- | --- |
| Rank: H | Level: 7 | Remedy: Monitor fuel element fabrication. |
| Rationale: Exposed kernels release fission products into the reactor system and are drivers for accident releases. | Rationale: The exposed kernel fraction can be reasonably identified by burn-leach methods as were used by the Germans for their fuel. HCl leaching prior to high firing can greatly reduce the exposed uranium fraction. | Closure Criterion: Monitor initial irradiation results to verify that product QA results are mirrored in R/B measurements. |

**Additional Discussion**

Two methods are convenient for examining the exposed kernel fraction. The first and cheapest is the burn-leach method that removes the matrix and OpyC from the fuel particles by burning and then leaches out the uranium by boiling them in nitric acid. Analysis of the leachant allows one to determine the uranium concentration and estimate the number of exposed kernels. The second method is to place the fuel elements in a small furnace and place this furnace in a neutron flux, say, from a TRIGA reactor. By measuring the R/B from the fuel element at particular temperatures, one can back calculate the exposed kernels.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Outer PyC layer<br>Anisotropy (initial) | Difference in grain orientation along principal directions as measured by the BAF |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 5 | Remedy: Perform PyC measurements with different techniques to determine the best way to characterize pyrocarbon. |
| Rationale: The initial anisotropy of the OpyC is important as it determines how the material will shrink as a function of fast flux. This shrinking imposes stresses on the layer and excessive stress will break the layer and threaten the structural integrity of the particle. | Rationale: The BAF of the layer can be measured, but practical results do not correlate well with irradiation behavior. In fact, it is not clear how to best approach this problem. The Germans have a process specification that address this issue, but the usefulness of the BAF measurement is in doubt. | Closure Criterion: A specification or fabrication process that leads to predictable behavior. The NRC may have to decide if it is comfortable with a process rather than product specification. |

**Additional Discussion**

As a general rule the BAF is related to coating rate, so by controlling the coating rate one can control the BAF. Other properties such as porosity are related however, so a compromise may be necessary. The lack of a hardcore standard for evaluating the affects of fast flux has resulted in problems.

Failure of the OPyC is much less problematic than the IPyC, but the failure can increase the likelihood of particle failure. The main issue is finding a measure of the material properties that connects well with irradiation performance. This is an area of current research.

For an overview of pyrocarbon see:

*Nuclear Technology*, Volume 35, Number 2, 1977 (entire issue is devoted to coated particle fuels).

*TRISO Fuel Particle Coating Design Basis*, DOE-GT-MHR-100225, 1994

The impact of coating parameters on fuel performance was recently evaluated in:

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

A useful reference covering a wide range of coatings, but somewhat dated (especially on fission product release) is:

*Coated-Particle Fuels*, T.G. Godfrey, et. al., ORNL-4324, 1968

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Outer PyC layer<br>Porosity | Interconnected void accessible to the surface |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: M | Level: 7 | Remedy: None |
| Rationale: The porosity of the OPyC controls how well the matrix binder attaches itself to the OPyC. Too strong an attachment can damage the OPyC as the matrix material shrinks. Porosity can also affect fission product transport. | Rationale: The porosity of the coating can be measured and there is a considerable amount of experience in fabricating high quality fuel elements. | Closure Criterion: None |

**Additional Discussion**

Again see:

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

*TRISO Fuel Particle Coating Design Basis*, DOE-GT-MHR-100225, 1994

for a discussion of this issue.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | SiC layer<br>Grain size and microstructure, e,g, alignment | Size and orientation of the grains and the pores |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 6 | Remedy: Investigate SiC properties to better connect SiC microstructure with irradiation performance. |
| Rationale: The microstructure of the SiC determines the material strength and its diffusion barrier properties. | Rationale: High quality SiC has been produced under the German program, but there is some uncertainty as to the quality of the US product. | Closure Criterion: A correlation between SiC microstructure and irradiation performance. |

**Additional Discussion**

Considerable work has been done in this area. For a start see:

*Nuclear Technology*, Volume 35, Number 2, 1977 (entire issue is devoted to coated particle fuels).

*Fluidized Bed Deposition and Evaluation of Silicon Carbide Coating on Microspheres*, J.I. Federer, ORNL/TM-5152

*TRISO Fuel Particle Coating Design Basis*, DOE-GT-MHR-100225, 1994

*Data Support Document: Operating Procedures for SiC Defect Detection*, DOE-HTGR-88359, 1991

*An Assessment of the Methods for Determining Defect or Failure Fractions in HTGR Coated Particle Fuels and Their Relationship to Particle Microstructure*, DOE-HTGR-88260, 1989

However, a strong connection between measured SiC properties and fuel performance is lacking:

*Influence Of Material Properties On The Retention Of Fission Products By Silicon Carbide Coatings*, R. Forthmann, et. al.. High Temperature – High Pressure, 1982, 14, pages 477-485.

For an evaluation of past US fuel behavior see:

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

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

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | SiC layer<br>Fracture strength | Mean tensile strength (Weibull parameter or equivalent) |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 6 | Remedy: Demonstrate that high quality SiC can be made and irradiated. Given the present knowledge, this should be forthcoming. |
| Rationale: The strength of a layer determines the integrity of the particles. The tails of the distribution determine the number of particles with marginal strength. | Rationale: A fair amount is known about SiC and the desirable properties. The Germans have a successful process, but some details are not well understood. Much strength testing has been done, so properties are known – connecting to irradiation performance is the issue. | Closure Criterion: A well-characterized SiC specification with good irradiation and accident performance. |

**Additional Discussion**

Attempts to correlate SiC properties with fission product behavior have not been completely successful. German attempts are summarized in:

*Silicon Carbide Coatings of Nuclear Fuel Particles – A Characterization Study*, KFA document Jul-1871, September 1983

*Influence Of Material Properties On The Retention Of Fission Products By Silicon Carbide Coatings*, R. Forthmann, et. al. High Temperature – High Pressure, 1982, 14, pages 477-485.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | SiC layer | Mass per unit volume |
| | Density | |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 8 | Remedy: None |
| Rationale: The density of the material is related to its properties. | Rationale: Density measurements can be easily made and are not a source of major uncertainty. Other microstructure concerns are more of an issue. | Closure Criterion: None. |

**Additional Discussion**

Density can be measured – the irradiation implications are the issue.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | SiC layer<br>Bonding strength (SiC to outer PyC) | Interfacial strength at the interface |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: L | Level: 2 | Remedy: Review the situation to determine if this effect is real for PyC thickness of interest. Measure this bond strength if important. |
| Rationale: The bonding strength can transmit forces from one layer to another which can, under some conditions, result in increased rates of failure. | Rationale: Little is known about the strength of this bond. It is an input parameter to the fuel modeling codes. | Closure Criterion: The relevance of this issue and any required measurements. |

**Additional Discussion**

The following two references discuss the effects of layer bonding:

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

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

The OPyC bonding is believed to be less important than IPyC bonding.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | SiC layer | Ratio of silicon to carbon (absence of gold spots, i.e., elemental Si) |
| | Stoichiometry | |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 6 | Remedy: Continue with the general characterization of SiC |
| Rationale: The quality of the SiC is paramount to fission product retention. | Rationale: The stoichiometry of the SiC layer, at least on a marco scale, does not appear to be a major problem. The flaws, such as gold spots, can be held to a minimum by QC methods. However, small defects from whatever sources have not been characterized. This issue is more likely to be connected with micro flaws than with a serious departure from stoichiometry on a marco scale. There are concerns that trace amounts of free silicon may contribute to fission product transport. | Closure Criterion: Show that measurable SiC properties can be connected with irradiation behavior or at least than a reproducible process is available and controllable. |

**Additional Discussion**

For a discussion of SiC quality issues see:

*An Assessment of the Methods for Determining Defect or Failure Fractions in HTGR Coated Particle Fuels and Their Relationship to Particle Microstructure*, DOE-HTGR-88260, 1989

*TRISO Fuel Particle Coating Design Basis*, DOE-GT-MHR-100225, 1994

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | SiC layer<br>Heavy metal dispersion | Amount of heavy metals dispersed in the layer present after manufacture |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 7 | Remedy: No specific action. Monitor the SiC to assume that this issue does not come back. |
| Rationale: Heavy metal in the SiC will fission and damage the layer. Only very small amounts of heavy metal can be tolerated in this layer. | Rationale: This issue has been investigated and determining heavy metal in SiC is usually done using X-rays. Contemporary fuel is expected to have very small amounts of heavy metal in the SiC. | Closure Criterion: SiC that passes the heavy metal specification. |

**Additional Discussion**

Heavy metal dispersion, as measured by X-radiography, is believed to result from HCl attack of the kernel during coating with SiC due to a permeable or cracked IPyC layer. For a description of some SiC quality issues see:

*TRISO Fuel Particle Coating Design Basis*, DOE-GT-MHR-100225, 1994

and the contained references.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | SiC layer<br>Defects | Initial undetected pinhole or other defects resulting from the manufacturing process |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 5 | Remedy: Continue the pursuit of SiC characterization. |
| Rationale: Defects in the SiC layer allow metallic fission products to diffuse out of the particle. This is the dominant issue as connecting SiC measurable properties to irradiation performance have not been completely successful. | Rationale: A fairly complete understanding of the gross SiC defects is at hand, but subtle factors appear to limit the understanding on the microscale. The only truly effective testing method to date is the cesium release test, performed at temperature in a reactor, which is impractical to conduct on a routine basis. | Closure Criterion: Either a QC methods that connects irradiation and accident performance with measurable properties or a well defined and controlled process for the fabrication of the particles. |

**Additional Discussion**

A connection between SiC performance and measurable properties has remained elusive. For a discussion of methods see:

*An Assessment of the Methods for Determining Defect or Failure Fractions in HTGR Coated Particle Fuels and Their Relationship to Particle Microstructure*, DOE-HTGR-88260, 1989

German attempts are summarized in:

*Silicon Carbide Coatings of Nuclear Fuel Particles – A Characterization Study*, KFA document Jul-1871, September 1983

*Influence Of Material Properties On The Retention Of Fission Products By Silicon Carbide Coatings*, R. Forthmann, et. al. High Temperature – High Pressure, 1982, 14, pages 477-485.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Inner PyC layer<br>Anisotropy (initial) | Difference in crystal orientation along principal directions as measured by the BAF |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 5 | Remedy: Perform PyC measurements with different techniques to determine the best way to characterize pyrocarbon. |
| Rationale: The initial anisotropy of the IPyC is important as it determines how the material will shrink as a function of fast flux. This shrinking imposes stresses on the layer and excessive stress will break the layer and threaten the structural integrity of the particle. | Rationale: The BAF of the layer can be measured, but practical results do not correlate well with irradiation behavior. In fact, it is not clear how to best approach this problem. The Germans have a process specification that address this issue, but the usefulness of the BAF measurement is in doubt. | Closure Criterion: A specification or fabrication process that leads to predictable behavior. The NRC may have to decide if it is comfortable with a process rather than product specification. |

**Additional Discussion**

See the discussion for OpyC anisotropy. Process knowledge exists for the fabrication of good IPyC, but connecting material properties to irradiation performance has been elusive.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Inner PyC layer<br>Bonding strength (inner PyC to SiC) | Interfacial strength at the interface |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 3 | Remedy: Review the situation to determine if this effect is significant (modeling) for PyC thickness of interest. Measure this bond strength if important. |
| Rationale: The bonding strength can transmit forces from one layer to another which can, under some conditions, result in increased rates of failure. There is some PIE evidence that IPyC cracking can place local forces on the SiC layer that then causes it to fail. However, this particular fuel had a thicker than normal IPyC layer and flawed IPyC properties. | Rationale: Little is known about the strength of this bond. It is an input parameter to the fuel modeling codes. High quality German fuel appears to have strong bonding between the IPyC and SiC. | Closure Criterion: The relevance of this issue and any required measurements. |

**Additional Discussion**

See the discussion for OPyC bonding strength. The models shown that strong IPyC bonding and good dimensional stability of the IPyC is very important. Experimental evidence seems to show that good fuel had very little IPyC cracking and debonding, while less well performing fuel had significant IPyC cracking and debonding. However, different irradiation conditions make comparisons difficult.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Inner PyC layer<br>Porosity | Interconnected void accessible to the surface |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 7 | Remedy: None other than to insure than good irradiation performance is not compromised for this issue. |
| Rationale: High porosity allows HCl liberated during SiC deposition to attack the kernel and spread fissile material to the SiC layer where it has a detrimental effect. | Rationale: This issue appears to be well enough understood and under control. The problem is the compromise between porosity, thickness, and other parameters. | Closure Criterion: Good pyrocarbon with low levels of heavy metal in the SiC layer. |

**Additional Discussion**

For the effects of the wrong compromise between pyrocarbon properties and porosity see:

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

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

Also see the discussion on heavy metal dispersion in SiC.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Buffer layer | Layer thickness less than specified or missing layer |
| | Thin or missing | |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 7 | Remedy: None other than good quality control. |
| Rationale: A thin Buffer layer will result in particle overpressure and failure. | Rationale: This issue appears to be well enough understood and under control. | Closure Criterion: None. |

**Additional Discussion**

This issue relates to how well the variation in the Buffer coating can be controlled and connects back to the operation of the coater.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Buffer Layer<br>Density and open porosity | Mass per unit volume and interconnected void accessible to the surface |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 7 | Remedy: None. Continue to monitor the test irradiations for buffer performance. |
| Rationale: The buffer layer is the void volume to accumulate the released fission gases and any generated CO. It helps control the particle pressure. | Rationale: The buffer layer appears to perform its function without difficulties. | Closure Criterion: Continued satisfactory performance. |

**Additional Discussion**

At the present time, there appears to be few issues associated with the buffer layer.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Kernel<br>Density | Mass per unit volume in final form |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: M | Level: 8 | Remedy: None. |
| Rationale: The density of the kernel determines the amount of fissile material present and thus the power. The density of the kernel may be related to the reactivity of the kernel to HCl. | Rationale: Measuring density is well established and uncertainties in density are not considered to responsible for past problems. | Closure Criterion: None. |

**Additional Discussion**

Dense and crack free kernels appear to be a sufficient specification.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Manufacturing | Kernel<br>Microstructure (UO2) | Grain size, pore structure (interconnectivity) and orientation in kernel |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: M | Level: 7 | Remedy: None. |
| Rationale: The microstructure of the kernel may influence its irradiation behavior. However, good performance has been obtained from dense $UO_2$ without other specifications. Past performance with low density kernels was not as good (kernels did not retain fission products well). | Rationale: The current high-density kernels appear to perform well under irradiation. | Closure Criterion: None. |

Additional Discussion

The dense $UO_2$ kernels appear to work well. UCO kernels have seen less work, but results to date are generally good. Thus far, density appears to be a sufficient parameter with the other properties implied by the process.

Some discussion of microstructure is contained in:

*Progress in the Development of Fuels and Fuel Elements for High Temperature Reactors of the Pebble Bed Type*, F.J. Hermann, et.al., Kerntechnik 12, Jahrgang (1970) Nno. 4.

# APPENDIX B

## PANEL MEMBER DETAILED PIRT SUBMITTALS FOR OPERATIONS

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

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

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

## Appendix B.1

## Detailed PIRT Submittal by the INEEL Panel Member

D. A. Petti

## TRISO Fuel PIRT: Operations

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Operations | Fuel element<br>Temperature | Local temperature in the fuel element |

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Operations | Kernel<br>Burnup | Fission of initial metal atoms |

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

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Operations | Kernel<br>Kernel swelling | Volumetric expansion of kernel resulting from fissioning |

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

**Remove one line above**

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

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

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

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

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

**Additional Discussion**

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

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

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Operations | Kernel<br>Temperature gradient | Temperature gradient across the kernel |

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Operations | Buffer layer<br>Shrinkage | Radiation or otherwise induced dimensional change |

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Operations | Buffer layer<br>Temperature gradient | Temperature difference across the buffer layer |

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**


1. G. K. Miller et al., "Statistical Approach and Benchmarking for Modeling of Multi-dimensional Behavior in TRISO-coated Fuel Particles," J. Nuclear Materials, forthcoming.
2. G.K. Miller et al., 2001, "Consideration of the Effects on Fuel Particle Behavior from Shrinkage Cracks in the Inner Pyrocarbon Layer," *Journal of Nuclear Materials*, Vol. 295, pp. 205-212.
3. D. A. Petti et al., "Development of Improved Models and Design for Coated Particle Gas Reactor Fuels," 2002 Annual Report, INEEL/EXT-02-01493, Nov. 2002.
4. L. L. Snead and D. A. Petti, "Improving the Integrity of Coated Particle Fuels: Measurements of Constituent Properties of SiC and ZrC, Effects of Irradiation and Modeling," NERI Proposal, April 2002.

