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 Process Variables (Current process; process may change)	Layer coating process specifications (Buffer, IPyC, SiC, OPyC) 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 Process Variables (Current process; process may change)	Layer coating process specifications (Buffer, IPyC, SiC, OPyC) 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 Process Variables (Current process; process may change)	Layer coating process specifications (Buffer, IPyC, SiC, OPyC) 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 Process Variables (Current process; process may change)	Layer coating process specifications (Buffer, IPyC, SiC, OPyC) 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 Process Variables (Current process; process may change)	Layer coating process specifications (Buffer, IPyC, SiC, OPyC) 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 Process Variables (Current process; process may change)	Layer coating process specifications (Buffer, IPyC, SiC, OPyC) 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 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	Filler mixed with resin
	Matrix and Binder	

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 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 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 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 Impurities control	Minimization of contamination of fuel form by process equipment (e.g., iron, chrome, etc)

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	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:
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 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	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: 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:

<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. 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 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	Interconnected void accessible to the surface
	Porosity	

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	Size and orientation of the grains and the pores
	Grain size and microstructure, e.g. alignment	

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:

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. 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 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 Density	Mass per unit volume

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	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:
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 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 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	Difference in crystal orientation along principal directions as measured by the BAF
	Anisotropy (initial)	

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:

<u>Additional Discussion</u>

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	Interfacial strength at the interface
	Bonding strength (inner PyC to SiC)	

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	Interconnected void accessible to the surface
	Porosity	

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 Thin or missing	Layer thickness less than specified or missing layer

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	Mass per unit volume and interconnected void accessible to the surface
	Density and open porosity	

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	Mass per unit volume in final form
	Density	

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 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 Process Variables (Current process; process may change)	Layer coating process specifications (Buffer, IpyC, SiC, OpyC) 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 Process Variables (Current process; process may change)	Layer coating process specifications (Buffer, IpyC, SiC, OpyC)	Ratio of active gas to total gas, including concentration
	Ratio of gases	

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.

<u>Additional Discussion</u>
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 Process Variables (Current process; process may change)	Layer coating process specifications (Buffer, IpyC, SiC, OpyC) 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.

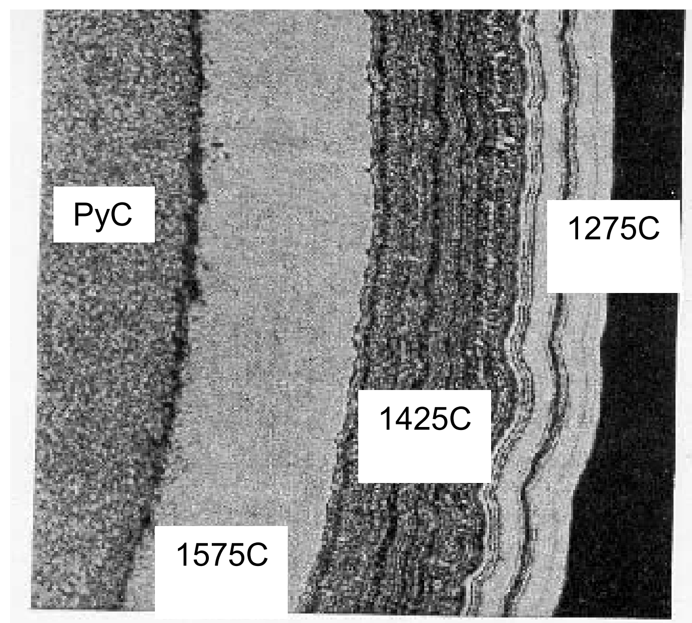
<u>**Additional Discussion**</u>

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 Process Variables (Current process; process may change)	Layer coating process specifications (Buffer, IpyC, SiC, OpyC) 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

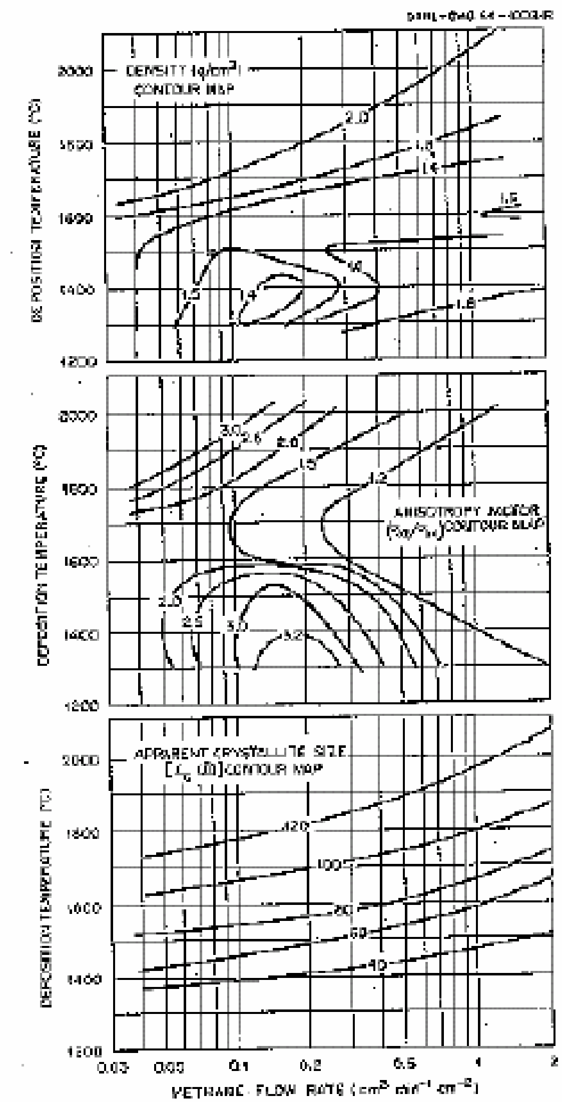
This issue has also received international examination as well.