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**


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

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

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

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Operations | Inner PyC layer<br>Debonding | Separation of PyC layer from SiC layer |

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

## Appendix B.2

## Detailed PIRT Submittal by the ORNL Panel Member
R. Morris

# TRISO Fuel PIRT: Operations

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Operations | Fuel element<br>Temperature | Local temperature in the fuel element |

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

**Additional Discussion**

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

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

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

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

**Additional Discussion**

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

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

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

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

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

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

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

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

**Additional Discussion**

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

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

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

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

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

**Additional Discussion**

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

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

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

**Additional Discussion**

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

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

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

Also see the entry on SiC corrosion.

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

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

**Additional Discussion**

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

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

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

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

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

**Additional Discussion**

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

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

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

**Additional Discussion**

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

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

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

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

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

**Additional Discussion**

See the entries on kernel migration. Also:

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

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

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Operations | Kernel<br>Burnup | Fission of initial metal atoms |

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

**Additional Discussion**

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

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

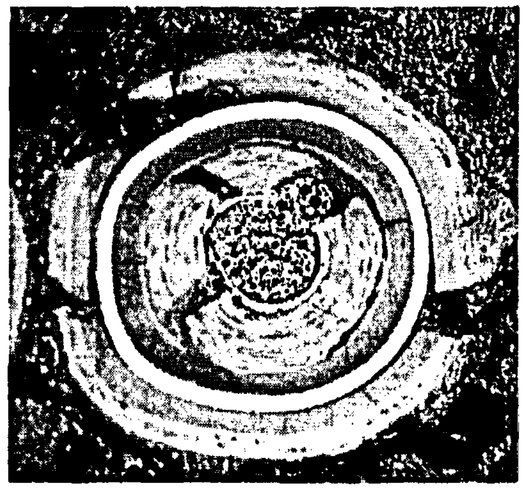
| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Operations | Kernel<br>Kernel swelling | Volumetric expansion of kernel resulting from fissioning |

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

**Additional Discussion**

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

**HRB-21 fuel (ORNL)**



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

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

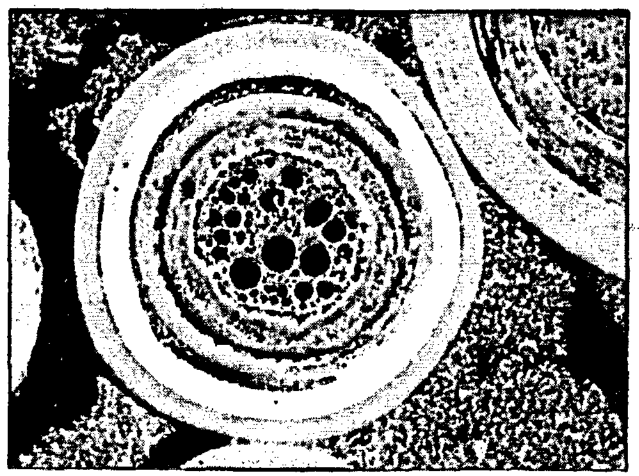
**Additional Discussion**

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

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

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

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



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

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

**Additional Discussion**

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

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

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

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

**Additional Discussion**

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

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

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

**Additional Discussion**

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

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

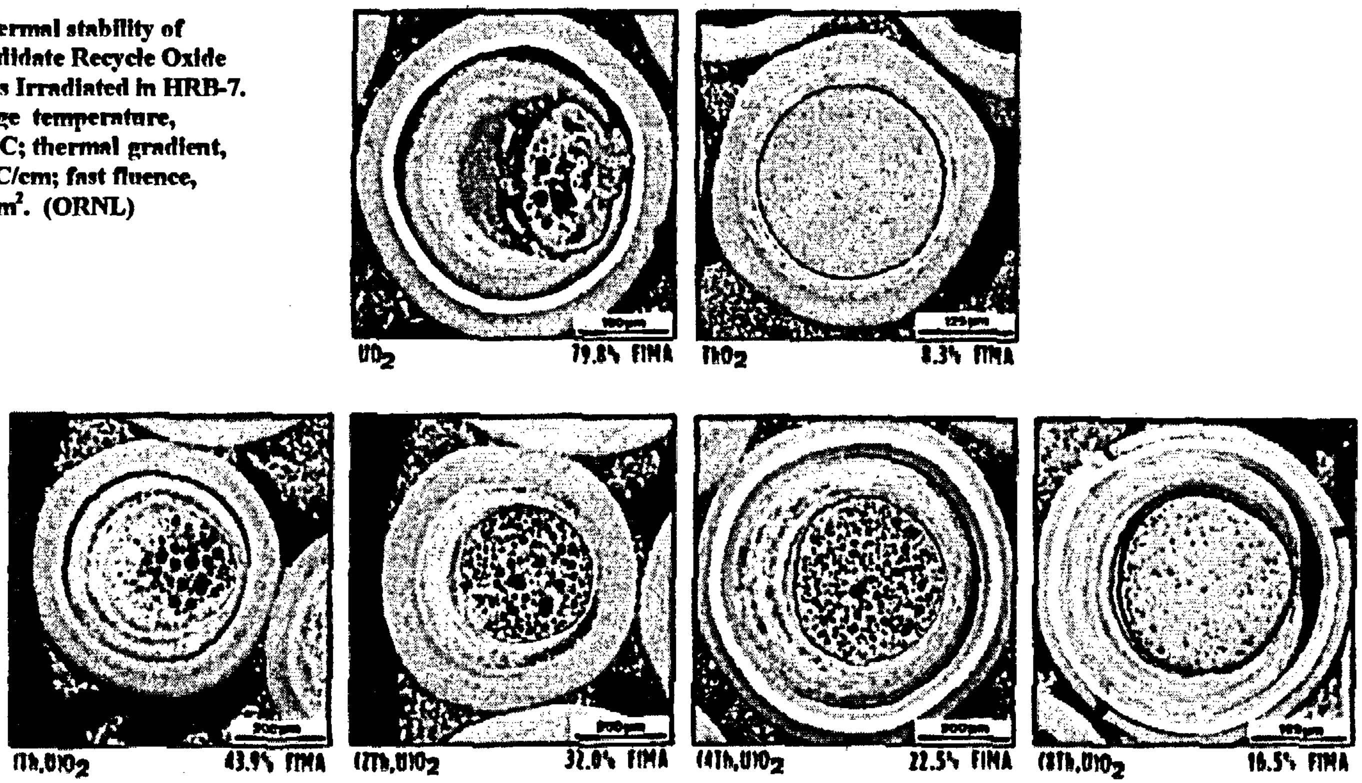
*Kernel Migration in Coated Carbide Fuel Particles*, O.M. Stansfield, et. al., Nuclear Technology, 25, pages 517-530

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

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

The microphotograph below illustrates the behavior.

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



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

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

**Additional Discussion**

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

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Operations | Kernel<br>Temperature gradient | Temperature gradient across the kernel |

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

**Additional Discussion**

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

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

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

**Additional Discussion**

This data should not be an issue.

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

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

**Additional Discussion**

Also see the entry on kernel CO.

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

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

**Additional Discussion**

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

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Operations | Buffer layer<br>Cracking | Shrinkage cracks produced in layer during operation |

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

**Additional Discussion**

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

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

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

**Additional Discussion**

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

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
| --- | --- | --- |
| Operations | Buffer layer<br>Temperature gradient | Temperature difference across the buffer layer |

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

**Additional Discussion**

Also see the entries on CO and kernel migration.

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

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

**Additional Discussion**

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

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

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

**Additional Discussion**

Recent PyC issues are discussed in:

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

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

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

For background see:

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

A somewhat dated, but still useful reference is:

*Coated-Particle Fuels*, ORNL-4324 (1968)

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

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

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

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

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

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

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

**Additional Discussion**

See entries on creep and anisotropy.

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

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

**Additional Discussion**

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

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

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

**Additional Discussion**

See entries on creep and anisotropy. Also see debonding.

Also see:

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

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Operations | Inner PyC layer<br>Debonding | Separation of PyC layer from SiC layer |

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

**Additional Discussion**

For a discussion of this issue see:

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

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

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

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

**Additional Discussion**

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

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

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

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

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

**Additional Discussion**

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

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

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

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

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

**Additional Discussion**

See the kernel migration entry.

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

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

**Additional Discussion**

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

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

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

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

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

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

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

**Additional Discussion**

For a discussion of fuel quality control methods see:

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

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

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

**Additional Discussion**

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

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

For more on fuel performance see:

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

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

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

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

**Additional Discussion**

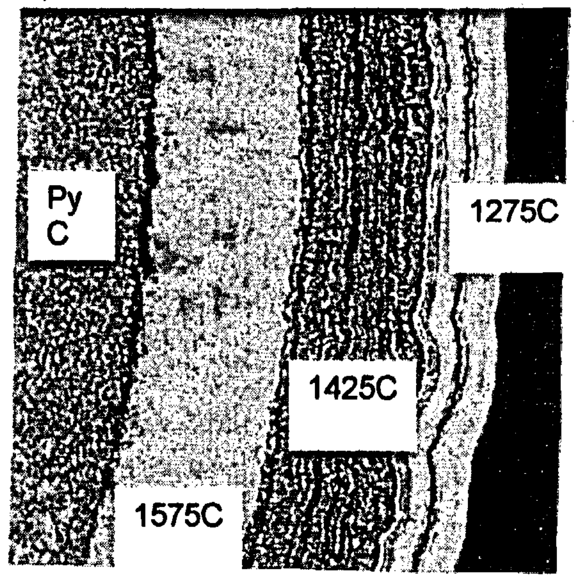
The SiC structure is usually determined by the coating conditions – gas mixtures, deposition rate, etc. – rather than a microstructure specification, although one is often included. Specific coater operation leads to a specific SiC structure. For a discussion of the desired SiC and coater conditions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

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

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

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

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




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

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

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

**Additional Discussion**

See the previous entry.

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

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

**Additional Discussion**

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

For more on fuel performance see:

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

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

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

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

**Additional Discussion**

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

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

For more on fuel performance see:

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

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

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

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

**Additional Discussion**

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

For more on fuel performance see:

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

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

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

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

**Additional Discussion**

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

For more on fuel performance see:

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

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

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

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

**Additional Discussion**

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

For more on fuel performance see:

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

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

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

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

**Additional Discussion**

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

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

# Appendix B.3

## Detailed PIRT Submittal by the SNL Panel Member

D. A. Powers

## TRISO Fuel PIRT: Operations

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

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Operations | Fuel element<br>Temperature | Local temperatures in the fuel element |

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

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

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

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Operations | Kernel<br>Burnup | Fission of initial metal atoms |

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

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Operations | Kernel<br>Kernel swelling | Volumetric expansion of kernel resulting from fissioning |

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Operations | Kernel<br>Temperature gradient | Temperature gradient across the kernel |

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Operations | Buffer layer<br>Shrinkage | Radiation or otherwise induced dimensional change |

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

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Operations | Buffer layer<br>Cracking | Shrinkage cracks produced in layer during operation |

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

**Additional Discussion**

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

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

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Operations | Buffer layer<br>Temperature gradient | Temperature difference across the buffer layer |

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

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

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

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

**Additional Discussion**

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

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

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Operations | Inner PyC layer<br>Debonding | Separation of PyC layer from SiC layer |

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

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

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

**Additional Discussion**

# APPENDIX C

## PANEL MEMBER DETAILED PIRT SUBMITTALS FOR TRISO FUEL DEPRESSURIZED HEATUP ACCIDENT

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

The ORNL submittal is provided in Appendix C.2 (pages C-49 through C-102).

The SNL submittal is provided in Appendix C.3 (pages C-103 through C-148).

## Appendix C.1

## Detailed PIRT Submittal by the INEEL Panel Member

D. A. Petti

## TRISO Fuel PIRT: Heatup Accident

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Fuel Element<br>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 : 5 for $UO_2$ fuel. 3 for UCO fuel | Remedy: DOE Advanced Gas Reactor Program will test UCO fuel at high temperature. |
| | > 1600 °C : 5 for $UO_2$ fuel and 3 for UCO fuel | |
| Rationale: Data from German heating tests suggest that irradiation history influences releases of fission products under accident conditions. | Rationale: (≤ 1600 °C) Data on $UO_2$ pebbles shows that irradiation conditions, especially burnup and fluence have an effect on fission product release at high temperature. No data on UCO fuel. | Closure Criterion: |
| | Rationale (> 1600 °C) Same as above for $UO_2$ except that the amount of fuel heated in excess of 1600°C is much smaller than that below 1600°C. No data on UCO fuel. | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Fuel Element<br>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 | ≤ 1600 °C : 5 | Remedy: |
| | > 1600 °C : 5 | |
| 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. | 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 U.S. compacts no holdup is assumed because of the rapid transport through this material. 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. Site poisoning could be important if the levels are high and the amount of fission products in the graphite are relatively low so that there is competition by the two species for the absorption sites. Impurity levels in graphite matrix material should be measured but no specific measurements are planned. Perhaps sensitivity studies can be performed to evaluate the magnitude of the effect. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup` Accident | Fuel Element<br>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: M | ≤ 1600 °C : 5 | Remedy: |
| | > 1600 °C : 5 | |
| Rationale: For fission gases, this mechanism in addition to bulk diffusion may be important at the high temperatures expected under accident conditions. Little holdup is expected under accident conditions. | Rationale: (≤ 1600 °C) A limited number of effective diffusion coefficients for noble gases and iodine have been measured. See IAEA TECDOC 978 Appendix A. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup 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 | ≤ 1600 °C : 5 | Remedy: |
| | > 1600 °C : 5 | |
| Rationale: Important to determine behavior in fuel element matrix | Rationale: (≤ 1600 °C) | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Outer PyC Layer<br>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: |
| | > 1600 °C : 7 | |
| Rationale: Perhaps the mechanism responsible for transport through the layer. Calculations suggest transport is much slower than would be predicted by Knudsen diffusion. | Rationale: (≤ 1600 °C) Effective diffusion coefficients for noble gases through PyC exist for both German and U.S. PyC. The Knudsen diffusion formalism has not been historically used in the modeling. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Outer PyC Layer<br>Condensed-phase diffusion | Inter-granular and/or intra-grannular solid-state diffusion |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | ≤ 1600 °C : 7 | Remedy: |
| | > 1600 °C : 7 | |
| Rationale: Probably the mechanism responsible for transport of fission product metals through PyC layer. | Rationale: (≤ 1600 °C) Data exist on the effective diffusivity of Cs, Ag, and Sr through the PyC layer. The mechanism responsible for the transport has not been definitively identified. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Outer PyC Layer<br>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 : 6 | Remedy: |
| | > 1600 °C : 6 | |
| Rationale: Oxidation of the OPyC layer has been studied in an integral sense. Its importance to fission product release in a heatup event in which no air is present is very low. | Rationale: ( ≤ 1600 °C) | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup 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 : 5 | Remedy: |
| | > 1600 °C : 5 | |
| Rationale: The OPyC layer is in compression during irradiation. Heating produces a reduction in the tangential compressive stress because of differential thermal expansion between the SiC and OPyC and an increase in internal pressure due to fission gases and CO. Impact on fission product release is small if SiC layer is intact. | Rationale: ( ≤ 1600 °C) | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Outer PyC Layer<br>Intercalation | Trapping of species between sheets of the graphite structure |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: M | ≤ 1600 °C : 4 | Remedy: |
| | > 1600 °C : 4 | |
| Rationale: Could be important in OPyC layer. Concentration of fission products is on the order of trap density. Thus, some trapping could influence transport. | Rationale: (≤ 1600 °C) In an intact particle, little diffusion of fission products is expected. If the level of adsorption or defect sites is high in the OPyC due to neutron irradiation for example, then these sites may be effective in holding up fission products if they are not annealed out during the high temperature heatup event. In a failed particle the number of fission product atoms is so large that such a mechanism is very small. This is based on diffusion and trapping modeling performed for tritium under the NPR program in the early 1990s. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Outer PyC Layer<br>Trapping | Adsorption of fission products on defects |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: M | ≤ 1600 °C : 4 | Remedy: |
| | > 1600 °C : 4 | |
| Rationale: Could be important in OPyC layer. Concentration of fission products is on the order of trap density. Thus, some trapping could influence transport. | Rationale: (≤ 1600 °C) In an intact particle, little diffusion of fission products is expected. If the level of adsorption or defect sites is high in the OPyC due to neutron irradiation for example, then these sites may be effective in holding up fission products if they are not annealed out during the high temperature heatup event. In a failed particle the number of fission product atoms is so large that such a mechanism is very small. This is based on diffusion and trapping modeling performed for tritium under the NPR program in the early 1990s. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Outer PyC Layer Cracking | Lengths, widths and numbers of cracks produced in layer during operation or an accident |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | ≤ 1600 °C :5 | Remedy: |
| | > 1600 °C : 5 | |
| Rationale: Modeling the cracking would be very important in the event the SiC layer failed during the heatup allowing the Kr, Xe, and iodine to be released more quickly than in the event of an intact OPyC. | Rationale: (≤ 1600 °C). Models can be used to calculate the stress state in the OPyC layer. A failed OPyC will not retain fission gases. OPyC tends not to retain metallic fission gases. OPyC tends not to retain metallic fission products like Cs very well at high temperature. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | SiC Layer<br>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: |
| | > 1600 °C : 7 | |
| Rationale: As the primary fission product barrier understanding the transport is very important A combination of bulk diffusion and Knudsen diffusion at these high temperatures but the two mechanisms have never been individually sorted out in any experiment. | Rationale: (≤ 1600 °C) Effective diffusion coefficients exist in both the U.S. and Germany for the fission gases through the SiC. (Knudsen diffusion requires porosity to be present in the material. Although SiC in coated particles is very dense and hence might not have significant porosity, small nanoscale porosity has been suggested as a mechanism for fission product release. This has never been definitively established but is included here as a possibility.) The parameters needed for such detailed models and the changes in microstructure of the SiC particle to particle and sometimes across the layer make such an effort very expensive and time consuming. The use of effective diffusion coefficients although less scientifically satisfying is more pragmatic and may be completely acceptable in system safety analysis when accompanied by proper sensitivity studies. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | SiC Layer<br>Condensed-phase diffusion | Inter-granular and/or intra-grannular solid-state diffusion. |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | ≤ 1600 °C : 7 | Remedy: |
| | > 1600 °C : 7 | |
| Rationale: As the primary fission product barrier understanding the transport is very important. A combination of bulk diffusion and grain boundary diffusion at these high temperatures are probably occurring, but the two mechanisms have never been individually sorted out in any experiment. | Rationale: (≤ 1600 °C) Effective diffusion coefficients exist in both the U.S. and Germany for the metallic fission products through the SiC. The parameters needed for such detailed models and the changes in microstructure of the SiC particle to particle and sometimes across the layer make such an effort very expensive and time consuming. The use of effective diffusion coefficients although less scientifically satisfying is more pragmatic and may be completely acceptable in system safety analysis when accompanied by proper sensitivity studies. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
| --- | --- | --- |
| Heatup Accident | SiC Layer<br>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: H | ≤ 1600 °C : 8 | Remedy: This will be studied in the EU program as they take German fuel to higher burnups and study the accident heatup behavior. |
| | > 1600 °C : 6 | |
| Rationale: The deterioration of the SiC layer has been postulated as a key mechanism of enhanced fission product release at high temperature. | Rationale: ( ≤ 1600 °C) Below 1600°C, this mechanism is not very important and simple bounding models for this phenomena have been developed and incorporated into accident source term codes in the U.S. and Germany. Above 1600°C, some enhanced release has been observed, especially at higher burnups and fast fluences, and attributed to fission product interactions with the SiC (perhaps Cs) that degrades the SiC layer. The kinetics of this mechanism is not known with certainty. More PIE after heating tests would help develop a better understanding of the phenomena and its impact above 1600°C. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | SiC Layer<br>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 | ≤ 1600 °C : 7 | Remedy: Current testing using non-fueled SiC specimens may help better elucidate kinetics. Additional PIE during accident heating tests of high burnup fuel in the U.S. and EU will help. |
| | > 1600 °C : 5 | |
| Rationale: The deterioration of the SiC layer via Pd attack has been postulated as a key failure mechanism because Pd forms silicides based on phase diagram and experimental measurements. This is very important for the high burnup fuel being proposed in new reactor designs since the Pd yield from Pu fission is much greater (~ 25 x) than from U fission. | Rationale: (≤ 1600 °C) Various research institutions have performed many measurements. The kinetics of this mechanism is not known with enough certainty since extrapolations from the database are required. More testing would help develop a better understanding of the phenomena and its impact above 1600°C. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | SiC Layer<br>Heavy metal diffusion | Diffusion of heavy metals through the intact layer |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: L | ≤ 1600 °C : 3 | Remedy: |
| | > 1600 °C : 3 | |
| Rationale: Heavy metal diffusion has never been observed in any accident heating tests performed in Germany or the U.S. | Rationale: ( ≤ 1600 °C) | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | SiC Layer<br>Layer oxidation | Uptake of oxygen by the layer through a chemical reaction |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: M | ≤ 1600 °C : 6 | Remedy: |
| | > 1600 °C : 6 | |
| Rationale: External oxidation by air is not considered for a heatup event. However, in $UO_2$ fuel, the CO that is produced during irradiation can react with the SiC causing degradation, if the CO can contact the SiC layer directly. This can happen if the IPyC layer is failed (cracked) or if there is some permeation of the CO through the IPyC layer. | Rationale: (≤ 1600 °C) Limited postheating examination of past fuel has been performed to verify that such a reaction is occurring. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
| --- | --- | --- |
| Heatup Accident | SiC Layer<br>Fission product release through undetected defects | Passage of fission products from the buffer region through defects in the SiC layer |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
| --- | --- | --- |
| Rank: H | ≤ 1600 °C : 6 | Remedy: |
| | > 1600 °C : 6 | |
| Rationale: As the primary fission product barrier understanding the transport is very important. | Rationale: (≤ 1600 °C) Effective diffusion coefficients exist in both the U.S. and Germany for the fission gases through the SiC. Release via defects has never been individually sorted out from the other transport mechanisms in any experiment. The parameters needed to model release via defects and the presence or absence of defects in the SiC layer particle to particle makes such an effort very expensive and time consuming. The use of effective diffusion coefficients although less scientifically satisfying is more pragmatic and may be completely acceptable in system safety analysis when accompanied by proper sensitivity studies that assume some percentage of defective SiC layers present in the core. There is sometimes evidence from some postirradiation examination of a few particles in a batch in which the cesium has been released suggesting enhanced transport in those few particles. The exact nature or reason for the cesium release (e.g. linking it to a defect or microstructural flaw) has never been performed. Nor has the presence of such flaws been linked to some aspect or anomaly in the fabrication of the particles. | Closure Criterion: |

| | | |
|---|---|---|
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | SiC Layer<br>Fission product release through failures, e.g., cracking | Passage of fission products from the buffer region through regions in the SiC layer that fail during operation or an accident. |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | ≤ 1600 °C : 7 | Remedy: |
| | > 1600 °C : 6 | |
| Rationale: A particle with a failed SiC layer but intact PyC layers will not release fission gas. The PyC layers must fail in order to have fission gas release. | Rationale: ( ≤ 1600 °C) Heating tests have clearly demonstrated this behavior when Cs is released from a particle with an initially failed SiC layer and then only after some time when the PyC layer fails will the fission gas be released. A failed layer sometimes is modeled as having no fission product retention characteristics in fuel performance models. This conservative assumption is reasonable assuming that the code can adequately calculate when an SiC layer can fail. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | SiC Layer<br>Thermodynamics of the SiC-fission product system | Chemical form of fission products including the effects of solubility, intermetallics, and chemical activity. |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | ≤ 1600 °C : 7 | Remedy: |
| | > 1600 °C : 7 | |
| Rationale: Understanding of thermodynamics of the SiC-fission product system is necessary to understand behavior expected in the heatup event. | Rationale: ( ≤ 1600 °C) Thermodynamic calculations have been performed for both the $UO_2$ and UCO systems over a broad temperature, burnup and enrichment range to establish the chemical forms of the fission products. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | SiC Layer<br>Sintering | Change of SiC microstructure as a function of temperature |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: L | ≤ 1600 °C : 5 | Remedy: |
| | > 1600 °C : 5 | |
| 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. | Rationale: ( ≤ 1600 °C) | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
| --- | --- | --- |
| Heatup Accident | Inner PyC Layer<br>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: |
| | > 1600 °C : 7 | |
| Rationale: The IPyC can hold up gaseous fission products A combination of bulk diffusion and Knudsen diffusion probably are the controlling mechanisms at these high temperatures but the two mechanisms have never been individually sorted out in any experiment. | Rationale: ( ≤ 1600 °C) Effective diffusion coefficients exist in both the U.S. and Germany for the noble gases through IPyC. The parameters needed for detailed models and the changes in microstructure of the IPyC particle to particle and sometimes across the layer make such an effort very expensive and time consuming. The use of effective diffusion coefficients although less scientifically satisfying is more pragmatic and may be completely acceptable in system safety analysis when accompanied by proper sensitivity studies. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Inner PyC Layer<br>Condensed-phase diffusion | Inter-granular and/or intra-grannular solid-state diffusion. |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | $\leq$ 1600 °C : 7 | Remedy: |
| | > 1600 °C : 7 | |
| Rationale: The IPyC does not significantly hold up metallic fission products. A combination of bulk diffusion and grain boundary diffusion at these high temperatures are probably responsible for transport, but the two mechanisms have never been individually sorted out in any experiment. | Rationale: ( $\leq$ 1600 °C) Effective diffusion coefficients exist in both the U.S. and Germany for the noble gases through IPyC. The parameters needed for detailed models and the changes in microstructure of the IPyC particle to particle and sometimes across the layer make such an effort very expensive and time consuming. The use of effective diffusion coefficients although less scientifically satisfying is more pragmatic and may be completely acceptable in system safety analysis when accompanied by proper sensitivity studies. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

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

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: M | ≤ 1600 °C : 8 | Remedy: |
| | > 1600 °C : 8 | |
| Rationale: The key pressure loading is noble gases. The pressure if too high can lead to particle failure. | Rationale: ( ≤ 1600 °C) This mechanism is easily calculated. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Inner PyC Layer<br>Pressure loading (Carbon monoxide) | Stress loading of the layer by carbon monoxide by increased pressure |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H for $UO_2$ and L for UCO | $\leq 1600$ °C : 7 | Remedy: |
| | $> 1600$ °C : 7 | |
| Rationale: CO is only important in $UO_2$ fuel and potentially in UCO fuel particles where the C/O ratio in the kernel is not correct. | Rationale: ( $\leq 1600$ °C) Thermodynamic estimates exist for CO pressure. The pressure if too high can lead to particle failure. This mechanism is easily calculated and has been attributed to particle failure observed during postirradiation heating tests of AVR spheres. | Closure Criterion: |
| | Rationale ( $> 1600$ °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
| --- | --- | --- |
| Heatup Accident | Inner PyC Layer<br>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 : 5 | Remedy: |
| | > 1600 °C : 5 | |
| Rationale: Excess oxygen from fission is either tied up with fission products, the UC phase in the case of UCO, or the buffer carbon to form CO in the case of $UO_2$. In a heatup event external air is not considered. | Rationale: ( ≤ 1600 °C) | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup 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: M | ≤ 1600 °C : 6 | Remedy: |
| | > 1600 °C : 6 | |
| Rationale: Moderately important compared to fission product/ SiC interactions as a precondition leading to failure. | Rationale: ( ≤ 1600 °C) The stress state of the IPyC can be calculated with reasonable accuracy given our current understanding of material properties and finite element models. Failure of the IPyC does not imply fission product release from the fuel since the SiC may still be intact. Finite element models can also examine the effect of failure of the IPyC on the stress state in the SiC and its propensity to fail. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Inner PyC Layer<br>Cracking | Lengths, widths and numbers of cracks produced in layer during accident |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | ≤ 1600 °C : 5 | Remedy: |
| | > 1600 °C : 5 | |
| Rationale: A cracked IPyC does not imply fission product release from the fuel since the SiC may still be intact. (under normal conditions about 1% of the SiC fails in particles with cracked IPyC). | Rationale: ( ≤ 1600 °C) The stress state of the IPyC with a crack can be calculated with reasonable accuracy given our current understanding of material properties and finite element models. Finite element models can also examine the effect of the crack in the IPyC on the stress state in the SiC and its propensity to fail. The stress in a particle with a cracked IPyC and intact SiC will increase during a heatup event according to finite element calculations. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Inner PyC Layer<br>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 | ≤ 1600 °C : 6 | Remedy: |
| | > 1600 °C : 6 | |
| Rationale: Surface and bulk diffusion with intercalation of Cs and Sr (trapping) is probably the underlying mechanism of transport through the PyC. Given the large number of Cs atoms, the trapping may be somewhat less important in the IPyC than in the OPyC where fewer Cs atoms are expected and their concentration may be more on the order of the number of trapping sites. | Rationale: ( ≤ 1600 °C) Transport models do not consider intercalation. Effective diffusion coefficients exist in both the U.S. and Germany for the Cs and Sr through IPyC. The data are probably a combination of diffusion and trapping via intercalation at these high temperatures but the two mechanisms have never been individually sorted out in any experiment. The parameters needed for such detailed models and the changes in microstructure of the IPyC particle to particle and sometimes across the layer make such an effort very expensive and time consuming. The use of effective diffusion coefficients although less scientifically satisfying is more pragmatic and may be completely acceptable in system safety analysis when accompanied by proper sensitivity studies. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
| --- | --- | --- |
| Heatup Accident | Inner PyC Layer<br>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 : 6 | Remedy: |
| | > 1600 °C : 6 | |
| Rationale: Number of defects are much less than number of fission product atoms expected in IPyC layer. Thus, trapping is not expected to be important in IPyC layer. | Rationale: ( ≤ 1600 °C) | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Buffer Layer<br>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: |
| | > 1600 °C : 7 | |
| Rationale: Mechanism responsible for transport of gaseous fission products. | 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. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Buffer Layer<br>Condensed-phase diffusion | Inter-granular and/or intra-grannular solid-state diffusion. |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | ≤ 1600 °C : 7 | Remedy:. |
| | > 1600 °C : 7 | |
| Rationale: 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 |
|---|---|---|
| Heatup Accident | Buffer Layer<br>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: L | ≤ 1600 °C : 4 | Remedy: EU irradiations in Petten will determine if this mechanism is important. |
| | > 1600 °C : 4 | |
| Rationale: Has been predicted by EU fuel modelers to be important at high burnup where swelling is large. Usually this is accommodated by appropriate changes in the buffer thickness to ensure that the kernel does not come in contact with the TRISO coating and cause large mechanical stresses. | Rationale: ( ≤ 1600 °C) Has not been shown to be a problem in current irradiation database at relatively low burnup. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Buffer Layer<br>Maximum fuel gaseous fission product uptake | Maximum loading of fission products that can deposit from the gas phase onto surfaces of materials surrounding the fuel kernel |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: L | ≤ 1600 °C : 2 | Remedy: |
| | > 1600 °C : 2 | |
| Rationale: Not important in heatup events; probably more important in reactivity related events. | Rationale: ( ≤ 1600 °C) | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Buffer Layer<br>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: H | ≤ 1600 °C : 6 | Remedy: |
| | > 1600 °C : 6 | |
| Rationale: Additional CO can be formed at high temperature as oxidic fission products become unstable. | Rationale:(≤ 1600 °C) In $UO_2$, excess oxygen from fission reacts with fission products and then carbon from the buffer. This is well known and can be calculated and has been measured at low burnups. In UCO fuel no oxidation is expected. Thermodynamic calculations provide CO yield as a function of temperature and burnup. | Closure Criterion: |
| | Rationale ( > 1600 °C): | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup 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: L | ≤ 1600 °C : 6 | Remedy: |
| | > 1600 °C : 6 | |
| Rationale: Temperature gradients can drive thermal diffusion (Soret effect). Temperature gradients under normal operation are very high in prismatic cores (up to 10000 K/cm), which can cause Soret effects in fission product transport. In pebble cores, the temperature gradients are much smaller because of the lower power per particle in the core. Thus, Soret effects are much less important. | Rationale: ( ≤ 1600 °C) Values of the heat of solution needed to model the fission product transport are sorely lacking. Thus, this effect is important as an initial condition for the accident. Under heatup events, the gradients are much smaller and thus much less important. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Buffer Layer<br>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 | ≤ 1600 °C : 7 | Remedy: |
| | > 1600 °C : 7 | |
| Rationale: The state of the buffer is an important initial condition in fission product modeling. Thermal densification is not expected to be important at these temperatures. | Rationale: ( ≤ 1600 °C) Rapid densification can occur in the buffer under exposure to neutrons. This is fairly well known and can be calculated. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
| --- | --- | --- |
| Heatup Accident | Kernel<br>Maximum fuel temperature | Maximum fuel temperature attained by the fuel kernel during the accident |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
| --- | --- | --- |
| Rank: H | ≤ 1600 °C : 7 | Remedy: |
| | > 1600 °C : 7 | |
| Rationale: Temperature is the key parameter that drives fission product migration in the coated particle fuel. | Rationale: ( ≤ 1600 °C) This can be calculated and sensitivity studies can determine its overall importance in any accident scenario. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Kernel<br>Temperature vs. time transient conditions | The time-dependent variation of fuel temperature with time |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | ≤ 1600 °C : 7 | Remedy: |
| | > 1600 °C : 7 | |
| Rationale: Similar to temperature and time at temperature, the thermal response of the particle is important to calculating fission product behavior in the particle. | Rationale: ( ≤ 1600 °C) Sensitivity studies can be easily performed to determine the impact of this factor on the overall progression of the accident. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup 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 | ≤ 1600 °C : 6 | Remedy: |
| | > 1600 °C : 6 | |
| Rationale: | Rationale: ( ≤ 1600 °C) Thermal conductivity of $UO_2$ is fairly high and reasonably well known. Conductivity of UCO is assumed to be that of $UO_2$. Can be varied easily in sensitivity studies to determine impact. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Kernel<br>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 : 7 | Remedy: |
| | > 1600 °C : 7 | |
| 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. 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 |
|---|---|---|
| Heatup Accident | Kernel<br>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: |
| | > 1600 °C : 7 | |
| Rationale: 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. | Rationale: ( ≤ 1600 °C) 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. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Kernel<br>Condensed-phase diffusion | Inter-granular and/or intra-grannular solid-state diffusion. |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | ≤ 1600 °C : 7 | Remedy: |
| | > 1600 °C : 7 | |
| Rationale: 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. | Rationale: ( ≤ 1600 °C) 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. | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Kernel<br>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 for $UO_2$, L for UCO | $\leq$ 1600 °C : 6 | Remedy: |
| | > 1600 °C : 6 | |
| Rationale: Kernel migration in $UO_2$ is driven by oxygen and carbon mutual diffusion across a temperature gradient in the particle. Influence on fission product release is not as important as it is on establishing the rate of kernel migration and the potential for fuel failure. | Rationale: ( $\leq$ 1600 °C) | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Kernel<br>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 : 4 | Remedy: |
| | > 1600 °C : 4 | |
| Rationale: Grain growth is not expected at these temperatures. Furthermore for the high burnups being proposed the crystal structure after irradiation is almost completely non-existent which makes the concept of a grain difficult. | Rationale: ( ≤ 1600 °C) | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Kernel<br>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 | ≤ 1600 °C : 6 | Remedy: |
| | > 1600 °C : 6 | |
| Rationale: The reaction of the kernel and the buffer is known to form a "rind" of $UC_2$ at the interface between the two layers. Photomicrographs show a different phase that is easily distinguished optically. | Rationale: ( ≤ 1600 °C) | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