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 Process Variables (Current process; process may change)	Layer coating process specifications (Buffer, IpyC, SiC, OpyC) 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 Process Variables (Current process; process may change)	Layer coating process specifications (Buffer, IpyC, SiC, OpyC)	Size is measured by the diameter of the coater
	Coater Size	

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 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

<u>Additional Discussion</u>

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.
.

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	Filler mixed with resin
	Matrix and Binder	

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)	

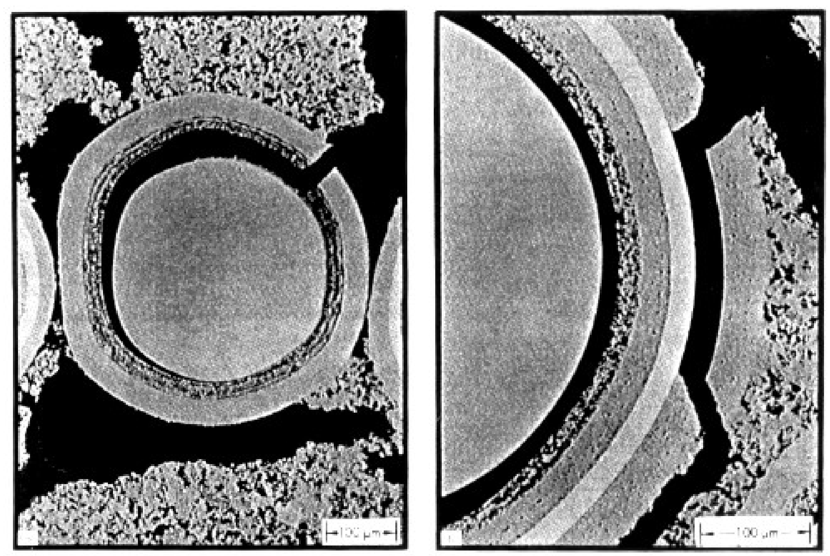
Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 7	Remedy: None if the current successful (German) process and materials are used. If changes are made, testing is warranted.
Rationale: If the bonding strength of the matrix 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.

<u>Additional Discussion</u>

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 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.

<u>Additional Discussion</u>

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	Baking full fuel element to drive off volatiles
	Carbonization	

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	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: 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.

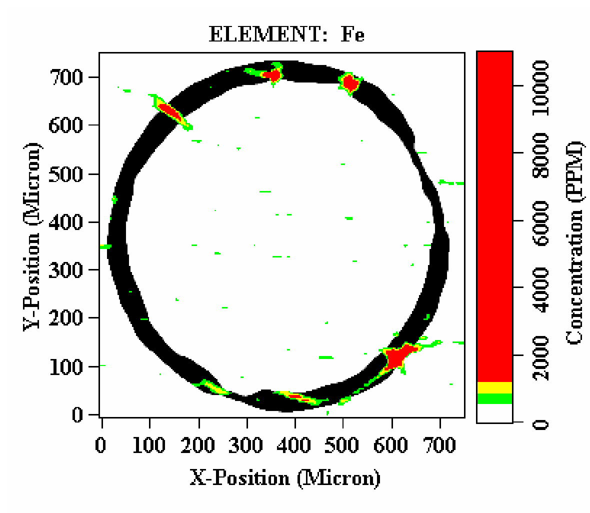
Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Manufacturing	Fuel element	Minimization of contamination of fuel form by process equipment (e.g., iron, chrome, etc)
	Impurities control	

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 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

<u>Additional Discussion</u>

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	Difference in grain orientation along principal directions as measured by the BAF
	Anisotropy (initial)	

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	Interconnected void accessible to the surface
	Porosity	

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

<u>Additional Discussion</u>

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	Size and orientation of the grains and the pores
	Grain size and microstructure, e,g, alignment	

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	Mean tensile strength (Weibull parameter or equivalent)
	Fracture strength	

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 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 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: 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	Amount of heavy metals dispersed in the layer present after manufacture
	Heavy metal dispersion	

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	Initial undetected pinhole or other defects resulting from the manufacturing process
	Defects	

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 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	Interfacial strength at the interface
	Bonding strength (inner PyC to SiC)	

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 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	Mass per unit volume and interconnected void accessible to the surface
	Density and open porosity	

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 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	Grain size, pore structure (interconnectivity) and orientation in kernel
	Microstructure (UO2)	

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.