## Appendix C.2

## Detailed PIRT Submittal by the ORNL Panel Member

R. Morris

## TRISO Fuel PIRT: Heatup Accident

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Fuel Element<br>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: 5 | None if the accident envelope remains the same, otherwise additional testing is necessary |
| 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 |
|---|---|---|
| Heatup Accident | Fuel Element<br>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: 5 | Defer to fission product transport area. |
| Rationale: The major barriers to fission product release are the particle coating layers. The diffusion through the fuel element matrix is considered to be relatively high, although it does sorb and trap some fission products. | Rationale: (≤ 1600 °C) The fuel element matrix sorbs some of the released fission products (metals), and can be a significant barrier to the release of some 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)

For general interest in the transport of volatile fission products through the reactor system 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 (1988), pages 7-12.

For a review of the types of models in use see:

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

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

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

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Fuel Element<br>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: 7 | None |
| 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. | 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. See the references in the previous entry.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup 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 | ≤ 1600 °C: 5 | Remedy: Determine the need for this detailed knowledge. |
| | > 1600 °C: 5 | Determine the need for this detailed knowledge. |
| 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 Technolgy, 94 (1991), pages 56-67.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Outer PyC Layer<br>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: 7 | Insure that proper PyC is manufactured |
| Rationale: The PyC layers hold gases well. The diffusion coefficients are generally quite low. The biggest concern is the rupture of the layer and the release of gases. | Rationale: (≤ 1600 °C) A great deal of testing has been conduced on PyC at the temperatures of interest. The primary concern is fabricating the proper material. | 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. The primary concern is fabricating the proper material. | 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 |
|---|---|---|
| Heatup Accident | Outer PyC Layer | Inter-granular diffusion and/or intra-granular solid-state diffusion |
| | Condensed phase diffusion | |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | ≤ 1600 °C: 7 | Remedy: None |
| | > 1600 °C: 7 | None |
| Rationale: Metallic fission products generally diffuse through the layer rapidly at high temperatures. | Rationale: (≤ 1600 °C) The OpyC offers little holdup to metallics at accident temperatures. | Closure Criterion: None |
| | Rationale (> 1600 °C) The OpyC offers little holdup to metallics at accident temperatures. | 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 |
|---|---|---|
| Heatup Accident | Outer PyC Layer<br>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: 6 | Remedy: None for helium heatup |
| | > 1600 °C: 6 | None for helium heatup |
| 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 |
|---|---|---|
| Heatup Accident | Outer PyC Layer<br>Stress state (compression/tension) | The state of the forces induced by external forces that are acting across the layer to resist movement |

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

**Additional Discussion**

See the PIRT Design Table for references on fuel design. Also see the accident models. The most common accident model is pressure vessel failure, although this may not reflect reality. 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 |
|---|---|---|
| Heatup Accident | Outer PyC Layer<br>Intercalation | Trapping of species between sheets of the graphite structure |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: L | ≤ 1600 °C: 2 | Remedy: Determine if relevant |
| | > 1600 °C: 1 | None |
| Rationale: The modeling often uses an effective diffusion coefficient and does not always look at this level of detail. The diffusion inventory can be computed. | Rationale: (≤ 1600 °C) At present, this level of detail has not been explored in much detail. It is an area of study. | Closure Criterion: None |
| | Rationale (> 1600 °C)) At present, this level of detail has not been explored in much detail. It is an area of study. | None |

**Additional Discussion**

The models generally do not go down to the mirco level. With good SiC, the fission product transport to the OPyC is very low. Current modeling efforts are investigating this effect. Even if it is a real effect, it may be consumed up by general data uncertainties.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Outer PyC Layer<br>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: Determine if relevant |
| | > 1600 °C: 1 | None |
| Rationale: Some trapping is used in the modeling and it may play a role in the transport. | Rationale: (≤ 1600 °C) This area has not been explored in much detail. | Closure Criterion: None |
| | Rationale (> 1600 °C) This area has not been explored in much detail. | None |

**Additional Discussion**

The models generally do not go down to the micro level. With good SiC, the fission product transport to the OPyC is very low. Current modeling efforts are investigating this effect. Even if it is a real effect, it may be consumed up by general data uncertainties.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Outer PyC Layer Cracking | Lengths, widths and numbers of cracks produced in layer during operation or an accident |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | ≤ 1600 °C: 5 (models determine failure rather than cracks) | Remedy: Better data and model for fuel performance, especially PyC behavior. |
| | > 1600 °C: 5 (models determine failure rather than cracks) | More careful examination of PyC & SiC in the 1600 to 1800°C region. |
| Rationale: Failure of the OpyC affects the likelihood of SiC failure. Cracking of particle layers can result in particle failure. One intact PyC can retain gases, but metallic release will be high if SiC has failed. Modeling often assumes that particles fail by overpressure rather than a small crack. A crack is assumed to equal failure. | Rationale: (≤ 1600 °C) Irradiation and heating tests has examined releases; cracks are hard to observe. Fuel models have been developed to model normal and accident behavior. Particles are assumed to fail when they meet some weakness criteria based on a layer stress. Details of cracks are not modeled (yet). Agreement has been good for high quality fuel. | Closure Criterion: Models that predict fuel behavior under normal and accident conditions. Does one need cracks or just failure? This adds a lot of complexity. |
| | Rationale (> 1600 °C) At this temperature, the models indicate that SiC decomposition is occurring and the particles slowly (~hours) begin to release. | Same. |

**Additional Discussion**
For some work on examining the effects of cracks on fuel performance and general models see:

*Consideration of the Effects on Fuel Particle Behavior from Shrinkage Cracks in the Inner Pyrocarbon Layer*, G.Miller, et. al., Journal of Nuclear Materials, 295 (2001), pages 205-212.
*Key Differences in the Fabrication, Irradiation and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance*, D.A. Petti, et. al., Nuclear Engineering and Design, 222 (2003) 281-297.
*MHTGR TRISO-P Fuel Failure Evaluation Report*, DOE-HTGR-90390*Compilation of Fuel Performance and Fission Product Transport Models and Database for MHTGR Design*, Martin, R.C., ORNL/NPR-91/6

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | SiC Layer<br>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 unless the fuel operation envelope is different. In that case, additional testing may be necessary. |
| | > 1600 °C: 5 | None unless the fuel operation envelope is different. In that case, additional testing may be necessary. |
| Rationale: The SiC is the primary fission product barrier. | Rationale: (≤ 1600 °C) Extensive testing by the Germans on their fuel has generated a database. Note that gas turbine fuel will operate at higher burnup and temperatures. | Closure Criterion: Adequate test fuel performance, particularly at higher burnups. |
| | Rationale (> 1600 °C) Less, but similar testing has been done at the higher temperature. | Adequate test fuel performance. |

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

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 |
|---|---|---|
| Heatup Accident | SiC Layer<br>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 unless the fuel operation envelope is different. In that case, additional testing may be necessary. Testing may be necessary for fuel made by a different process. |
| | > 1600 °C: 5 | None unless the fuel operation envelope is different. In that case, additional testing may be necessary. |
| Rationale: The SiC is the major barrier to the migration of metallic fission products. Its integrity is important. | Rationale: (≤ 1600 °C) Extensive testing by the Germans on their fuel has generated a database. Note that gas turbine fuel will operate at higher burnup and temperatures. | Closure Criterion: Adequate test fuel performance, particularly at higher burnups. |
| | Rationale (> 1600 °C) Less, but similar testing has been done at the higher temperature. | Adequate test fuel performance. |

**Additional Discussion**

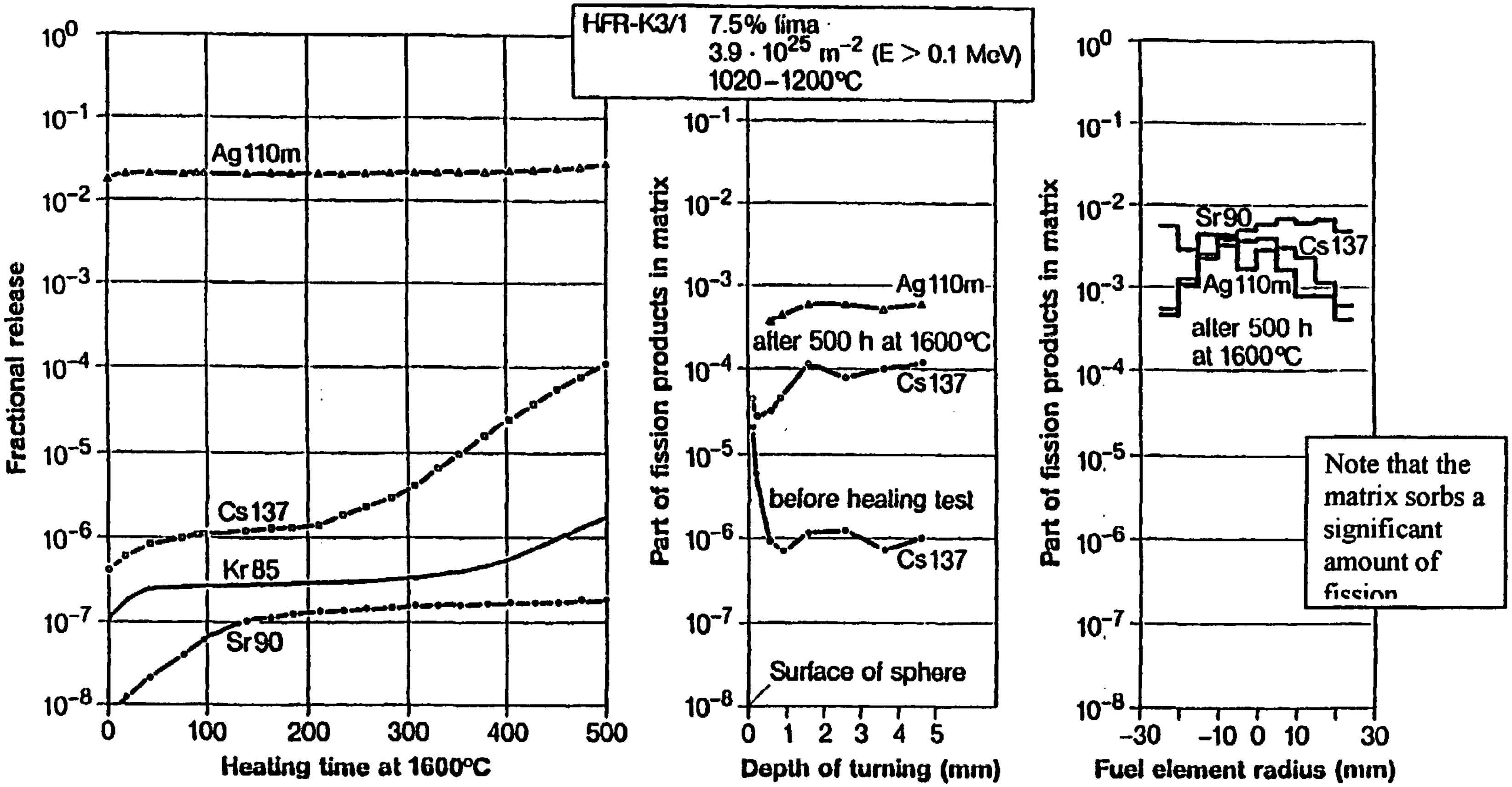
The German fuel design performance is summarized in:

*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. A new fuel line will probably require extensive testing as the product depends on process specifications as well as product specifications.

From Schenk & Nabielek, *Testing of Irradiated Spherical Fuel Elements at HTR MODUL Relevant Accident Conditions* (1991). Also in IAEA TECDOC-978




Note that the matrix sorbs a significant amount of fission

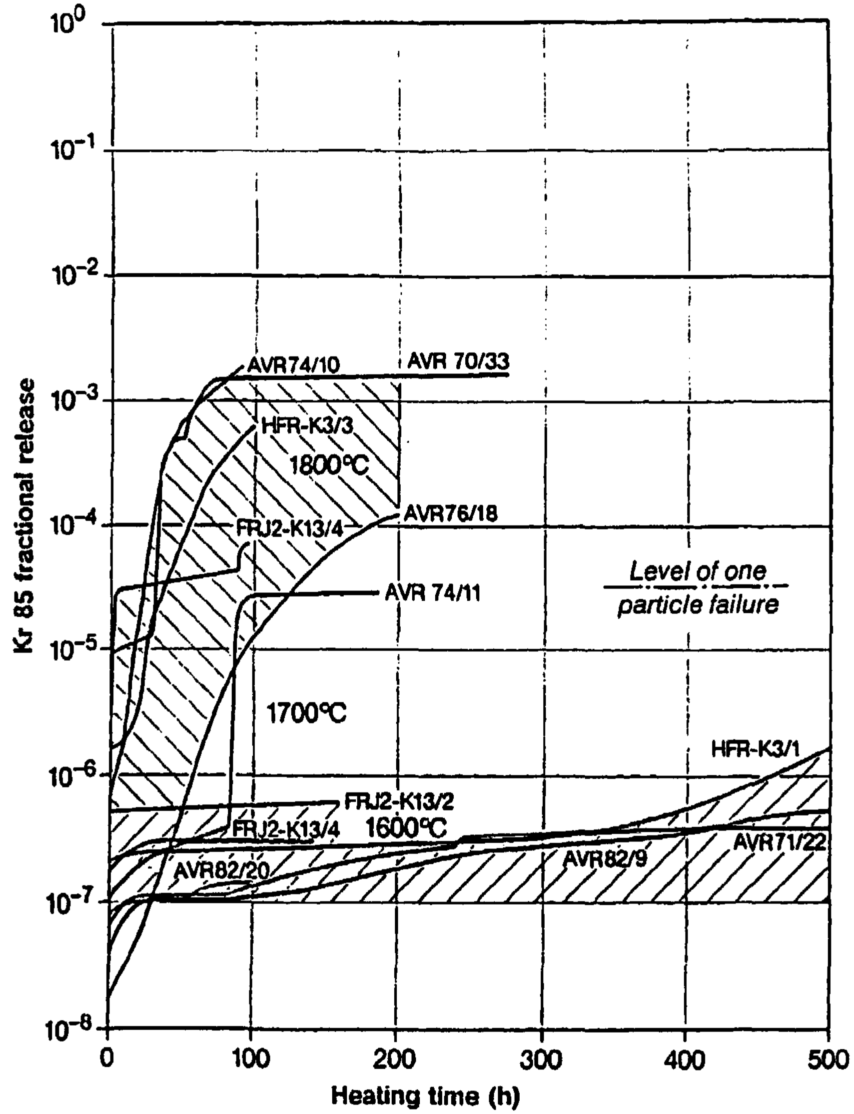
| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | SiC Layer<br>Thermal deterioration/decomposition | Decline in the quality of the layer due to thermal loading |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | ≤ 1600 °C: 7 | Remedy: If 1600°C and the irradiation envelope are adequate then okay; otherwise testing may be necessary. |
| | > 1600 °C: 5 | Better resolution in the 1600°C to 1800°C range. |
| Rationale: The thermal decomposition of the SiC layer will result in particle failure. Generally 1600°C has been used as the limit. | Rationale: (≤ 1600 °C) Extensive testing at 1600°C has shown it to be a "safe" limit for low burnup fuel. | Closure Criterion: Satisfactory fuel performance, particularly at higher burnups. |
| | Rationale (> 1600 °C) Significant, but much less testing has been done above 1600°C | Satisfactory fuel performance. |

**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. Also, the reference fuel envelope was for 10% burnup fuel. Higher burnup fuel may not work as well due to high temperature corrosion.

FP Releases Increase with Accident Temperature




From Schenk & Nabielek, *Testing of Irradiated Spherical Fuel Elements at HTR MODUL Relevant Accident Conditions* (1991) Also see IAEA TECDOC- 978

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | SiC Layer<br>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 | ≤ 1600 °C: 7 | Remedy: None, if the particle operating temperature/time and burnup is below an acceptable damage limit. |
| | > 1600 °C: 5 | None, thermal effects become important. |
| Rationale: Some fission products may migrate to the SiC layer and damage it. This corrosion process is a function of temperature. The corrosion mostly occurs during normal operation at the higher temperatures and weakens the particle for the accident. At the higher accident temperatures, thermal decomposition effects dominate. | Rationale: (≤ 1600 °C) This effect has been studied both in-pile and out of pile. Controlling the maximum operating temperature is a major factor. | Closure Criterion: Insure that the operating conditions are acceptable, including consideration of fuel type and FP 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.

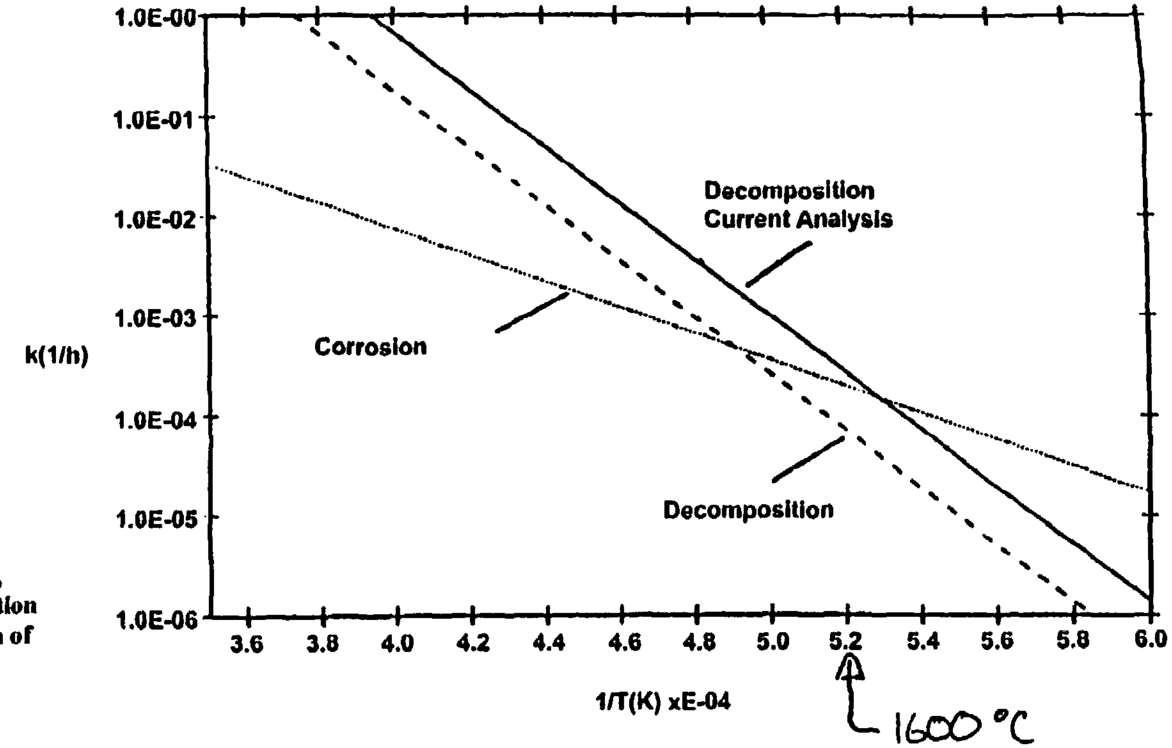
*Silicon Carbide Corrosion in High-Temperature Gas-Cooled Reactor Fuel Particles*, H. Grubmeier, et. al., Nuclear Technology, 35 (1977), pages 413-427

*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

Note that higher burnup material will see less kernel retention and larger amounts of corrosive material. This could significantly affect the performance of the fuel.

Thermal decomposition
Vs. corrosion as a
function of temperature




**Prediction for US Fuel: 16% FIMA, Fluence of 4.0 x $10^{15}$ n/m 2/s, Irradiation Temperature of 1000C. Comparison of frequency factors for failure (from Goodin, 1989).**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | SiC Layer<br>Heavy metal diffusion | Diffusion of heavy metals through the intact layer |

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

**Additional Discussion**

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

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | SiC Layer<br>Layer oxidation | Uptake of oxygen by the layer through a chemical reaction |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: M | ≤ 1600 °C: 5 | Remedy: None, as long as the integrity of the IPyC layer is good. |
| | > 1600 °C: 5 | None, as long as the integrity of the IPyC layer is good. |
| Rationale: If the IPyC breaks, the SiC layer may be exposed to CO that could slowly corrode it. This is less of a concern for UCO fuel. Also a concern for air/water ingress with OPyC failure (but not in a He environment). | 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. |

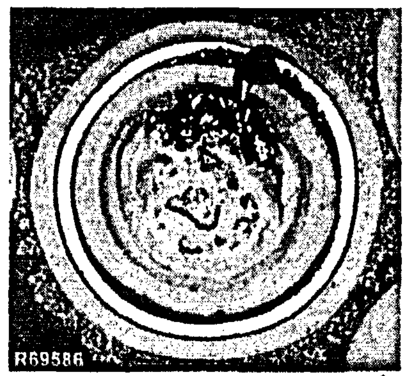
**Additional Discussion**

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

CO can oxidize SiC (through cracked IPyC) at high temperatures and CO pressures over a period of weeks/months

- Weakens SiC
- Minor concern for UCO




WAR $UO_2$ kernel at ~1500C in HRB-10 (ORNL)

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | SiC Layer<br>Fission product release through undetected defects | Passage of fission products from the buffer region through defects in the SiC layer |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | ≤ 1600 °C: 5 | Remedy: Defer to fuel fabrication |
| | > 1600 °C: 5 | Defer to fuel fabrication |
| Rationale: Defective SiC will allow gas transport if the PyCs both fail. This is more of a manufacturing issue that shows up when the fuel is stressed. | Rationale: (≤ 1600 °C) Good quality SiC has been made. Process knowledge exists as to how to make it. This is a manufacturing issue that shows up during accident conditions. | Closure Criterion: None |
| | Rationale (> 1600 °C) Same, thermal decomposition effects begin to dominate. | 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.

Poor SiC can have much higher diffusion coefficients that good SiC.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
| --- | --- | --- |
| Heatup Accident | SiC Layer<br>Fission product release through failures, e.g. cracking | Passage of fission products from the buffer region through regions in the SiC layer that fail during operation or an accident. |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
| --- | --- | --- |
| Rank: H | $\leq$ 1600 °C: 6 | Remedy: If the fuel is used outside of its tested region, more testing is needed. |
| | > 1600 °C: 5 | Thermal decomposition models are needed. |
| Rationale: Failure of the SiC (with cracked IPyC) will allow fission gas to pass through it.. If the OPyC remains intact, the gas will not be released, if not, the gas will be released. Metallics will be released in both cases. See previous entry. | Rationale: ($\leq$ 1600 °C) Accident testing has not shown much SiC failure for high quality material Accident models have been compared to experiments to approximately model the situation. If material properties are consistent, useful predictions can be made. | Closure Criterion: Acceptable performance |
| | Rationale (> 1600 °C) Above this temperature the decomposition is important. | Acceptable performance |

**Additional Discussion**

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)
German testing has shown good results for 10% burnup fuel. Few failures were seen during heatup testing. Good PyC seems to be important.
During normal or accident conditions, the SiC can crack or break due to over pressure or an interaction with cracked PyC. High temperatures increase the pressure in a particle. Above 1600 °C or so, decomposition begins to weaken the SiC and it can fail.

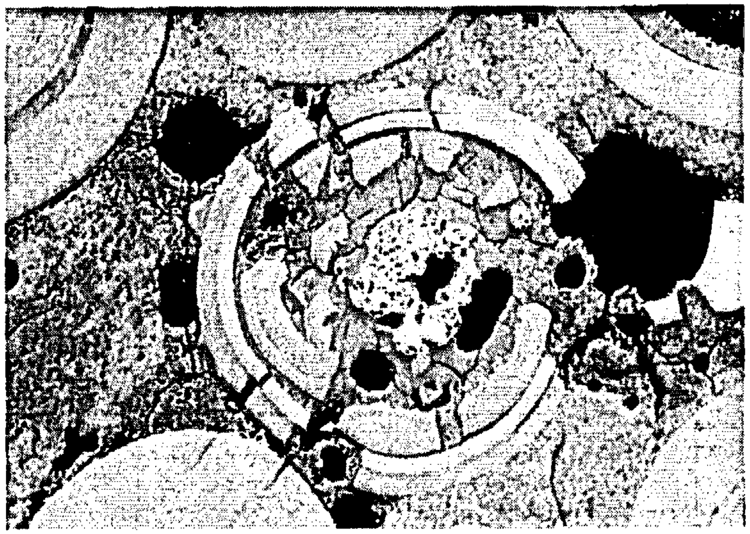
For some work on examining the effects of cracks on fuel performance and general models see:

*Consideration of the Effects on Fuel Particle Behavior from Shrinkage Cracks in the Inner Pyrocarbon Layer*, G.Miller, et. al., Journal of Nuclear Materials, 295 (2001), pages 205-212.
*Key Differences in the Fabrication, Irradiation and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance*, D.A. Petti, et. al., Nuclear Engineering and Design, 222 (2003) 281-297.

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

*Compilation of Fuel Performance and Fission Product Transport Models and Database for MHTGR Design*, Martin, R.C., ORNL/NPR-91/6
*Revised MHTGR High-Temperature Fuel Performance Models*, R.C. Martin, ORNL/NPR-92/16
*Methods and Data for HTGR Fuel Performance and Radionuclide Release Modeling during Normal Operational and Accidents for Safety Analysis*, K. Verfondern, et. al., Jul-2721
*Fuel Performance and Fission Product Behavior in Gas Cooled Reactors*, IAEA-TECDOC-978 (1997)

High pressures and/or weakened layers can lead to failure



**Pressure Vessel Failure in HRB-8, Specimen 5 ($UO_2$).**
**Holman and Long 1976 (ORNL)**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup 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: H | ≤ 1600 °C: 7 | Remedy: None, if the particle operating temperature/time is below an acceptable damage limit. |
| | > 1600 °C: 5 | None, thermal effects become important. |
| Rationale: Some fission products may migrate to the SiC layer and damage it. This corrosion process is a function of temperature. See the entry on corrosion. | 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. Corrosion could be a limit to high burnup.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | SiC Layer<br>Sintering | Change of SiC microstructure as a function of temperature |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: L | ≤ 1600 °C: 7 | Remedy: None if temperatures are below 1600 °C. |
| | > 1600 °C: 7 | Testing would be necessary if one want to operate at somewhat higher temperatures like 1600-1700°C |
| 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.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Inner PyC Layer<br>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: 6 | Additional testing if credit for higher temperatures is desired. |
| Rationale: Gas diffusion through the PyCs is generally quite low at the temperatures of interest. The SiC layer must be breeched for the gases to get out. | 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. | Closure Criterion: Acceptable test fuel behavior |
| | Rationale (> 1600 °C) Significant, but less testing has been done above this temperature. | 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. See:

*Performance Evaluation of Modern HTR TRISO Fuel*, R. Gontard, H. Nabielek, HTA-1B-05/90, July 1990
*Fuel Performance and Fission Product Behavior in Gas Cooled Reactors*, IAEA-TECDOC-978 (1997)
*Fission-Product Release During Postirradiation Annealing of Several Types of Coated Fuel Particles*, R.E. Bullock, Journal of Nuclear Materials, 125 (1984), pages 304-319

For accident models see:

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

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Inner PyC Layer | Inter-granular diffusion and/or intra-granular solid-state diffusion |
| | Condensed-phase diffusion | |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | ≤ 1600 °C: 7 | Remedy: None, nothing can be done |
| | > 1600 °C: 7 | None, nothing can be done |
| Rationale: The diffusion of metallic fission products through the PyCs is known to be fairly high. Only modest credit can be taken for PyC as a barrier or release delay for metallics. | Rationale: (≤ 1600 °C) The PyCs are generally assumed to provide limited retention to metallic fission products at accident temperatures. | 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.

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

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

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

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Inner PyC Layer<br>Pressure loading (Carbon monoxide) | Stress loading of the layer by carbon monoxide by increased pressure |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | ≤ 1600 °C: 7 | Remedy: Control pressure by design |
| | > 1600 °C: 7 | Control pressure by design |
| Rationale: High CO product will result in high particle pressures, especially at the higher accident temperatures. Changing the kernel composition can control CO production. (See previous entry) | Rationale: (≤ 1600 °C) Pressure can be controlled by particle design, burnup, and kernel composition. Analysis and designs are available | Closure Criterion: Proof testing of final fuel design |
| | Rationale (> 1600 °C) 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 |
|---|---|---|
| Heatup Accident | Inner PyC Layer<br>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: 7 | None |
| 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 the outer protective layers fail.

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

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

**Additional Discussion**

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

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Inner PyC Layer<br>Cracking | Lengths, widths and numbers of cracks produced in layer during accident |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | ≤ 1600 °C: 6 (failure only, cracking is not calculated) | Remedy: Review and collect new data for the codes if necessary. |
| | > 1600 °C: 6 (failure only, cracking is not calculated) | Review and collect new data for the codes if necessary. |
| Rationale: Failure of the IPyC affects the likelihood of SiC failure. See the entry on stress state. The lengths, widths, and number of cracks don't really matter – the failure does. Many models assume the SiC layer will dominate the particle failure. | Rationale: (≤ 1600 °C) There is some evidence that IPyC failure can drive SiC failure, mostly from fuel with bad PyC. Fuel models have been developed to model normal and accident behavior. | Closure Criterion: Models that predict fuel behavior under normal and accident conditions. Does one need cracks or just failure? This adds a lot of complexity. |
| | Rationale (> 1600 °C) At this temperature, the models indicate that SiC decomposition is occurring and the particles slowly (~hours) begin to release. Intact PyC will still hold gases. | Adequate test fuel performance |

**Additional Discussion**

Under accident conditions, a pressure vessel type failure model has been used with the particle failing when the pressure exceeds a critical value. Particles are assumed to fail when they meet some weakness criteria. Details of cracks are just starting to be modeled. Models indicate that cracks and debonding in the IPyC can lead to local stresses in the SiC that result in SiC failure.

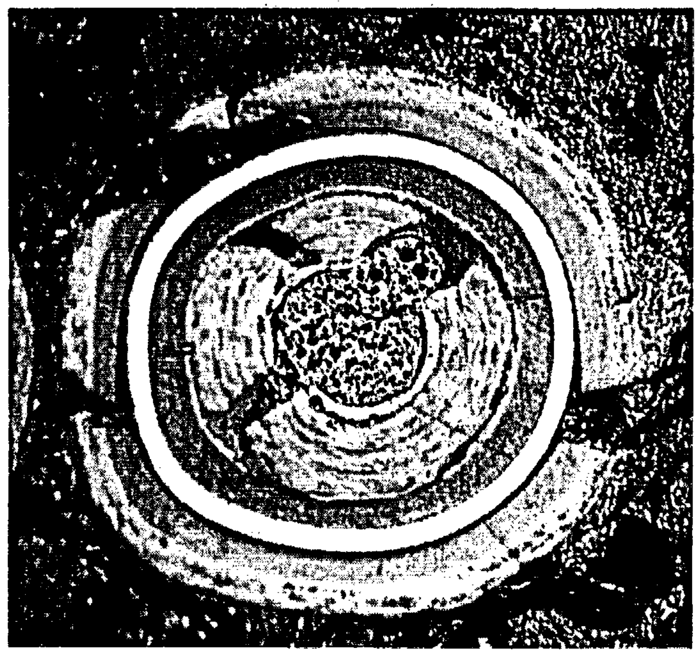
For some work on examining the effects of cracks on fuel performance and general models see:

*Consideration of the Effects on Fuel Particle Behavior from Shrinkage Cracks in the Inner Pyrocarbon Layer*, G.Miller, et. al., Journal of Nuclear Materials, 295 (2001), pages 205-212.
*Key Differences in the Fabrication, Irradiation and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance*, D.A. Petti, et. al Nuclear Engineering and Design, 222 (2003) 281-297.

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

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

*Revised MHTGR High-Temperature Fuel Performance Models*, R.C. Martin, ORNL/NPR-92/16
*Methods and Data for HTGR Fuel Performance and Radionuclide Release Modeling during Normal Operational and Accidents for Safety Analysis*, K. Verfondern, et. al., Jul-2721
*Fuel Performance and Fission Product Behavior in Gas Cooled Reactors*, IAEA-TECDOC-978 (1997)



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

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

| 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: 1 | None |
| Rationale: The IPyC is likely to be saturated with fission products so this effect may not be important. | 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 performance models generally do not use micro data (to date). Recent model development is examining some of these effects. It is likely that data uncertainties will overwhelm this effect.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Inner PyC Layer<br>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: 1 | None |
| Rationale: Some modeling has investigated trapping. The IPyC is likely to be saturated with fission products so this effect may not be important. | 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 performance models generally do not use micro data. It is likely that data uncertainties will overwhelm this effect.

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

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | ≤ 1600 °C: 7 | Remedy: None |
| | > 1600 °C: 7 | None |
| 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. | Rationale: (≤ 1600 °C) The buffer layer appears to work as planned. Gases are expected to diffusive through this layer. | Closure Criterion: None |
| | Rationale (> 1600 °C) The buffer layer appears to work as planned. Gases are expected to diffusive through this layer. | None |

**Additional Discussion**

See the design PIRT for the Buffer layer design.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Buffer Layer<br>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: 7 | None |
| 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**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
| --- | --- | --- |
| Heatup Accident | Buffer Layer<br>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: L | ≤ 1600 °C: 7 | Remedy: None |
| | > 1600 °C: 7 | None |
| 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. | Closure Criterion: None |
| | Rationale (> 1600 °C) All evidence to date indicates that the buffer layer performs as expected. | None |

**Additional Discussion**

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

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Buffer Layer<br>Maximum fuel gaseous fission product uptake | Maximum loading of fission products that can deposit from the gas phase onto surfaces of materials surrounding the fuel kernel |

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

**Additional Discussion**

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

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Buffer Layer<br>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: 7 | None |
| 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.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
| --- | --- | --- |
| Heatup 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: L | ≤ 1600 °C: 7 | Remedy: None |
| | > 1600 °C: 7 | None |
| Rationale: During accident conditions, the particle gradient is even lower than normal because the power production is low relative to operating conditions. | Rationale: (≤ 1600 °C) The codes can compute these temperatures. | Closure Criterion: None |
| | Rationale (> 1600 °C) The codes can compute these temperatures. | None |

**Additional Discussion**

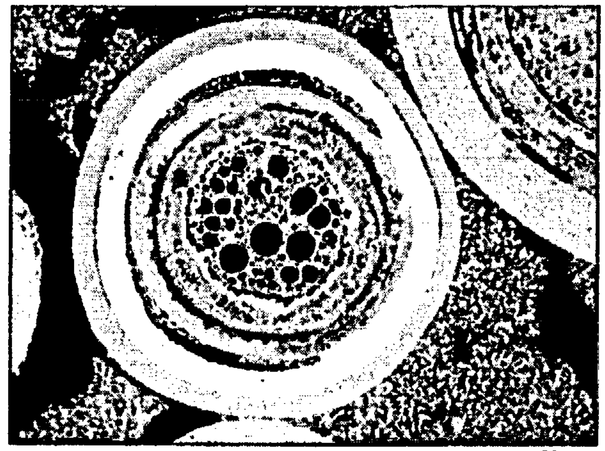
Controlling the gradients across the particle is a design issue.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Buffer Layer<br>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 | ≤ 1600 °C: 6 | Remedy: None |
| | > 1600 °C: 6 | None |
| Rationale: Ideally, the buffer layer should isolate the kernel from the IPyC, but small cracks or limited shrinkage do not seem to cause trouble. | Rationale: (≤ 1600 °C) Modest buffer shrinkage and small cracks don't seem to result in problems. | Closure Criterion: None |
| | Rationale (> 1600 °C) Modest buffer shrinkage and small cracks don't seem to result in problems | None |

**Additional Discussion**

In this high burnup Pu kernel (ORNL), considerable shrinkage took place in the buffer layer and the II less behavior of this sort, the particle performed well under irradiation.



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| 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 | |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | ≤ 1600 °C: 7 | Remedy: Determine what is required of the kernel to meet accident limits for a given damaged fuel fraction. |
| | > 1600 °C: 7 | Determine what is required of the kernel to meet accident limits for a given damaged fuel fraction. |
| Rationale: The kernel retains a considerable amount of material and release is a function of temperature. | 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 | Acceptable fuel performance. |

**Additional Discussion**

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

In some accident situations, retention of some key fission products may be required to meet accident release goals.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Kernel<br>Temperature vs. time transient conditions | The time-dependent variation of fuel temperature with time |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | ≤ 1600 °C: 7 | Remedy: None expect to watch for hot spots. |
| | > 1600 °C: 7 | None expect to watch for hot spots. |
| Rationale: The temperature history of the fuel is important. Higher temperature operation (hot spots) even if it is followed by lower temperature operation can result in greater corrosion problems. High temperatures also increase fission product diffusion. (See previous entry) | 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.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Kernel<br>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: L | ≤ 1600 °C: 7 | Remedy: None |
| | > 1600 °C: 7 | None |
| Rationale: Temperature gradients within the kernel during heat up accidents are very small. | Rationale: (≤ 1600 °C) These numbers have been calculated for the fuels of interest. No major issues are associated with them. | Closure Criterion: None |
| | Rationale (> 1600 °C) These numbers have been calculated for the fuels of interest. No major issues are associated with them. | None |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Kernel | Chemical and physical state of fission products |
| | Thermodynamic 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: 6 | If fuel kernels other than $UO_2$ are to be used, testing is required to assure that they work as expected. |
| 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 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. |

**Additional Discussion**

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

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

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Kernel<br>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: 6 | Remedy: Determine what is required of the kernel to meet accident limits for a given damaged fuel fraction. |
| | > 1600 °C: 6 | Determine what is required of the kernel to meet accident limits for a given damaged fuel fraction. |
| Rationale: While the SiC layer is the primary barrier to fission product release, diffusion through the kernel does have a modest influence. It may be important during accidents for damaged fuel. | Rationale: (≤ 1600 °C) Data on fission product diffusivities has been collected. | Closure Criterion: Demonstrated performance under the conditions of interest. |
| | Rationale (> 1600 °C) Some data is available, but the release may be so high as not to matter. | Demonstrated performance under the conditions of interest. |

**Additional Discussion**

A considerable amount of work has been done on gas diffusion in $UO_2$. It is of great importance in LWR fuels. One can look into the latest LWR models or the historical references such as:

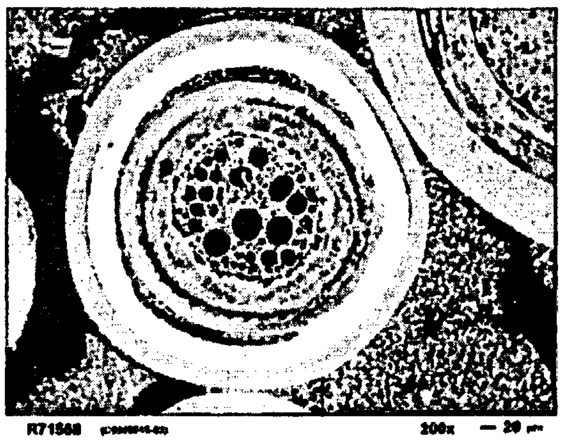
*The Diffusion Coefficients of Gaseous and Volatile Species During the Irradiation of Uranium Dioxide*, J.A. Turnbull, et. al., Journal of Nuclear Materials, 107 (1982), 168-184.

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

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Kernel<br>Condensed phase diffusion | Bulk diffusion is diffusion through the grain of a material. Surface diffusion is diffusion on the surface of the grain of material. Grain boundary diffusion is diffusion through the material at grain edges in the material |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | ≤ 1600 °C: 6 | Remedy: Determine what is required of the kernel to meet accident limits for a given damaged fuel fraction. Significant retention may be required for several key isotopes. |
| | > 1600 °C: 4 | Determine what is required of the kernel to meet accident limits for a given damaged fuel fraction. Significant retention may be required for several key isotopes. |
| Rationale: While the SiC layer is the primary barrier to fission product release, diffusion through the kernel does have a modest influence. It may be important during accidents for damaged fuel. | Rationale: (≤ 1600 °C) Data on fission product diffusivities has been collected. | Closure Criterion: Acceptable performance |
| | Rationale (> 1600 °C) Some data is available, but the release may be so high as not to matter. | Acceptable performance |

**Additional Discussion**



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

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

Also, the kernel must retain some corrosive fission products for good performance. To meet accident limits, damaged fuel releases may need to be bounded and this implies limits on the kernel diffusion. This is a tradeoff between kernel retention, fuel quality, and reactor design.

At low burnups the kernel crystal is intact and can help retain fission products. As the burnup continues and bubbles and gaps appear, the ability to retain the mobile fission products drops greatly.

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

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Kernel<br>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: 3 | Determine if this area is of any significance. |
| Rationale: The mass of oxygen from the kernel will determine the rate at which CO is formed and particle pressure. Since the particles are designed assuming maximum pressure, the rate does not seem that important, but his area is somewhat unexplored. | Rationale: ( ≤ 1600 °C) Some work has been done in this area. The full implications are not clear. | 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 |
|---|---|---|
| Heatup Accident | Kernel<br>Grain growth | Enlargement of grains as a result of diffusion |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: L | ≤ 1600 °C: 3 | Remedy: None |
| | > 1600 °C: 3 | None |
| Rationale: Kernel grain growth has not been an issue. The higher burnups of coated particles fuels often results in the destruction of any structure. See grain boundary separation entry. | Rationale: (≤ 1600 °C) The grain growth issue appears to be less important with coated particle fuel because the layers form the fission product boundary. | Closure Criterion: None |
| | Rationale (> 1600 °C) Same | None |

**Additional Discussion**

Unlike LWR fuel, the grain structure appears to be less important. Grain growth can result in the release of fission products from the kernel. So far, this has not been a big issue, because the coatings are used for fission product retention. However, under accidents conditions with tight limits, kernel release may need to be better quantified.

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup 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 | ≤ 1600 °C: 5 | Remedy: None |
| | > 1600 °C: 5 | None |
| Rationale: No significant problems in this area have been observed. | Rationale: (≤ 1600 °C) Reactions of this nature can be investigated using thermochemical codes. Nothing has come up to date. | Closure Criterion: None |
| | Rationale (> 1600 °C) Reactions of this nature can be investigated using thermochemical codes. Nothing has come up to date. | None |

**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.

Generally, this issue has not been a problem under accident conditions. Under normal operation it can lead to kernel migration.

## Appendix C.3

### Detailed PIRT Submittal by the SNL Panel Member

D. A. Powers

TRISO Fuel PIRT: Heatup 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 |
|---|---|---|
| Heatup Accident | Fuel Element<br>Irradiation history | The temperature, burnup and fast fluence history of the layer |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 3 | Remedy: |
| Rationale: Fast fluence will determine the amount of radiation damage sustained by the fuel element material, its 'growth' and possible cracking. These items will affect the transport of radioactive material released from fuel particles through the matrix material. Cracks will provide short circuit pathways. Defects will provide adsorption sites for transporting gases and vapors | Rationale: Whereas there is some limited information on the effects of radiation on graphite material, we do not have a usefully large data base on the specific materials to be used in the proposed fuel. Nor do we have a reliable irradiation history for the material | Closure Criterion: |

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Fuel Element<br>Condensed phase diffusion | Intergrannular diffusion and/or intragrannular solid-state diffusion |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: M | Level: 2 | Remedy: |
| Rationale Condensed phase mass transport of radioactive materials through fuel elements will not be a significant transport mechanism in comparison to gas phase diffusion. Condensed phase mass transport may affect some limited aspects of the mass transport such as the accumulation and release of material from basal planes of the graphite | Rationale We have some limited understanding of mass transport in graphite. What information we have suggests that condensed phase diffusion is strongly dependent on the particular graphitic material and that it is challenging to apply results for one material to another that differ in microstructure and impurity levels. We donot have the detailed information to predict condensed phase mass transport for the particular graphitic material making up the fuel matrix. | Closure Criterion: |

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Fuel Element<br>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: 4 | Remedy: |
| | | |
| Rationale: Gas phase mass transport will be the fastest mechanism for the transport of fission products released from the fuel particles to reach the fuel element surface. The mass transport will involve flow through a porous medium that has been irradiated and probably has a thermal gradient. Permeability data are not available now for this material. | We have some generic knowledge of gas phase mass transport through irradiated porous media. Unfortunately, we do not now have the material characterization data to apply this understanding in any quantitative sense to the matrix material, nor do we have the gas phase species data to predict transport through the matrix. | Closure Criterion: |
| | | |

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup 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 | Level: 3 | Remedy: |
| Rationale: The chemical form of the fission product species will largely dictate the relative efficiencies of transport of the various fission products released from fuel particles through the fuel element material. | Rationale We have a fairly primitive understanding of the chemical forms of fission products that could be present in the fuel element material. To a real extent this understanding is based on experience in systems that are fairly oxidizing and only involve oxides and elemental forms. In the reducing circumstances of graphite coated particle fuels, vapor phase carbides, carbonyls and even cyanides could be important forms of the fission products. | Closure Criterion: |

Additional Discussion

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Outer PyC Layer<br>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: |
| | | |
| Rationale: Gas phase diffusion through the porous outer PyC layer will be the fastest mechanism for fission product transport across this layer even if the layer is nominally intact but has pores and microscopic cracks | Rationale: We have at best a generic knowledge of gas phase mass transport through porous PyC. We do not have the detailed characterization of permeability and tortuosity needed to predict the rates of gas phase mass transport through this layer. Of course, if the layer is cracked in a macroscopic fashion, transport can be estimated more easily. | Closure Criterion: |
| | | |

Additional Discussion

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Outer PyC Layer<br>Condensed Phase Diffusion | Inter-granular diffusion and/or intra-granular solid-state diffusion |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: M | Level: 2 | Remedy: |
| | | |
| Rationale: Condensed phase diffusion will be expected to contribute modestly to fission product transport across the Outer PyC layer relative to gas phase mass transport. Of the various mass transport mechanisms, it is likely that grain boundary diffusion will be the only significant condensed phase mass transport mechanism | Rationale We lack adequate data for the specific material to estimate bulk diffusion , grain boundary diffusion or surface diffusion. The later two diffusion process are known to depend critically on the specifics of the material and we do not have detailed material property data for Outer PyC layer | Closure Criterion: |
| | | |

<u>Additional Discussion</u>

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Outer PyC Layer<br>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: 8 | Remedy: |
| | | |
| Rationale: The kernel will release oxygen and this oxygen can react with the carbon in the outer pyrolytic graphite layer. But, before the oxygen can reach this layer it will have to pass through the more reactive and hotter buffer layer and the Inner pyrolytic graphite layer. Consequently, it seems unlikely that much oxygen will survive this transport and be available to react with the Outer Pyrolytic Graphite layer | Rationale: We understand a lot about the reaction of oxygen with graphite and can be reasonably confident that there will not be a lot of oxygen from the kernel reaching the outer graphite layers | Closure Criterion: |

<u>Additional Discussion</u>

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Outer PyC Layer<br>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 | Level: 4 | Remedy: |
| Rationale: The forces are only important if they lead to rupture of the layer. Such a rupture will permit the short-circuit release of gas and vapor fission products | Rationale: The evolution of the forces and the potential for rupture under accident conditions have not been definitively described in the literature | Closure Criterion: |

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Outer PyC Layer<br>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: 3 | Remedy: |
| Rationale It is known that fission products do accumulate in the basal planes of the graphite regions of pyrolytic graphite. They become intercalated. This, however, can be viewed as a peculiarity of the graphite structure that makes diffusion potentially anisotropic. Still the potential for intercalation can be handled in the diffusion formulation rather than as a unique topic. As temperature increases, the preferential accumulation of fission products in the basal planes will abate | Rationale: There is not a great deal of quantitative information on the intercalation of fission products in the particular type of graphite to be used for the outer pyrolytic layer | Closure Criterion: |

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Outer PyC Layer<br>Trapping | Adsorption and defect occupation |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: L | Level: 3 | Remedy: |
| Rationale: It is known that irradiation produces defects in graphite that will absorb species including, but not exclusively fission product species. This adsorption can be significant during operations. It probably has only a transient importance during a heat up accident for at least two reasons. First, heat up thermally anneals the defects and when this happens the adsorbed fission products are released. Second, at the higher temperatures the vapor pressures of the fission products in equilibrium with the defects are higher so the impact of adsorption becomes less significant | Rationale: There is not a great deal of information on the defect adsorption (See review article in the Chemistry and physics of Carbon). Certainly, there is nothing specific to the particular carbon that will be selected eventually for the fuel particles | Closure Criterion: |

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Outer PyC Layer<br>Cracking | Lengths, widths and numbers of cracks produced in layer during accident |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 2 | Remedy: |
| | | |
| Rationale: Cracks provide short circuit pathways for the release of gaseous and vapor fission products across the layer | Rationale: We do not have the capability to predict the occurrence or characteristics of cracks formed in the layer. We have limited capabilities to predict the flow rates of gases through these cracks. | Closure Criterion: |
| | | |

Additional Discussion

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | SiC Layer<br>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: |
| Rationale: Gas phase transport will certainly be the most rapid means of fission product transport across the SiC layer if the layer has macroscopic cracks. Even if the layer is nominally intact, pores and microscopic cracks should be numerous enough in this rapidly formed material to mean that gas phase mass transport across the layer will be more rapid than any of the condensed phase mass transport mechanisms discussed below. The pressure driven term in the diffusion equation for this layer will be particularly important to consider. | Rationale: There is not sufficient information on the specific, rapidly formed SiC material to predict gas phase mass transport across this layer. Permeability data, porosity data, pore structure data as well as data on the effects of radiation damage and stress will be needed and don't appear to be forthcoming with the kind of detail needed to predict fuel performance. | Closure Criterion: |

Additional Discussion

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
| --- | --- | --- |
| Heatup Accident | SiC Layer<br>Condensed-phase diffusion | Inter-granular diffusion and/or intra-granular solid-state diffusion |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
| --- | --- | --- |
| Rank: : M | Level: 2 | Remedy: |
| Rationale: : Condensed phase diffusion across the SiC layer is thought to contribute to the transport of some fission products, notably radioactive silver. But, for most fission products condensed phase diffusion will be a modest mechanism for transport relative to gas phase diffusion even if the layer is nominally intact with no macroscopic cracks. Of the condensed phase diffusion processes, grain boundary diffusion and surface diffusion are likely to be more important than bulk diffusion even if diffusion along the basal planes is included in bulk diffusion. Grain boundary diffusion and surface diffusion are notoriously sensitive to details of microstructure and impurity levels of the material. | Rationale : There is not the material characterization for the SiC layer to predict condensed phase diffusion processes. Certainly, diffusion coefficients for the specific material are not available though there is an active research program at MIT looking at unirradiated material. More importantly, the SiC formed by chemical vapor deposition processes at very high rates will be quite unlike bulk materials for which there are some data. | Closure Criterion: |

Additional Discussion

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | SiC Layer<br>Thermal deterioration/decomposition | Decline in the quality of the layer due to thermal loading |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: : M | Level: 3 | Remedy: |
| Rationale: : Whereas, we cannot be certain whether the equilibrium SiC structure actually exists in the coated particle fuel as opposed to one of the Many metastable forms of SiC, it appears that temperatures envisaged for the hypothetical accident are too low to produce significant decomposition of SiC. Perhaps irradiation might cause some decomposition | Rationale : Detailed data on the specific material that is formed in the very dynamic coating process and its irradiation stability for the protracted irradiation times now envisaged are simply not available. Furthermore, it is not at all clear how any incipient decomposition will affect the transport of fission products. | Closure Criterion: |

Additional Discussion

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | SiC Layer<br>Fission product corrosion | Attack of layer by fission products, e.g., Pd |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: : L | Level: 3 | Remedy: |
| | | |
| Rationale: : Some fission products, notably palladium, are thought to attack SiC by the formation of stable silicides or carbides. The inventories of these fission products that are likely to reach the layer are however low and unless there is some feature of the asymmetry of the particles that lead to concentration of these fission products at some particular location, it is unlikely that they can breach the layer by themselves | Rationale : A quantitative analysis of phase equilibria in the M-Si-C system where M is represents various fission products has not been undertaken to evaluate this potential failure mechanism. | Closure Criterion: |
| | | |

Additional Discussion

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | SiC Layer<br>Heavy metal diffusion | Diffusion of heavy metals through layer |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: M | Level: 2 | Remedy: |
| | | |
| Rationale: It is not entirely clear what is meant by "heavy metals" here. It may mean U, Pu, Th, etc. It could mean any element from the second and third transition series to the Actinides and Lanthanides. Regardless, the transport of these materials will be entire like the transport of fission products discussed above – dominated by gas phase mass transport. | Prediction of transport across the SiC layer is just not possible with the limited characterization data now available in the literature. | Closure Criterion: |

Additional Discussion

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | SiC Layer<br>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: |
| | | |
| Rationale: The only source of oxygen for this particular accident is from the kernel. Oxygen released from the kernel will have to pass through the reactive buffer layer and the inner pyrolytic graphite layer both of which may be hotter and more reactive than the SiC layer. It is difficult to see how much oxygen will actually reach the SiC layer to react. | Rationale Though there are data on the reaction of SiC with oxygen it is not evident that these data are applicable to the particular form of SiC that will be produced in a strained condition in the coated particle fuels. | Closure Criterion: |
| | | |

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | SiC Layer<br>Fission product release through undetected defects | Passage of fission gas from the buffer region through defects in the SiC layer |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 3 | Remedy: |
| Rationale: this could be a predominant mode of fission product release in the intial stages of an accident before accident progression causes additional damage to the SiC layer. | Rationale: We do not have a good data base on the kinds of likely defects or the ability of fission products to pass through these defects. | Closure Criterion: |

Additional Discussion

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | SiC Layer<br>Fission gas release through failures | Passage of fission gas from the buffer region through regions in the SiC layer that fail during operation or an accident |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 3 | Remedy: |
| | | |
| Rationale: this will be an important mechanism of fission product venting from the region bounded by the SiC layer | Rationale: We do not have a capability to predict the performance of the SiC layer under a wide range of accident conditions. | Closure Criterion: |
| | | |

Additional Discussion

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | SiC Layer<br>Thermodynamics of the SiC-fission product system | Include solubility, intermetallics, and chemical activity |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 4 | Remedy: |
| Rationale: The thermodynamics of these systems will dictate whether fission products corrode the SiC layer and lead to rupture of the layer | Rationale: the carbide systems are not easily predicted and there are scant data for very high temperatures. The reliability of what data there are for the particular SiC that will be used in the particles is not well established. | Closure Criterion: |

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | SiC Layer | Change of SiC microstructure as a function of temperature |
| | Sintering | |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: M | Level: 6 | Remedy: |
| | | |
| Rationale:Sintering will refine the structure of the SiC perhaps making it stronger and more resistant to failure | Rationale: There is a lot of data on the sintering of SiC. Its applicability to the SiC used in particulate fuel is open to question | Closure Criterion: |
| | | |

Additional Discussion

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Inner PyC Layer<br>Gas Phase Diffusion | Diffusion of gaseous fission products through layer (Knudsen and bulk diffusion through pore structure, and pressure driven permeation through structure) |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 6 | Remedy: |
| | | |
| Rationale: Gas phase diffusion across the inner PyC layer will be a dominant mechanism of mass transport of fission products across this layer. The transport across an intact layer (no macroscopic cracks) will involve both chemical diffusion and Knudsen diffusion. There may be some modest contribution from pressure diffusion across the layer. | Rationale: We have some generic understanding of the gas phase mass transport across porous graphite layers. This understanding leads us to the identification of properties of the material that are not available for the inner PyC layer. Without this information on permeability, pore structure, tortuosity etc., it is just not possible to make meaningful estimations of the gas phase mass transport across this layer. | Closure Criterion: |
| | | |

Additional Discussion

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Inner PyC Layer<br>Condensed phase diffusion | Inter-granular diffusion and/or intra-grannular solid state diffusion |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: M | Level: 2 | Remedy: |
| | | |
| Rationale: The situation with respect to condensed phase mass transport in the inner PyC layer is quite like that in the outer PyC layer – so much so that one wonders why the layer will have to be repeated. Condensed phase diffusion will be slow relative to gas phase diffusion. Of the condensed phase diffusion processes, surface and grain boundary diffusion will be more important than bulk phase diffusion at the relatively modest temperatures envisaged for the hypothesized accident. | Rationale: We know that surface and grain boundary diffusion are critically dependent on the microstructure and impurity levels in the host material. Neither of these are known with the detail needed for analysis of condensed phase diffusion of fission products in the inner PyC layer. Attempts to make estimates based on the behavior of fission products in other materials would be susceptible to error of unpredictable magnitude. | Closure Criterion: |
| | | |

Additional Discussion

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Inner PyC Layer<br>Pressure loading (Fission products) | Stress loading of the layer by fission products by increased pressure |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: L | Level: 7 | Remedy: |
| Rationale: The pressure loading will be on the SiC layer rather than on the inner PyC layer and that loading will come more from CO gas than from fission gases, though clearly fission gases could contribute. | Rationale:<br>Some estimates of the pressure loading from fission gases are possible using crude release models. | Closure Criterion: |

Additional Discussion

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

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 2 | Remedy: |
| | | |
| Rationale: Reaction of the buffer layer with oxide fuel will be the source of a lot of CO within the confines of the SiC layer. | Rationale: The magnitude of the pressure drop across the inner PyC layer is not known, so it is not possible to assure that the loading is on the inner PyC layer rather than on the SiC layer. In either case, the extent of reaction of the buffer layer with the fuel oxide during the accident is not known well. Equilibrium calculations of the CO partial pressure suggest very high partial pressures. What limited experimental data there are suggest high partial pressures but partial pressures that may be a factor of 4 less than equilibrium for fuel that has not experienced the temperature transient of the hypothesized accident. | Closure Criterion: |
| | | |

Additional Discussion

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Inner PyC Layer<br>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 | Level: 3 | Remedy: |
| | | |
| Rationale: The only source of oxygen for this accident is from the kernel. The source is quite small and the oxygen released from the kernel has to pass through the buffer which is inherently more reactive and hotter than the Inner PyC layer. Much of the oxygen may react with the buffer before it reaches the Inner PyC. But, still it is possible that local pore pathways may alloy oxygen to impinge on the Inner PyC layer and create preferential pathways for release of fission products across the layer | Rationale: We don't have the capability now to predict the transport of oxygen from the kernel through the various layers of the coated particle fuel especially when reactive defects are present. | Closure Criterion: |

Additional Discussion

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup 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 | Level: 2 | Remedy: |
| | | |
| Rationale: It is known that the stress state of a material can affect both condensed phase diffusion and gas phase diffusion. These effects are rather subtle. More important is whether the layer remains intact or develops macroscopic cracking that will allow the venting of the pressurized gases from within the SiC layer. This issue is, however, treated in other questions. | Rationale: There is some limited information on the stress state of the layer. There is no information on how this layer will affect fission product transport across the layer baring layer failure which is treated in other questions. | Closure Criterion: |
| | | |

Additional Discussion

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Inner PyC Layer<br>Cracking | Lengths, widths and numbers of cracks produced in layer during accident |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 1 | Remedy: |
| | | |
| Rationale: Gross cracking of the layers will allow venting of the pressurized gases containing fission product vapors in an exceptionally rapid mass transport process. More problematical is the formation of micro-cracks that do not allow venting but do provide short circuit pathways for gas phase mass transport across the layer. | Rationale: There is no evidence of a calculational capability to predict details of layer failure. It is difficult enough just to define criteria when failure will occur. | Closure Criterion: |
| | | |

Additional Discussion

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Inner PyC Layer<br>Intercalation | Trapping of species between sheets of the graphite structure |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: M | Level: 2 | Remedy: |
| | | |
| Rationale: Intercalation could help retain or at least retard the release of fission products. Intercalation is known to occur for some species such as potassium and could be expected for cesium. Of more interest is the generalized tendency of fission products to accumulate preferentially at the basal plains of the graphite structure | Rationale: There does not seem to have been a systematic examination of intercalation for the range of fission products that are of interest. | Closure Criterion: |
| | | |

Additional Discussion

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Buffer Layer<br>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: |
| Rationale: Gas phase diffusion will be the dominant transport mechanism for fission products across the highly porous buffer layer | Rationale: We have some generic knowledge of the transport of gases across a porous layer. This layer is complicated by the existence of radiation-induced defects that can absorb fission products, a thermal gradient that can enhance or inhibit fission product release, and the existence of a pressure gradient with simultaneous flow of the majority gas – carbon monoxide. The necessary material characterization data and even the gas properties are not available to make predictions at this time. | Closure Criterion: |

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Buffer Layer<br>Condensed phase diffusion | Intergrannular 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 | Level: 1 | Remedy: |
| | | |
| Rationale: Because of the highly porous nature of the buffer material, it will be unlikely that condensed phase mass transport will contribute significantly to transport across this layer on the time scales of the hypothesized accident. | Rationale: Insufficient material characterization or condensed phase diffusion coefficients are available to estimate mass transport by condensed processes. | Closure Criterion: |
| | | |

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Buffer Layer<br>Response to kernel swelling | Mechanical reaction of the layer to the growth of the kernel via swelling |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: M | Level: 4 | Remedy: |
| Rationale: The buffer layer is included to absorb the swelling of the kernel during normal operations and one just presumes that it will be capable of absorbing the incremental swelling that might occur in the accident. The crushing of the layer could have some effect on the material permeability and because of this fission product transport by gas phase processes could be affected. | Rationale: There is almost no information on how the buffer layer behaves under accident conditions. There are not data characterizing the gas phase mass transport characteristics of the material at any condition – accidents or normal operations. | Closure Criterion: |

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Buffer Layer<br>Maximum fuel gaseous fission product uptake | Maximum loading of fission products that can deposit from the gas phase onto surfaces of materials surrounding the fuel kernel |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: L | Level: 2 | Remedy: |
| | | |
| Rationale: Even if the layer can uptake a lot of fission products the temperatures reached in the heat up accident will essential reverse this uptake | Rationale No definitive data on the potential uptake of irradiated buffer material | Closure Criterion: |
| | | |

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Buffer Layer<br>Layer oxidation | Reaction of buffer layer with oxide materials in the kernel. |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 3 | Remedy: |
| Rationale: The uptake resulting in pressurization by CO is quite important during operations and the reactions will remain important during the accident. Also the reaction will produce release by the refinement of the reacting urania fuel. | Rationale: Little data on reaction rates of either the buffer or the urania. Useful data would have to be for irradiated materials | Closure Criterion: |

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Buffer Layer<br>Thermal gradient | Change in temperature with distance |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 2 | Remedy: |
| Rationale: Thermal gradients can affect multicomponent gas phase diffusion across porous media in unexpected ways | Rationale: We don't have the data needed to assess the effects of gradients on the transport across the layer in a multicomponent system | Closure Criterion: |

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
| --- | --- | --- |
| Heatup Accident | Buffer Layer<br>Irradiation and thermal shrinkage of buffer | Dimension changes in the buffer layer or changes in its porosity produced by irradiation or by exposure to elevated temperatures |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
| --- | --- | --- |
| Rank: L | Level: 5 | Remedy: |
| | | |
| Rationale:These phenomena are more important for operations and as initial conditions for the accident. During the accident the irradiation will be modest. The temperature scenario is sufficiently modest that no major sintering of the graphite is to be expected | Rationale: Some understanding of these processes exists in a qualitative sense. I doubt we are predictive for the materials of interest. | Closure Criterion: |
| | | |

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Kernel<br>Maximum fuel temperature | Maximum fuel temperature attained by the fuel kernel during the accident |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 5 | Remedy: |
| Rationale: Temperature is well known to be one of the dominant factors affecting the releases of fission products from uranium dioxide fuel kernels | Rationale In principle, it should be possible to calculate the maximum temperature of the kernel. But, complexities of the thermal conductivities of layer surrounding the fuel kernel mean that major uncertainties in the fuel temperatures under accident conditions must exist – on the order of 50 to 200 Kelvin. Fission product releases from the highly burned kernels are not especially well known since the existing data base extends to only burnups of about 35 GWd/t | Closure Criterion: |

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Kernel<br>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 | Level: 4 | Remedy: |
| | | |
| Rationale: See above; time at temperature is, of course an important consideration in thinking about the release of radionuclides. | Rationale: See above. | Closure Criterion: |
| | | |

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

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: M | Level: 3 | Remedy: |
| Rationale: Ordinarily the conduction of heat in urania fuel is calculable. The urania kernels for coated particle fuel are expected to be taken to much higher levels of burnup than is usual for such fuel. The development of a 'rim' region and macroscopic porosity in the urania as the irradiated material restructures will greatly complicate the calculation of temperatures. | Rationale: A predictive model of the effects of burnup on fuel heat transfer for very high burnups in coated particle fuel is not available. | Closure Criterion: |

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Kernel<br>Thermodynamic state of fission products | Chemical and physical state of fission products |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 5 | Remedy: |
| | | |
| Rationale: Fission product release depends on the chemical activity of the fission products. Completely diluted in the urania matrix, the fission product chemical activities could be quite low. But, fission products are known to segregate under more oxidizing conditions to form metallic nodules and urinates. This can greatly affect the chemical activities of these fission products. | Rationale We have quite a lot of information on fission product chemical form and physical state in conventional urania fuels. There is much less such information for fuel kernels in the more reducing conditions of coated particle fuels and the information gets very scarce when very high burnups are achieved in the fuel. | Closure Criterion: |
| | | |

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Kernel<br>Gas phase diffusion | Diffusion of gaseous fission products through the kernel (Knudsen and bulk diffusion through pore structure, and pressure driven permeation through the structure) |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 3 | Remedy: |
| | | |
| Rationale: This is the dominant mechanism of fission product transport through the pore structure of urania fuel | Rationale Difficult to model for the high burnup high porosity kernel material which may not have a simple geometry. | Closure Criterion: |
| | | |

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Kernel | Intergranular diffusion and/or intragranular solid state diffusion |
| | Condensed phase diffusion | |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 3 | Remedy: |
| | | |
| Rationale: This is the predominant mechanism for transport of fission products from inside fuel grains to the interconnected pore structure of the kernel | Rationale A defensible set of diffusion coefficients does not exist. The formalism for calculating the diffusion has not been developed since it appears the Booth type modeling is grossly inapplicable | Closure Criterion: |
| | | |

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Kernel<br>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: H | Level: 3 | Remedy: |
| | | |
| Rationale: Usually in urania fuels, the oxygen flux is accommodated by the molybdenum-molybdenum dioxide equilibria and the reaction with clad which quickly becomes passivated. For coated particle fuels, the oxygen flux will be to the strongly reducing buffer graphite. This flux will affect the flux of fission products through the fuel as a result of multicomponent effects. | Rationale We lack the necessary fundamental data to accurately predict the effect of an oxygen flux to the surface of fuel kernels on fission product release. | Closure Criterion: |
| | | |

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
| --- | --- | --- |
| Heatup Accident | Kernel<br>Grain growth | Enlargement of grains as a result of diffusion |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
| --- | --- | --- |
| Rank: L | Level: 8 | Remedy: |
| | | |
| Rationale: Grain growth is not the problem because fission products tend to pin the grain boundaries. Far more important is the restructuring of the fuel as burnup progresses | Rationale There is a fairly good understanding of grain growth in urania fuels. | Closure Criterion: |
| | | |

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Heatup Accident | Kernel<br>Buffer carbon-kernel interaction | Chemical reaction between carbon and the fuel (UO2 or UOC) to form UC2 and CO ( gas) |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | Level: 3 | Remedy: |
| | | |
| Rationale: This is a crucial interaction that affects both the thermodynamic state of fission products and the pressurization of the gases within the SiC layer. | Rationale There is very little information on the rates of buffer carbon reaction with highly irradiated urania fuel | Closure Criterion: |
| | | |

# 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<br>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)<br>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<br>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 | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Rapid Reactivity Accident | Fuel Element<br>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: ( $\leq$ 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) | |

**Additional Discussion**

| 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<br>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: ( $\leq$ 1600 °C) | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Rapid Reactivity Accident | Outer PyC Layer<br>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<br>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) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Rapid Reactivity Accident | Outer PyC Layer<br>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<br>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<br>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: ( $\leq$ 1600 °C) | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Rapid Reactivity Accident | SiC Layer<br>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<br>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<br>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<br>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<br>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<br>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<br>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<br>Fission product release through failures, e.g., cracking | Passage of fission products 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 | 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<br>Thermodynamics of the SiC-fission product system | Chemical form of fission products including the effects of solubility, intermetallics, and chemical activity |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: 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 | Change of graphite microstructure as a function of temperature |
| | Sintering | |

| 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<br>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<br>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) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Rapid Reactivity Accident | Inner PyC Layer<br>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)<br>Can be calculated | Closure Criterion: |
| | Rationale ( > 1600 °C) | |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Rapid Reactivity Accident | Inner PyC Layer<br>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<br>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<br>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<br>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<br>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: ( $\leq$ 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<br>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<br>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: ( $\leq$ 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<br>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<br>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<br>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<br>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<br>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<br>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<br>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<br>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: ( $\leq$ 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<br>Energy Transport: Conduction within kernel | Flow of heat within a medium from a region of high temperature to a region of low temperature |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: M | 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 | Chemical and physical state of fission products |
| | Thermodynamic 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:<br>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<br>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<br>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<br>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<br>Buffer carbon-kernel interaction | Chemical reaction between carbon and the fuel ($UO_2$) to form $UC_2$ and CO ( gas) |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: L | 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: ( $\leq$ 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<br>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<br>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<br>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<br>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<br>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<br>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: 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<br>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 | ≤ 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. |

**Additional Discussion**

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

*Revised MHTGR High-Temperature Fuel Performance Models*, R.C. Martin, ORNL/NPR-92/16*Methods and Data for HTGR Fuel Performance and Radionuclide Release Modeling during Normal Operational and Accidents for Safety Analysis*, K. Verfondern, et. al., Jul-2721

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

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

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

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Rapid Reactivity Accident | Outer PyC Layer<br>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: I | 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<br>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<br>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<br>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<br>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<br>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<br>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<br>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<br>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<br>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 |

**Additional Discussion**

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<br>Thermodynamics of the SiC-fission product system | Chemical form of fission products including the effect of solubility, intermetallics, and chemical activity |

| 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 | Change of graphite microstructure as a function of temperature |
| | Sintering | |

| 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<br>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<br>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<br>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<br>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<br>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<br>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 | ≤ 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<br>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<br>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: 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<br>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<br>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<br>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<br>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<br>Thermal gradient | Change in temperature with distance |

| 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. |

**Additional Discussion**

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<br>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<br>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<br>Temperature vs. time transient conditions | The time-dependent variation of fuel temperature with time |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | ≤ 1600 °C: 7 | Remedy: None, expect to watch for hot spots. |
| | > 1600 °C: N/A | Remedy: N/A |
| Rationale: The temperature history of the fuel is important 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<br>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. |

**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)

| **Life Cycle Phase** | **Factor, Characteristic or Phenomenon** | **Definition** |
|---|---|---|
| Rapid Reactivity Accident | Kernel<br>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<br>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 | Chemical and physical state of fission products |
| | Thermodynamic 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. |

**Additional Discussion**

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

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

The 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<br>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<br>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<br>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<br>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 | Chemical reaction between carbon and the fuel (UO2) to form UC2 and CO ( gas) |
| | Buffer carbon-kernel interaction | |

| 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<br>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<br>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<br>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: |

**Additional Discussion**

| 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<br>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<br>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<br>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<br>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: ( $\leq$ 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<br>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<br>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<br>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<br>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<br>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 | 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<br>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<br>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<br>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<br>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<br>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 | Chemical forms 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 | 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<br>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<br>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<br>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<br>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<br>Pressure loading (Carbon monoxide) | Stress loading of the layer by carbon monoxide pressure |

| 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<br>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<br>Stress state (compression/tension) | The state of the forces induced by external forces that are acting across the layer to resist movement |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: H | 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<br>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<br>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<br>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<br>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<br>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<br>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 | Change in temperature with distance |
| | Thermal gradient | |

| 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<br>Irradiation and thermal shrinkage of buffer | Dimension changes in the buffer layer or changes in its porosity produced by irradiation or by exposure to elevated temperatures |

| Importance Rank and Rationale | Knowledge Level and Rationale | Remedy for Inadequate Knowledge/Issue Closure Criteria |
|---|---|---|
| Rank: L | Level: 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<br>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 | 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 | 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 | Closure Criterion: |

**Additional Discussion**

| Life Cycle Phase | Factor, Characteristic or Phenomenon | Definition |
|---|---|---|
| Reactivity Accident | Kernel<br>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<br>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<br>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 | 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<br>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<br>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<br>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<br>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:<br>Define a model of Mo acitivity in inclusion<br>Estimate the kinetics of reaction of Mo in the inclusions with diffusing oxygen<br>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<br>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<br>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**

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10. SUPPLEMENTARY NOTES

M. B. Rubin, NRC Project Manager


11. ABSTRACT *(200 words or less)*

TRISO-coated particle fuel is to be used in the next generation of gas-cooled reactors. In anticipation of future licensing applications for gas-cooled reactors, the United States Nuclear Regulatory Commission (NRC) seeks to fully understand the significant features of TRISO-coated particle fuel design, manufacture, and operation, as well as behavior during accidents. The objectives of the TRISO Phenomena Identification and Ranking Table (PIRT) program are to (1) identify key attributes of gas-cooled reactor fuel manufacture which may require regulatory oversight, (2) provide a valuable reference for the review of vendor fuel qualification plans, (3) provide insights for developing plans for fuel safety margin testing, (4) assist in defining test data needs for the development of fuel performance and fission product transport models, (5) inform decisions regarding the development of NRC's independent reactor fuel performance code and fission product transport modules, (6) support the development of NRC's independent models for source term calculations, and (7) provide insights for the review of vendor fuel safety analyses. To support those objectives, the NRC commissioned a PIRT panel to identify and rank the factors, characteristics, and phenomena associated with TRISO-coated particle fuel. PIRTs were developed for (1) Manufacturing, (2) Operations, (3) a Depressurized Heatup Accident, (4) a Reactivity Accident, (5) a Depressurization Accident with Water Ingress, and (6) a Depressurization Accident with Air Ingress.



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